THE R-PROCESS: STELLAR ABUNDANCES AND AGES AND UNANSWERED QUESTIONS

J.J. Cowan (Univ. of Oklahoma)

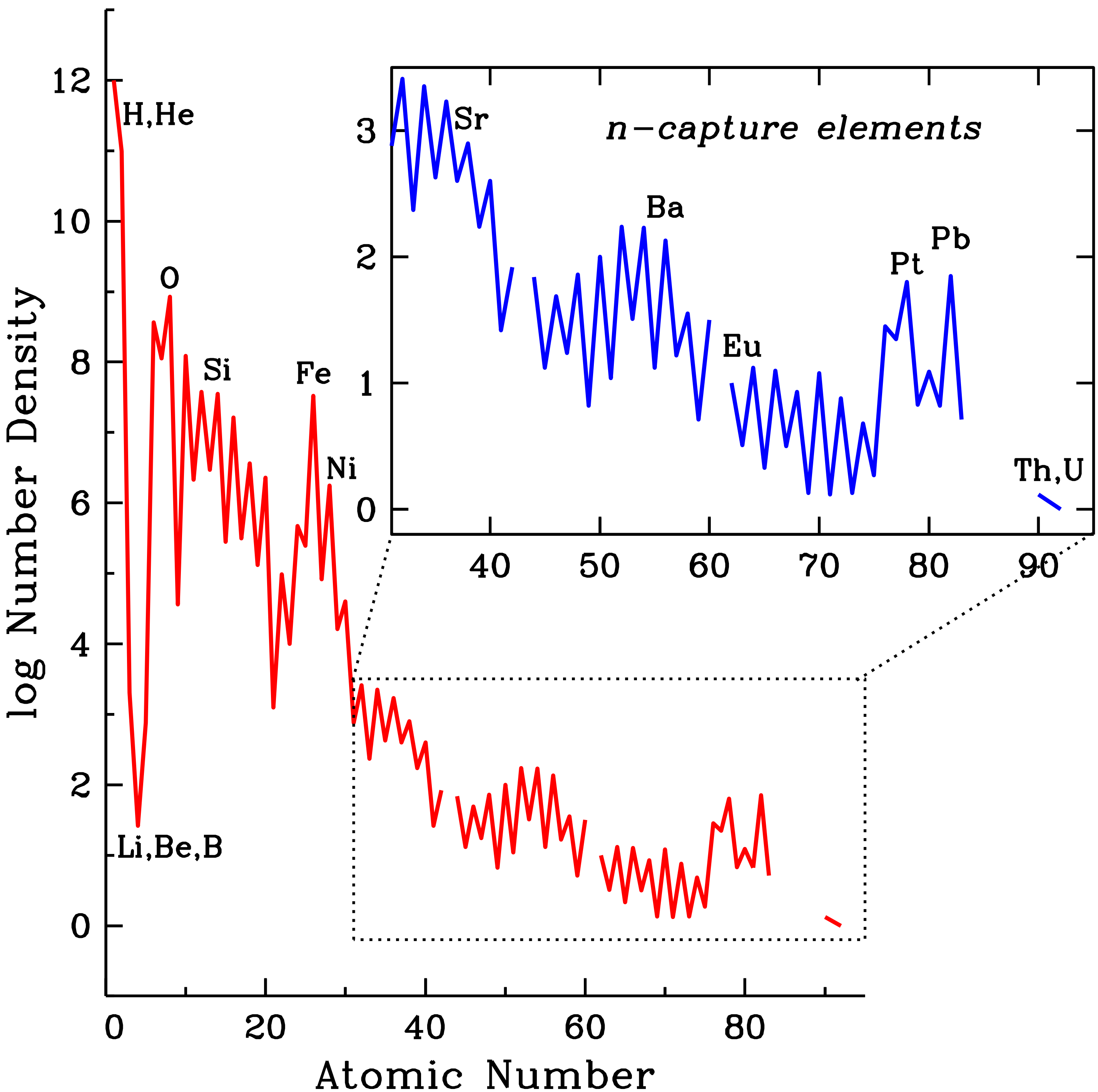
Speaking on behalf of my friends and colleagues at :

Univ. Texas
Univ. Chicago
MSU
Univ. Mainz
Univ. Wisconsin
Indiana Univ.
MIT
ESO
UCSD
....

TOP 11 GREATEST UNANSWERED QUESTIONS OF PHYSICS[1]

1. **What is dark matter?**
2. **What is dark energy?**
3. **How were the heavy elements from iron to uranium made?**
4. **Do neutrinos have mass?**
5. **Where do ultrahigh-energy particles come from?**
6. **New light and matter theory needed at ultra-high energies?**
7. **New states of matter at ultrahigh temperatures and densities?**
8. **Are protons unstable?**
9. **What is gravity?**
10. **Are there additional dimensions?**
11. **How did the universe begin?**

[1] Discover Magazine, February 2002.


n−capture elements
Sr
Ba
Eu
Pt
Pb
Th,U
H,He
O
Si
Fe
Ni
Li,Be,B
log Number Density
Atomic Number
0
20
40
60
80
2
4
6
8
10
12
0
1
2
3
40
50
60
70
80
90

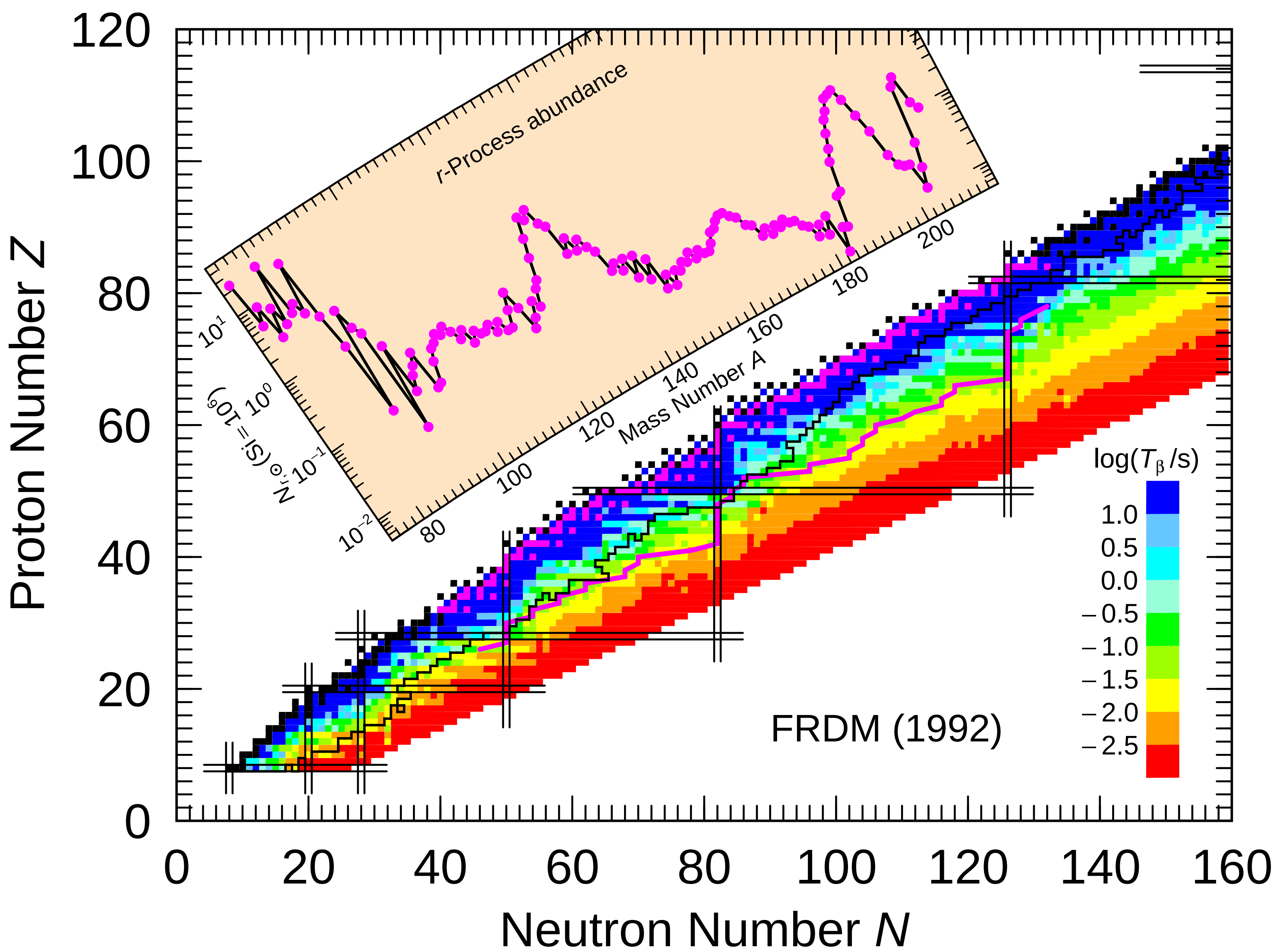
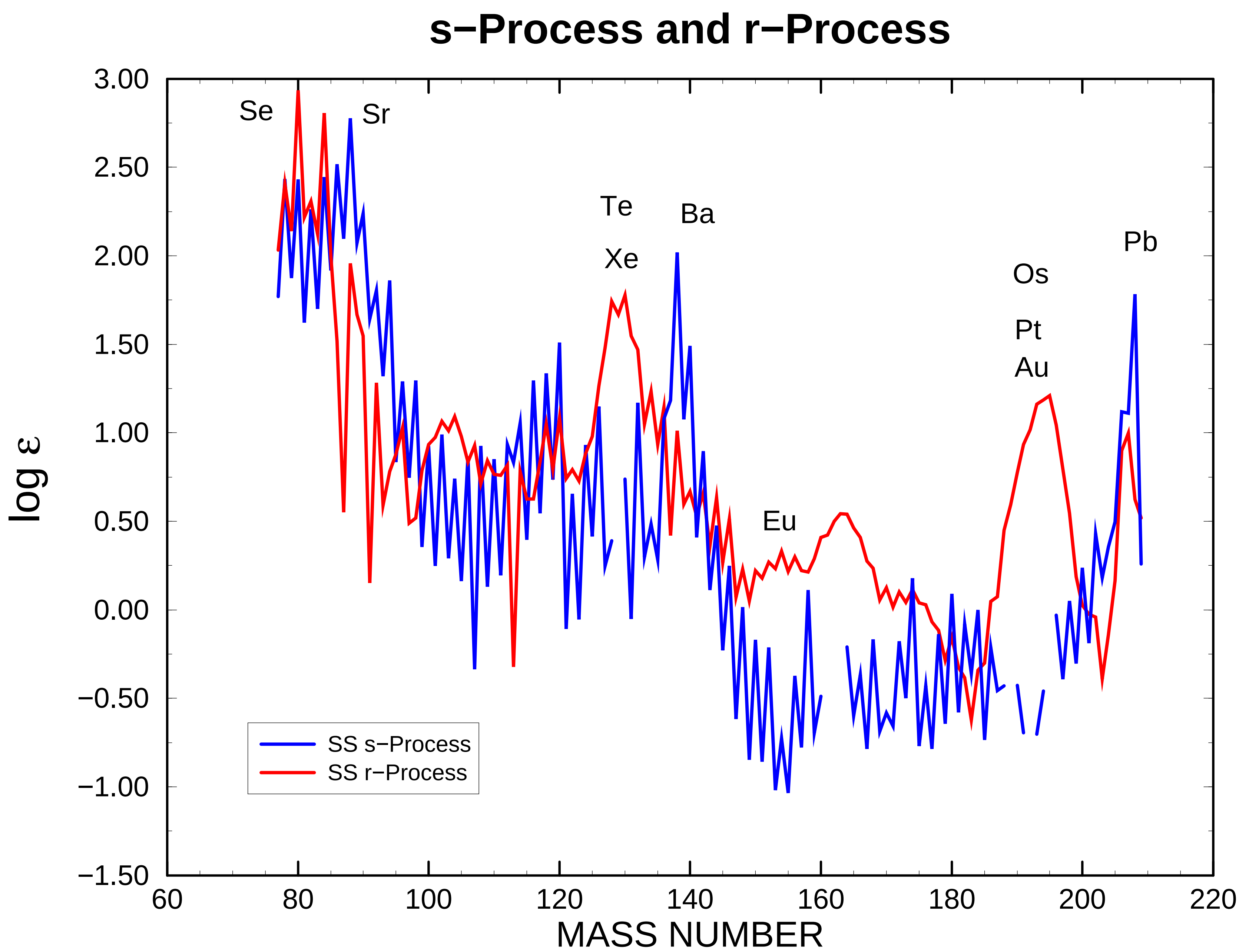

