THE R-PROCESS IN HALO STARS

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Matter & Energy in the Universe: from Nucleosynthesis to Cosmology
(Recontres de Blois) - May 25, 2007

Abundance Clues and Constraints

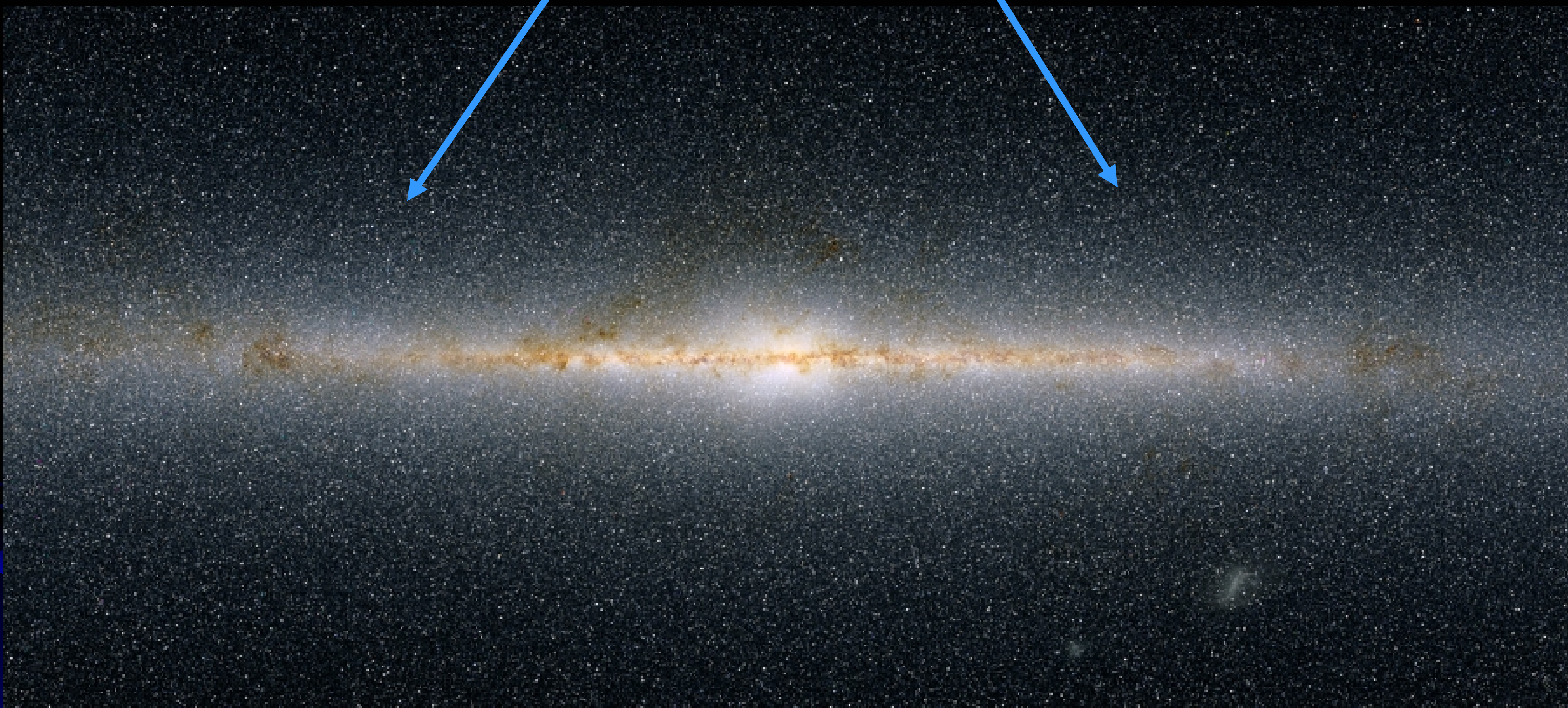
- New observations of n-capture elements in low-metallicity Galactic halo stars providing clues and constraints on:

1. Synthesis mechanisms for heavy elements early in the history of the Galaxy
2. Identities of earliest stellar generations, the progenitors of the halo stars
3. Suggestions on sites, particularly site or sites for the r-process
4. Galactic chemical evolution
5. Ages of the stars and the Galaxy → chronometers

Solar System Abundances

2MASS View of the Milky Way

Galactic Halo Stars