Proton Number Z
Neutron Number N
r-Process abundance
Mass Number A
N_r,⊙ (Si = 10^6)
log(T_β /s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
FRDM (1992)

Figure 16

Solar System Abundances



WHERE IN NATURE ARE THE R-PROCESS ELEMENTS FORMED?

• Large fluxes of neutrons suggests explosive conditions and supernovae.

BUT WHERE AND HOW?

MANY SUGGESTIONS

• Supernovae
Regions just outside the neutronized core (1957)
  Jets and bubbles

Helium zones
Carbon zones

OTHER SITES

• Red Giants
  Low mass helium core flashes

• Neutron Star-Neutron Star and Neutron Star-Black Hole Binaries
  Neutron Star Accretion Disks

• The big bang (inhomogeneous model)

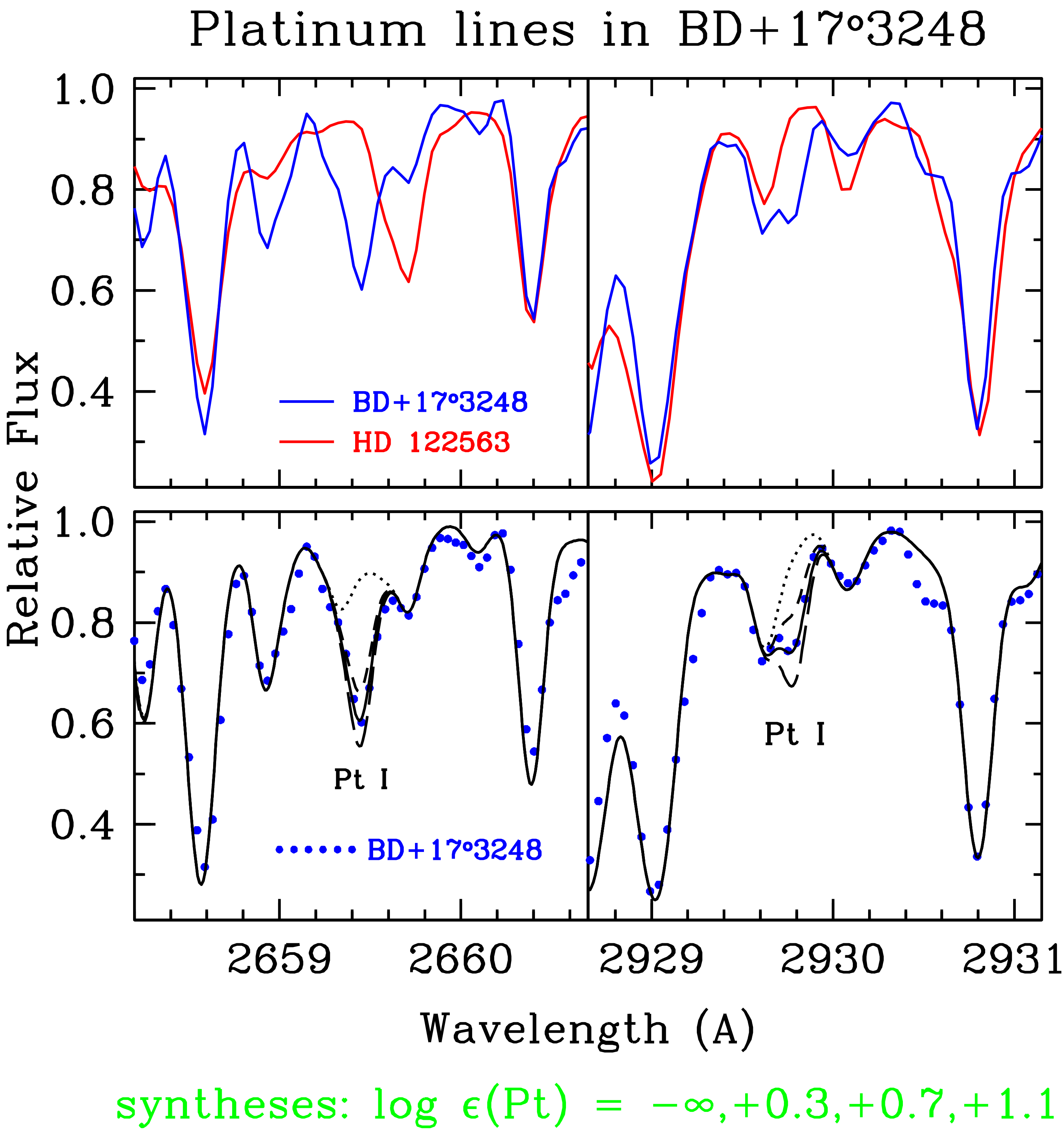
MOST LIKELY SITE (OR SITES ?) FOR THE R-PROCESS

- Supernovae

Regions just outside the neutronized core (1991)

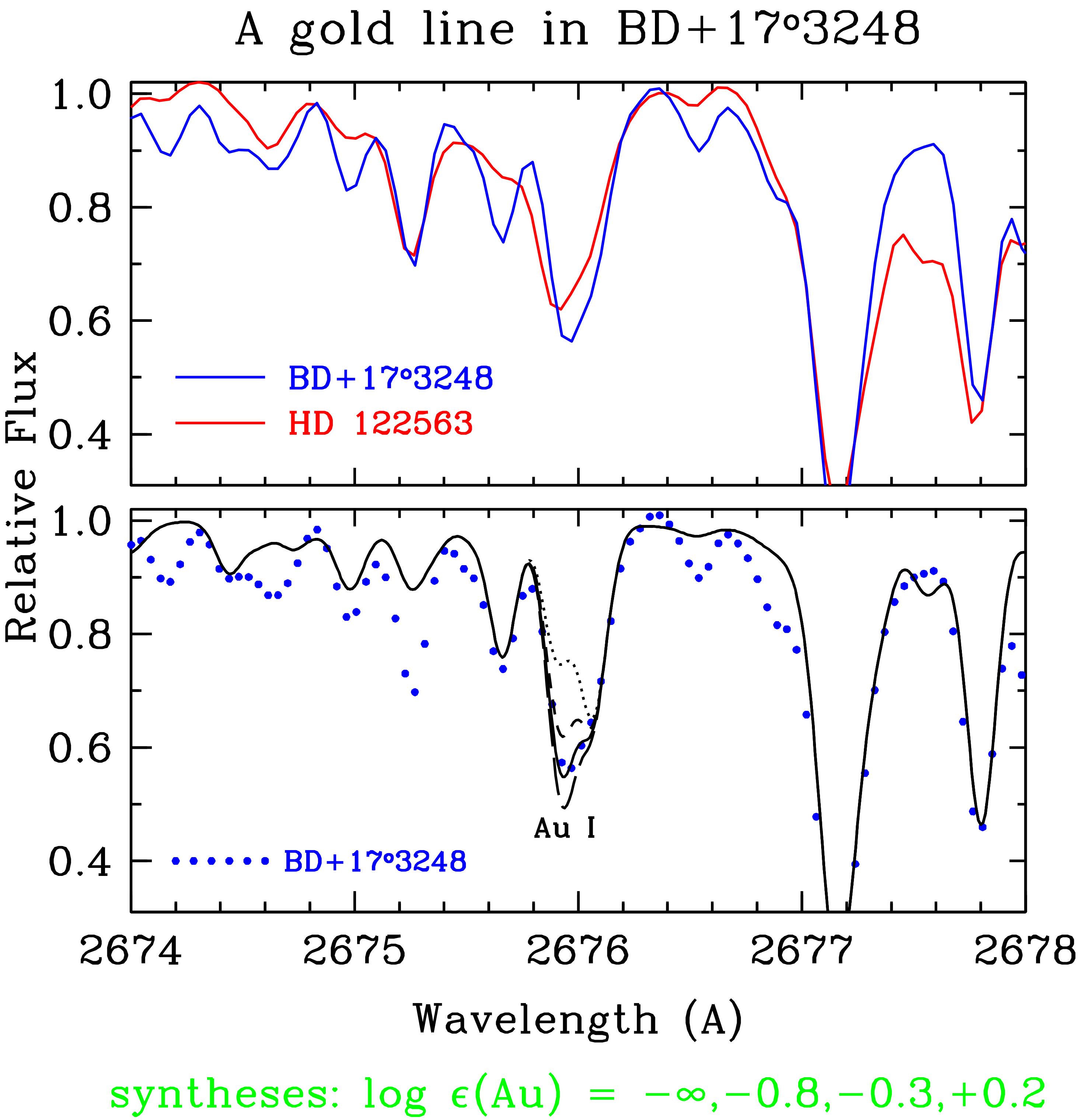
Jets and bubbles

- Neutron Star-Neutron Star and Neutron Star-Black Hole Binaries



Platinum lines in BD+17°3248
Relative Flux
1.0
0.8
0.6
0.4
BD+17°3248
HD 122563
Pt I
Pt I
BD+17°3248
2659
2660
2929
2930
2931
Wavelength (A)
syntheses: log ϵ(Pt) = −∞,+0.3,+0.7,+1.1

Observed HST-STIS and synthetic (computed) spectra in the region surrounding the gold spectral line at a wavelength of 2675.94 Angstroms. (One Angstrom = 1/100 millionth of a centimeter).

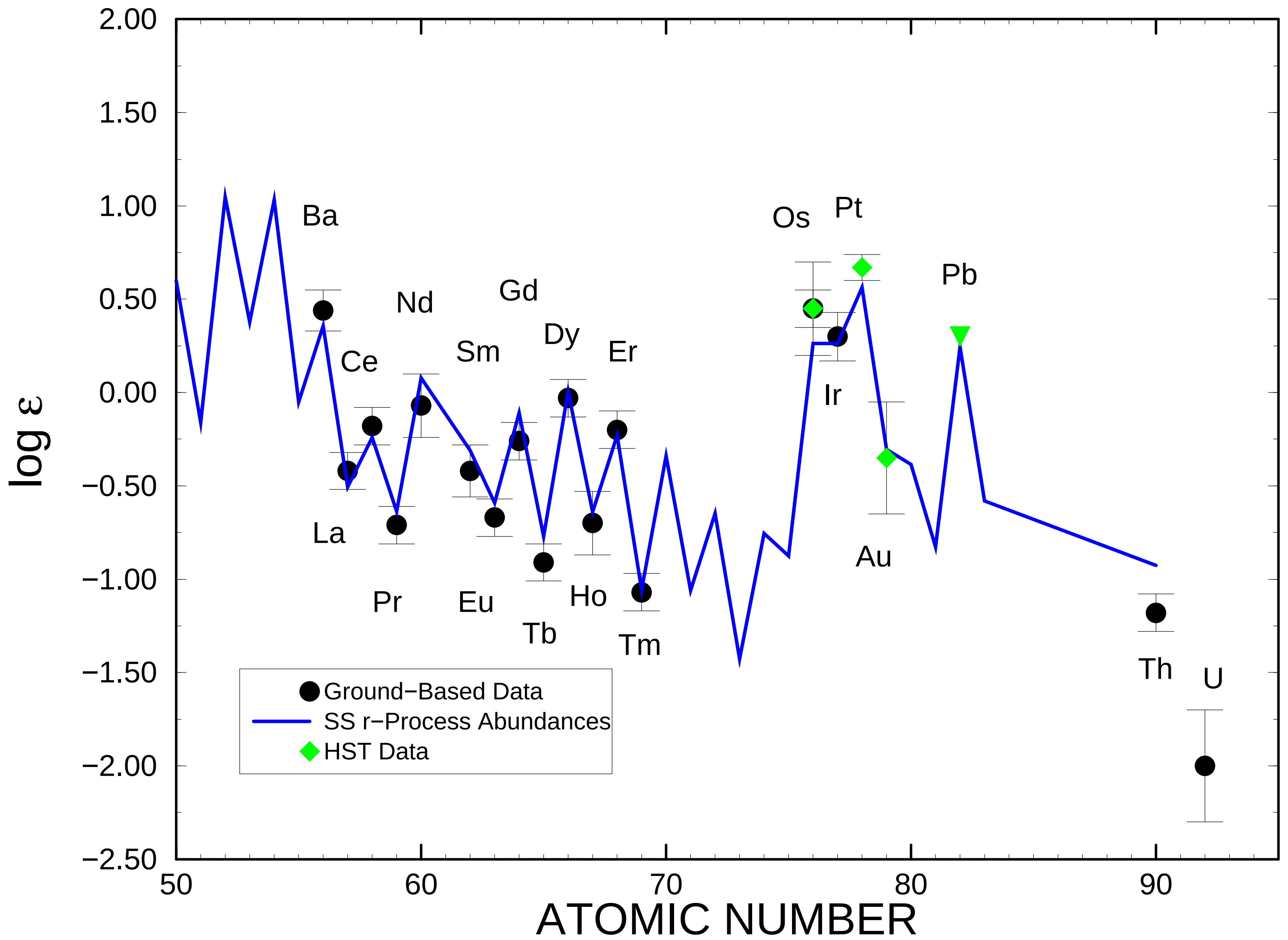


(Top) The observed spectrum of BD +17 3248, shown in blue, is compared to that of another old halo star in our Galaxy known as HD 122563, shown in red. The atomic gold spectral line is seen in BD +17 3248, but not in HD 122563. This detection could only be made using space telescopes such as the Hubble Space Telescope.

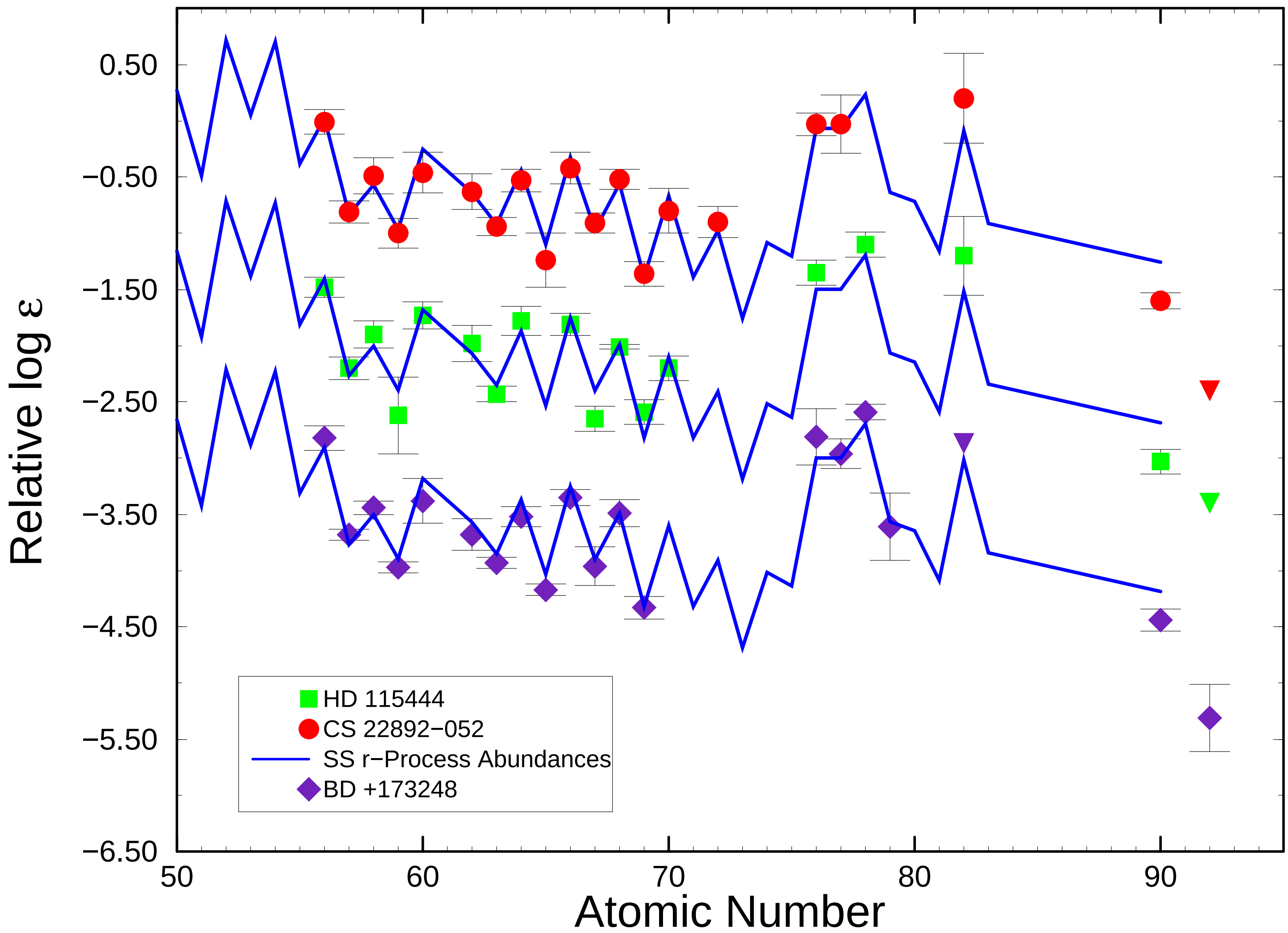
(Bottom) The observed BD +17 3248 spectrum, shown in blue dots, is compared to four synthetic spectra to determine the abundance of gold. The computed values, shown in order of increasing abundance of goldby dotted, short-dashed, solid, and long-dashed lines computed for these abundances are: log epsilon (Au) = -infinity, -0.80, -0.30, +0.2. The best fit is seen to be for log epsilon = -0.3, which indicates that gold in this star is less than a trillion times as abundant as hydrogen.

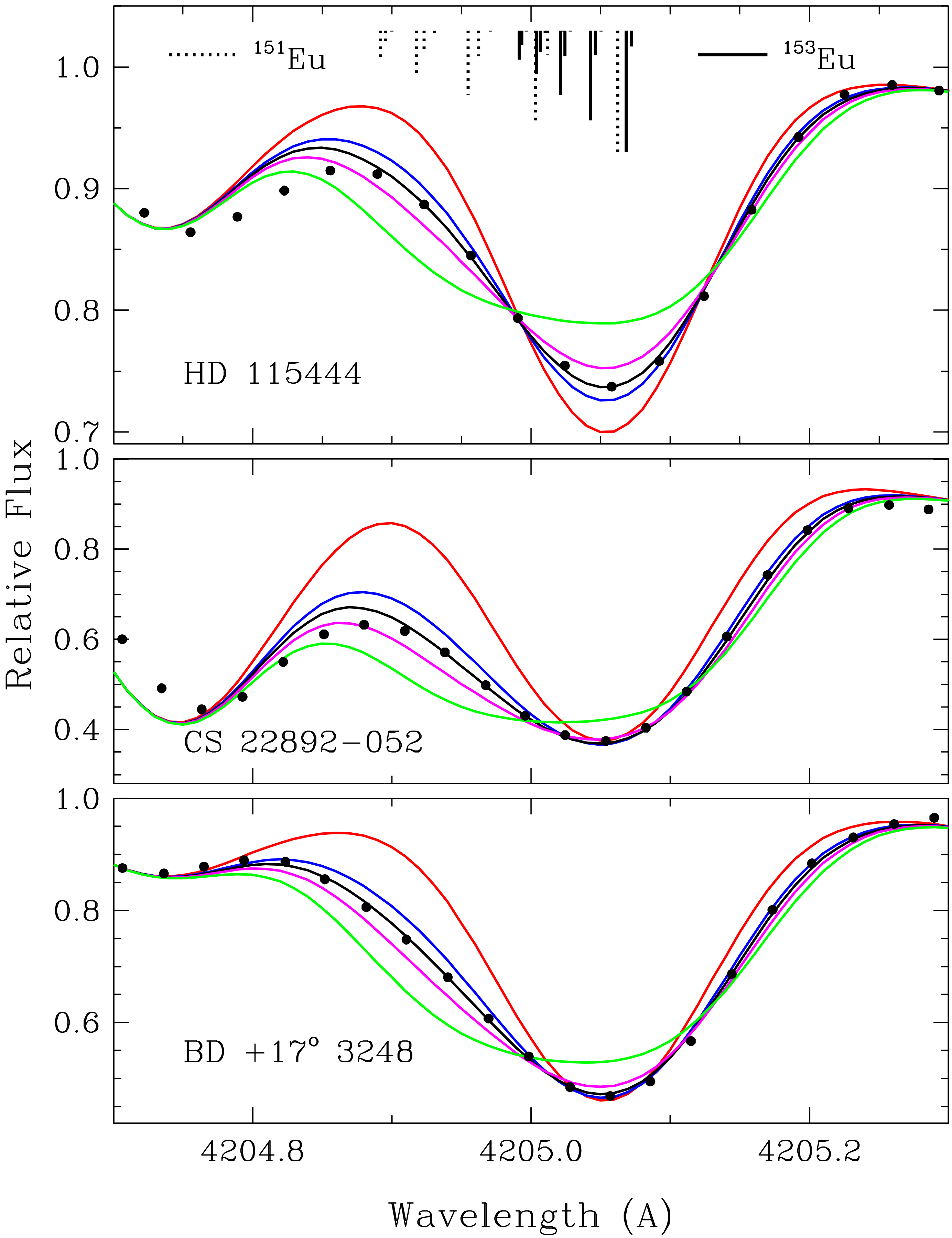
r−Process Abundances in BD+17 3248

(Cowan et al. 2002)



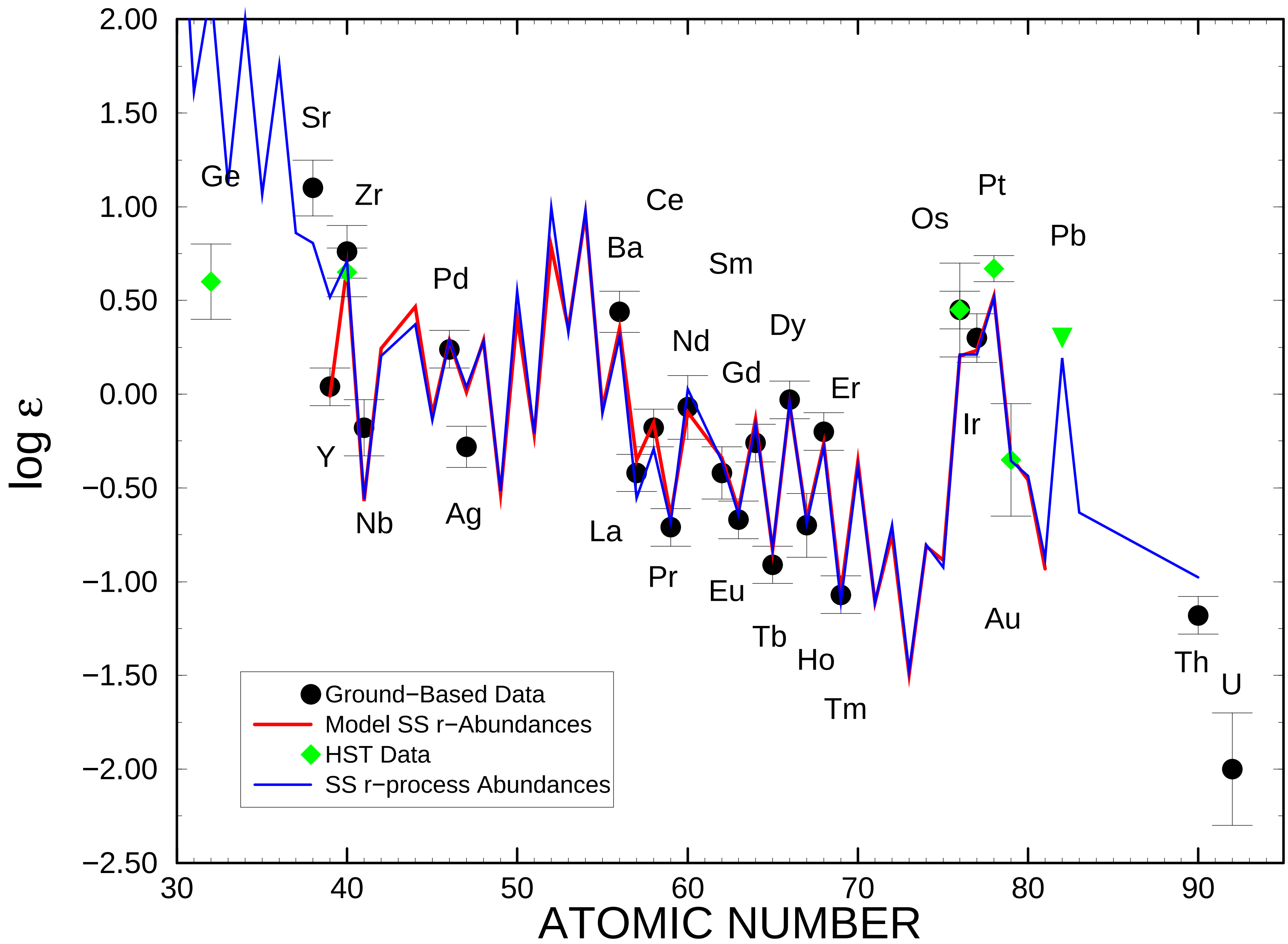
r−Process Abundances in Halo Stars

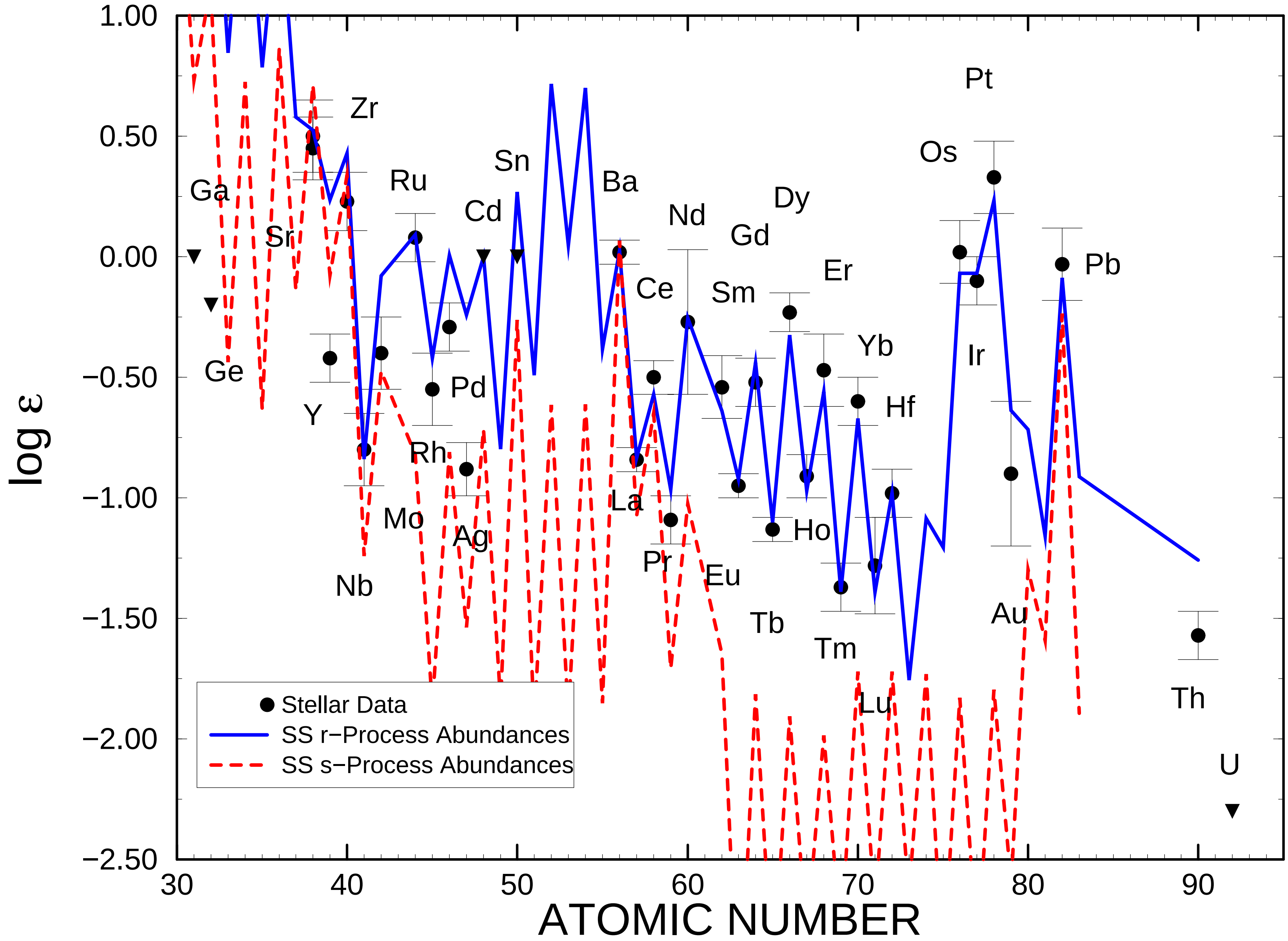


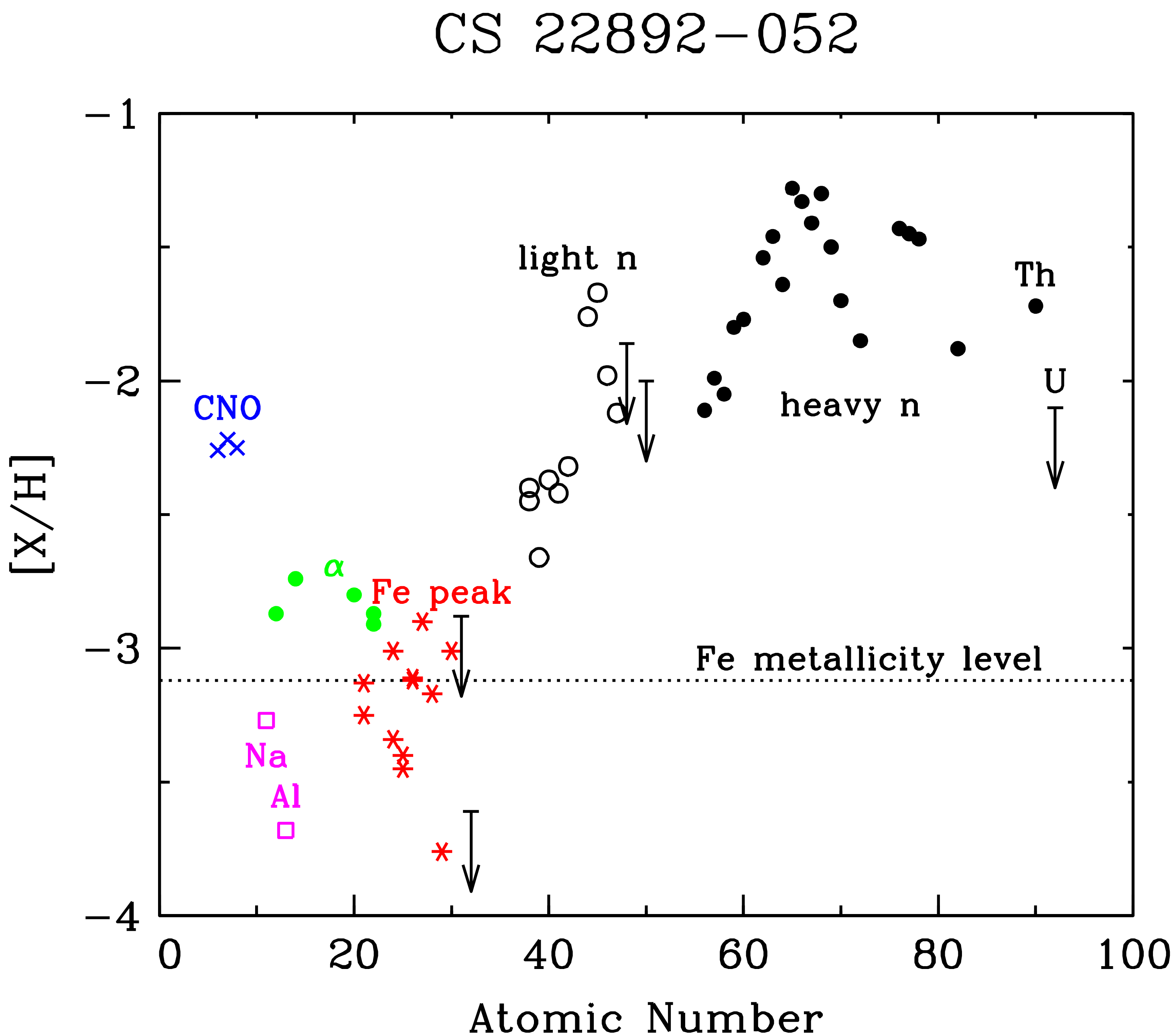


151Eu
153Eu
HD 115444
CS 22892−052
BD +17° 3248
Relative Flux
1.0
0.9
0.8
0.7
0.6
0.4
4204.8
4205.0
4205.2
Wavelength (A)

r−Process Abundances in BD+17 3248




log ε
ATOMIC NUMBER
1.00
0.50
0.00
−0.50
−1.00
−1.50
−2.00
−2.50
30
40
50
60
70
80
90
Ga
Ge
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
Sn
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Os
Ir
Pt
Au
Pb
Th
U
Stellar Data
SS r−Process Abundances
SS s−Process Abundances



CS 22892−052
[X/H]
Atomic Number
−1
−2
−3
−4
0
20
40
60
80
100
CNO
α
Fe peak
Na
Al
light n
heavy n
Th
U
Fe metallicity level

NEW DETECTIONS OF NEUTRON-CAPTURE ELEMENTS IN CS 22892–052, HD 115444 & BD +17 3248

- **Elements with atomic number Z = 40-50, including niobium, ruthenium, rhodium, palladium, silver and cadmium have been detected now in CS 22892–052, HD 115444 and BD +17°3248.**

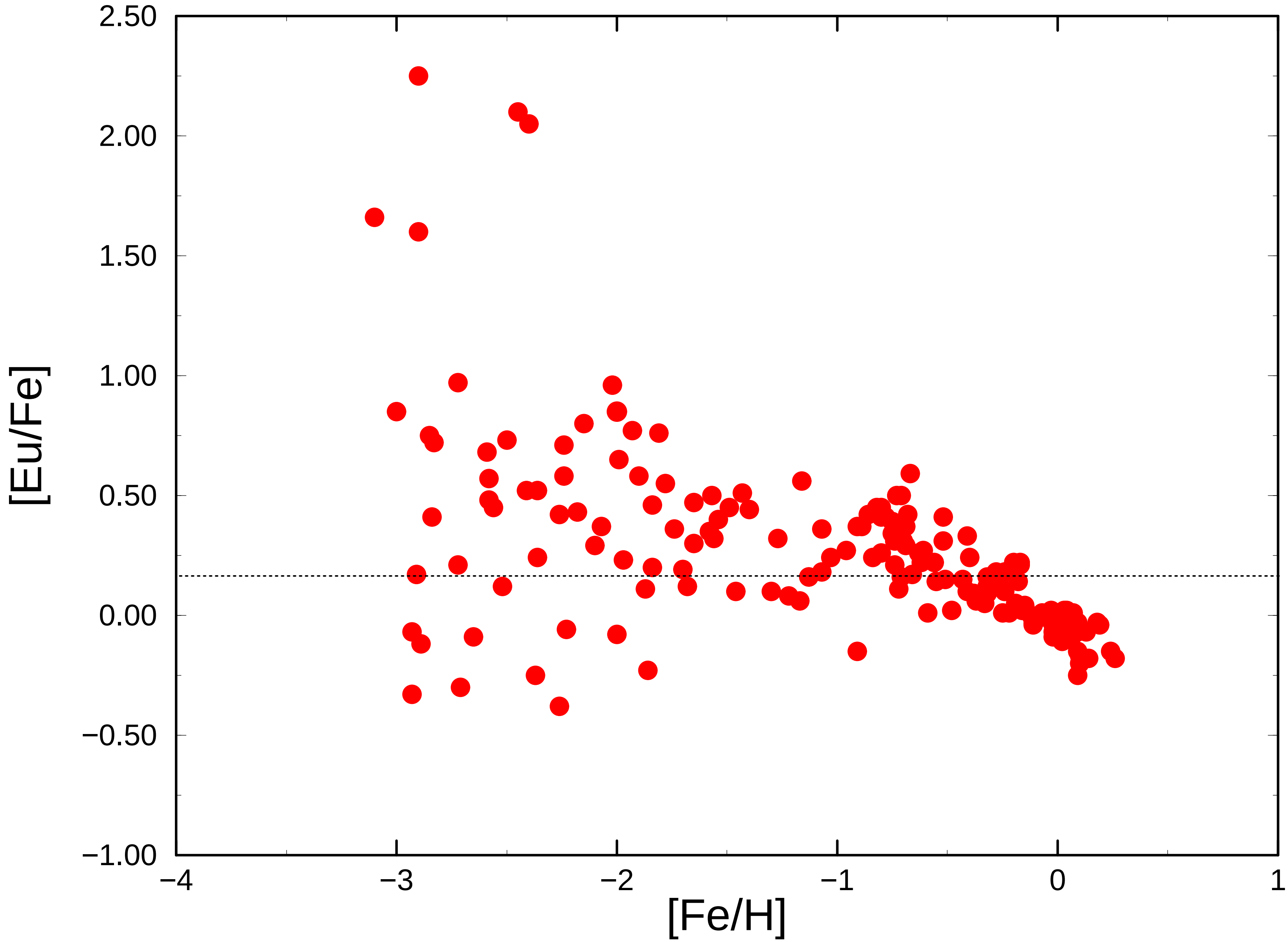
A SECOND R-PROCESS?

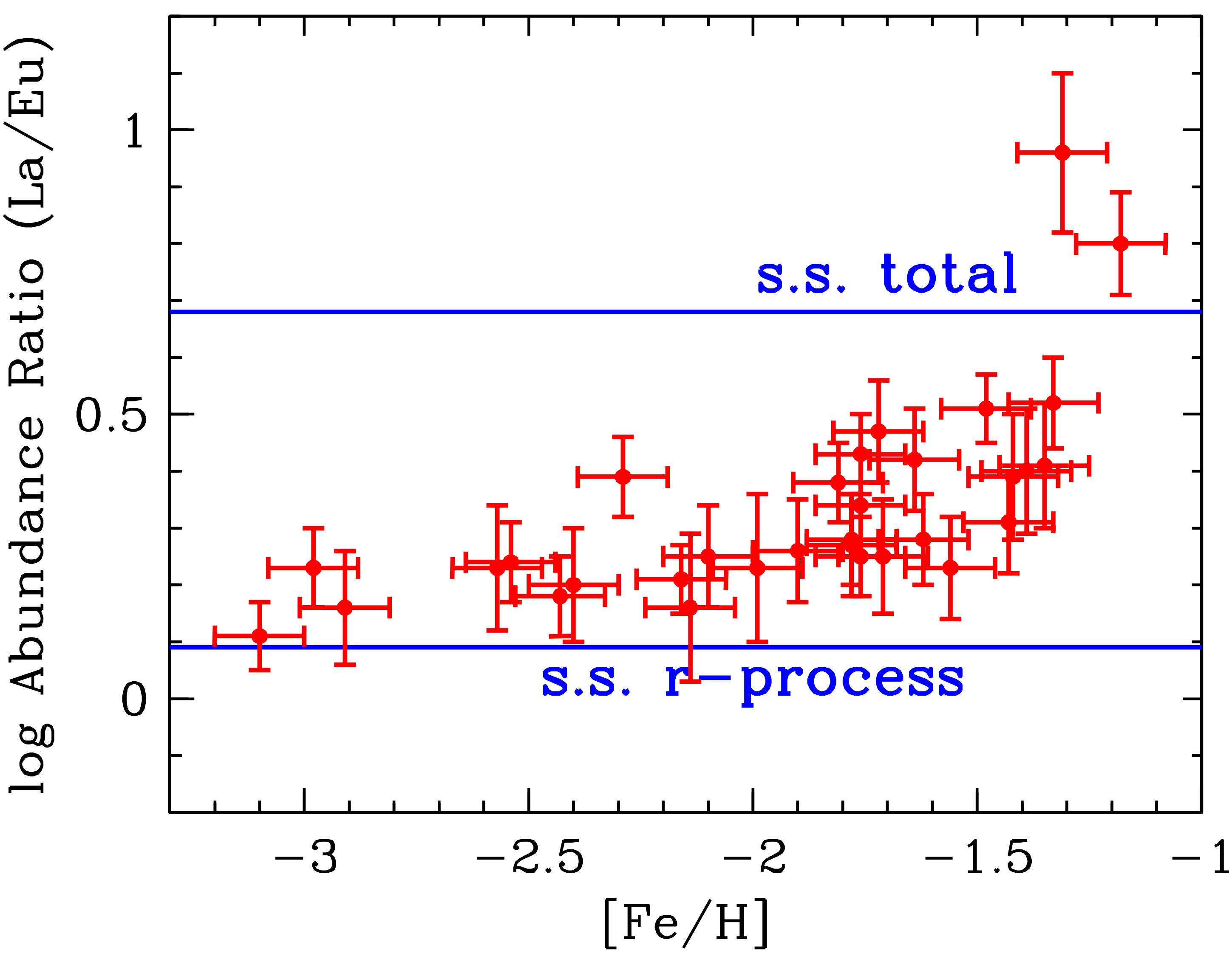
- **Abundances of the neutron-capture elements Z ≥ 56 (i.e. Ba and above) are consistent with the scaled solar system *r*-process curve (blue line) indicating that the relative elemental *r*-process abundances have not changed over the history of the Galaxy and further suggests that there is one *r*-process site in the Galaxy, at least for elements Z ≥ 56. Robust.**
- **Abundances of the newly determined elements from Z=40-50 in general fall below the scaled solar system *r*-process curve. These data seem to support the suggestion (Wasserburg, Busso & Gallino 1996, Wasserburg & Qian 2000) that there may be two *r*-process sites, with one responsible for the heavier elements (occurring on a more rapid time-scale) and a less frequently occurring synthesis producing the elements below Ba.**

- **Strong and a Weak r-Process?**

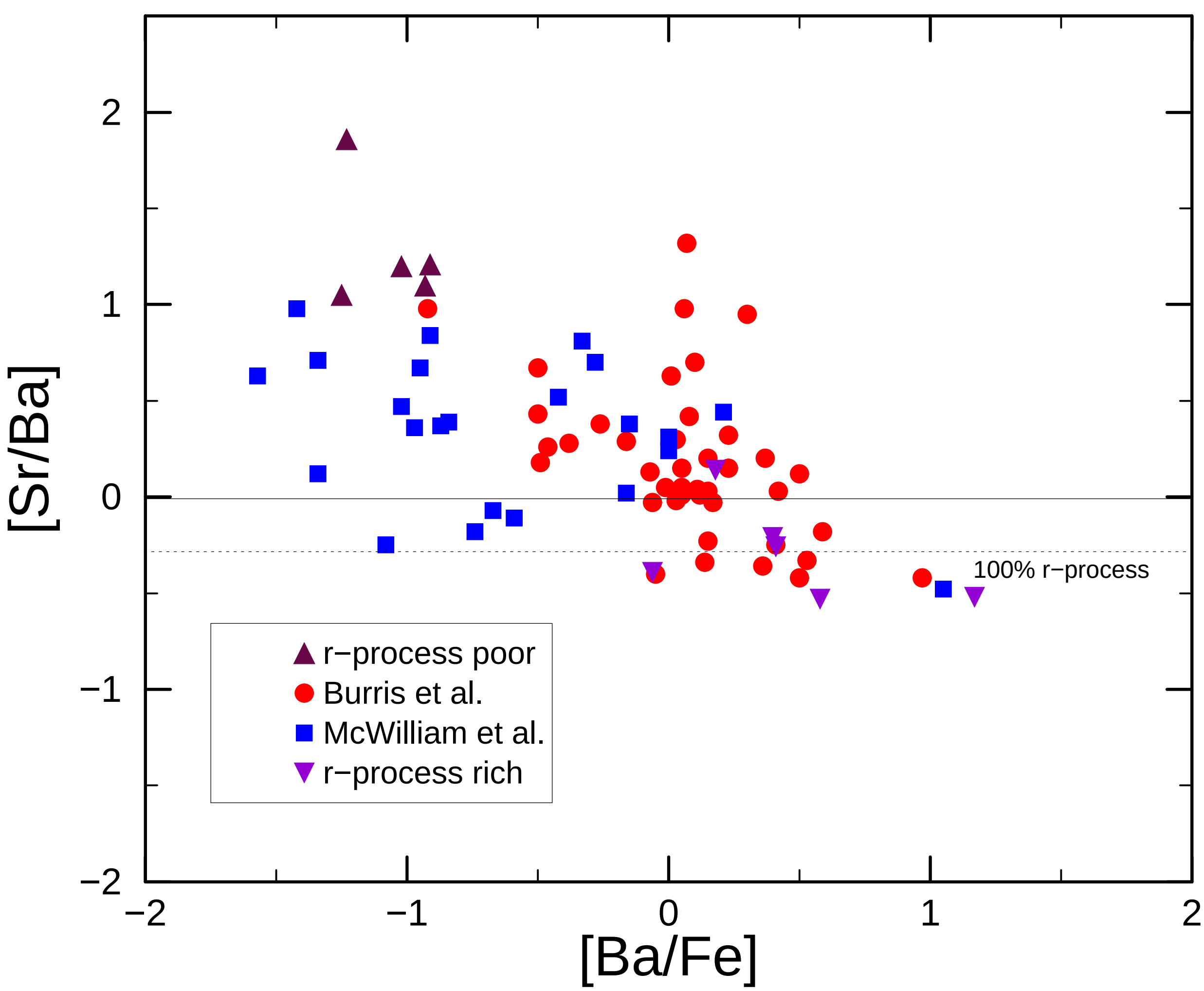
- **Alternative explanations: one supernova site with two different epochs in the explosion/ejection process or different regions of the same neutron-rich jet of a core-collapse supernova (Sneden et al. 2000; Cameron 2001).**

ABUNDANCE SCATTER IN THE GALAXY





log Abundance Ratio (La/Eu)
1
0.5
0
s.s. total
s.s. r−process
−3
−2.5
−2
−1.5
−1
[Fe/H]



r−process poor
Burris et al.
McWilliam et al.
r−process rich
100% r−process
[Sr/Ba]
[Ba/Fe]
2
1
0
−1
−2
−2
−1
0
1
2

Radioactive-Decay Age Estimates

The measured abundance of Th presents the opportunity to determine the age of CS 22892–052, by use of the known Th half-life (14.05 Gyr):

$$N_{Th}(t) = N_{Th}(t_0)exp(-t/\tau_{Th})$$

Where

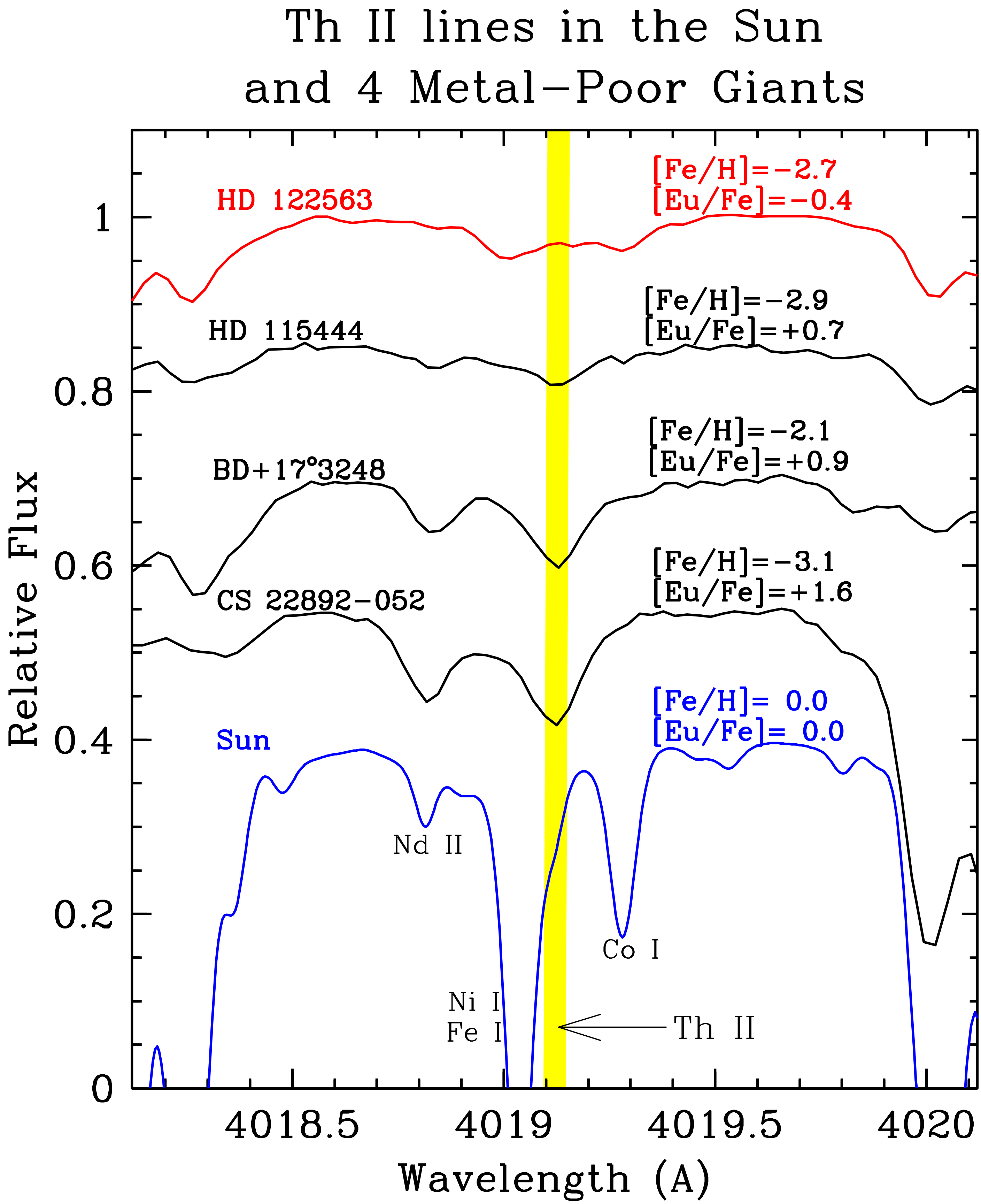
$$\tau_{Th} = \frac{14.05}{ln2} = 20.27Gyr$$

$\Longrightarrow$ Solar System Th/Eu (at formation) = 0.463

$\Longrightarrow$ Solar System Th/Eu (today) = 0.344

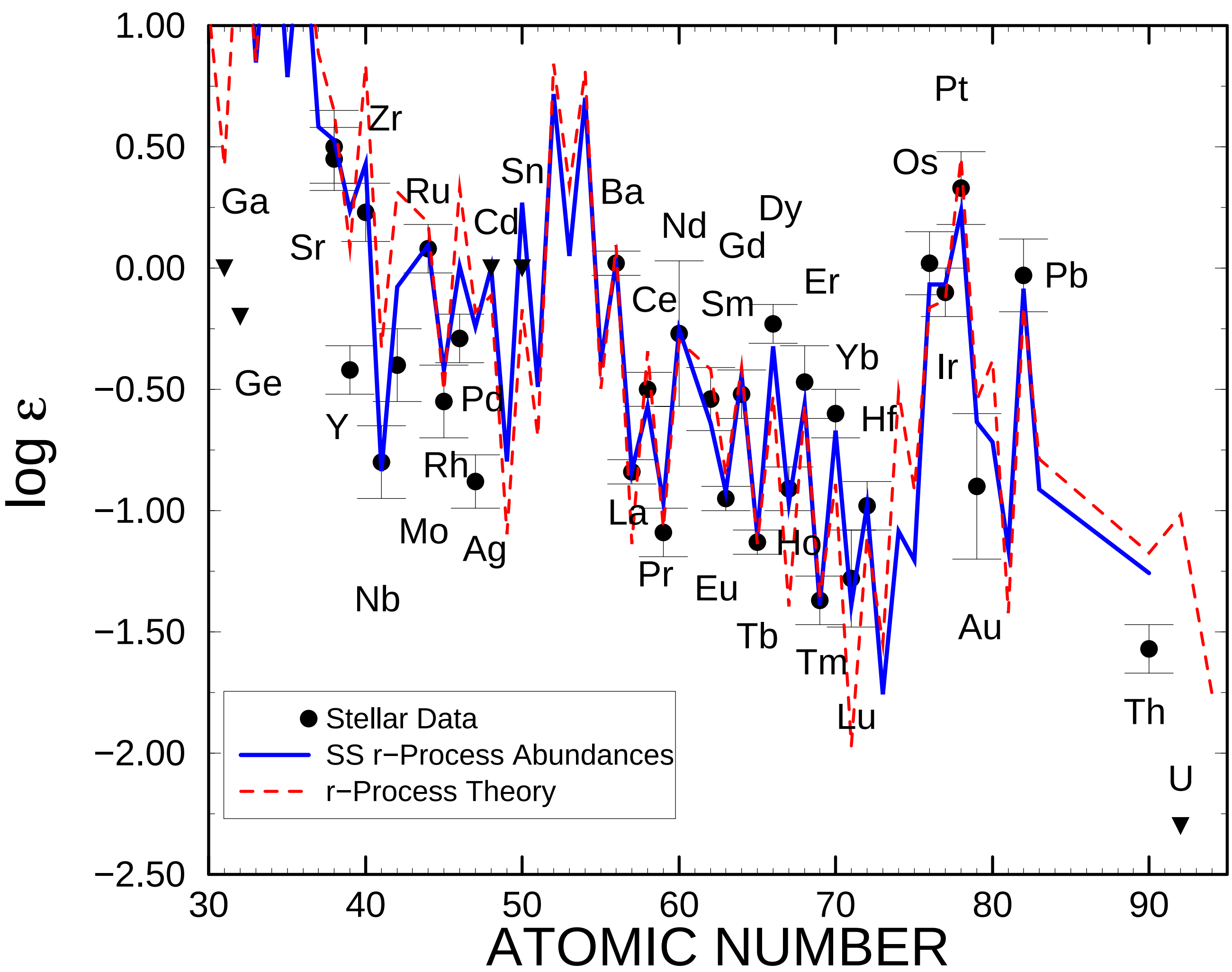
$\Longrightarrow$ Observed Th/Eu in CS 22892-052 = 0.219

It is important to note, that since the solar-system Th/r ratio is larger than the observed ratio in CS 22892–052 then CS 22892–052 must be older than the solar system r-process material.



Th II lines in the Sun
and 4 Metal-Poor Giants
HD 122563
[Fe/H]=−2.7
[Eu/Fe]=−0.4
HD 115444
[Fe/H]=−2.9
[Eu/Fe]=+0.7
BD+17°3248
[Fe/H]=−2.1
[Eu/Fe]=+0.9
CS 22892−052
[Fe/H]=−3.1
[Eu/Fe]=+1.6
Sun
[Fe/H]= 0.0
[Eu/Fe]= 0.0
Nd II
Co I
Ni I
Fe I
Th II
Relative Flux
0
0.2
0.4
0.6
0.8
1
4018.5
4019
4019.5
4020
Wavelength (A)

r−Process Abundances in CS 22892−052



Th/Eu Chronometers

Model	$\frac{Th}{Eu}\vert_{model}$	Age (Gyr)
Solar	0.463	13.8
FRDM	1.770	41.0
ETFSI-1	0.488	14.9
HFB/SkP	0.388	10.2
FRDM+HFB	0.496	$15.2 \pm \simeq 4$
ETFSI-Q	0.546	$17.1 \pm \simeq 4$
ETFSI-Q(lsq)	0.480	$14.5 \pm \simeq 4$

ABUNDANCE RATIOS AND AGES

Star	$\Delta log\epsilon(Th/Eu)\|_{obs.}$	< Age >
CS 22892-052	-0.66	16.6
CS 22892-052 + HD 115444	-0.63	15.6
M15	-0.59	14.3
5 Halo Stars	-0.6	11.4 ± 4.2
BD+17 3248	-0.52	10.2
CS 31082-001	-0.22	3.8 !!

Sneden et al. (2000), Johnson & Bolte (2001), JC et al. (2002), Schatz et al. (2002)

GLOBULAR CLUSTERS: $\simeq 11 - 16$ Gyr (Chaboyer et al. 1996, Gratton et al. 1997, Pont et al. 1999)

SNIa: 14.9 ± 1.5 Gyr (Perlmutter et al. 1999); 14.2 ± 1.7 Gyr (Riess et al. 1998)

CHRONOMETRIC AGE ESTIMATES FOR BD +17°3248

Pair	Predicted Value	Observed Value	Age (Gyr)	Solar[1] Value	Age (Gyr)
Th/Eu	0.51	0.31	10.0	0.46	8.2
Th/Ir	0.091	0.031	21.7	0.065	14.8
Th/Pt	0.023	0.014	10.3	0.032	16.8
Th/U	1.80	7.41	13.4	2.32	11.0
U/Ir	0.050	0.004	15.5	0.037	13.5
U/Pt	0.013	0.002	12.4	0.018	14.6

[1] Burris *et al.* (2000)

REMAINING PROBLEMS

- The site of the r-process is still unknown. Are there two r-process sites?

$\Downarrow$

NEED BETTER NUCLEAR PHYSICS DATA: For very radioactive nuclei limited experimental data available $\rightarrow$ Rely on theoretical predictions for the near future.

$\Downarrow$

NEED IMPROVED ASTROPHYSICAL MODELS: Details of the supernova explosion. Can they synthesize the heaviest n-capture nuclei? What about neutron star binaries?

- Radioactive age uncertainties directly related to nuclear physics and observational uncertainties.

$\Downarrow$

AGAIN WE NEED BETTER NUCLEAR PHYSIC DATA: Nuclear mass models that are reliable $\rightarrow$ for very neutron-rich nuclei.

MORE HIGH QUALITY STELLAR OBSERVATIONAL DATA : More U detections.

SUMMARY

An overview of the the rapid neutron capture process (*i.e.*, the r-process) is presented. Abundances of these neutron-capture nuclei and elements in solar system material can be compared with elemental and isotopic abundance patterns in certain stars. Abundance observations indicate the presence of these r-process elements in old Galactic halo and globular cluster stars. These observations demonstrate that the earliest generations of stars in the Galaxy, responsible for neutron-capture synthesis and the progenitors of the halo stars, were rapidly evolving. Abundance comparisons among large numbers of stars provide clues about the nature of neutron-capture element synthesis both during the earliest times and throughout the history of the Galaxy. In particular, these comparisons suggest differences in the way the heavier (including Ba and above) and lighter neutron capture elements are synthesized in nature. Understanding these differences will help to identify the astrophysical site (or sites) of and conditions in the r-process. The abundance comparisons also demonstrate a large star-to-star scatter in the neutron-capture/iron ratios at low metallicities- which disappears with increasing [Fe/H]- and suggests an early, chemically unmixed and inhomogeneous Galaxy. The very recent neutron-capture element observations indicate that the early phases of Galactic nucleosynthesis, and the associated chemical evolution, are quite complex, with the yields from different (progenitor) mass-range stars contributing to different chemical mixes. Stellar abundance comparisons indicate a change from the r-process to the slow neutron capture (*i.e.*, s-) process at higher metallicities (and later times) in the Galaxy. In addition the detection of thorium and uranium in halo and globular cluster stars offers a promising, independent age-dating technique that can put lower limits on the age of the Galaxy and thus the Universe. The models and comparisons are also discussed in the context of the remaining problems and open questions in the r-process. These include the general lack of nuclear data for the most neutron-rich nuclei and the critical nature of the nuclear mass formulae; differences in the production of the heavier (above barium) and lighter neutron-capture elements; and the uncertainties in identifying the actual astrophysical site for the r-process and the evidence for, and the possible existence of, more than one such site.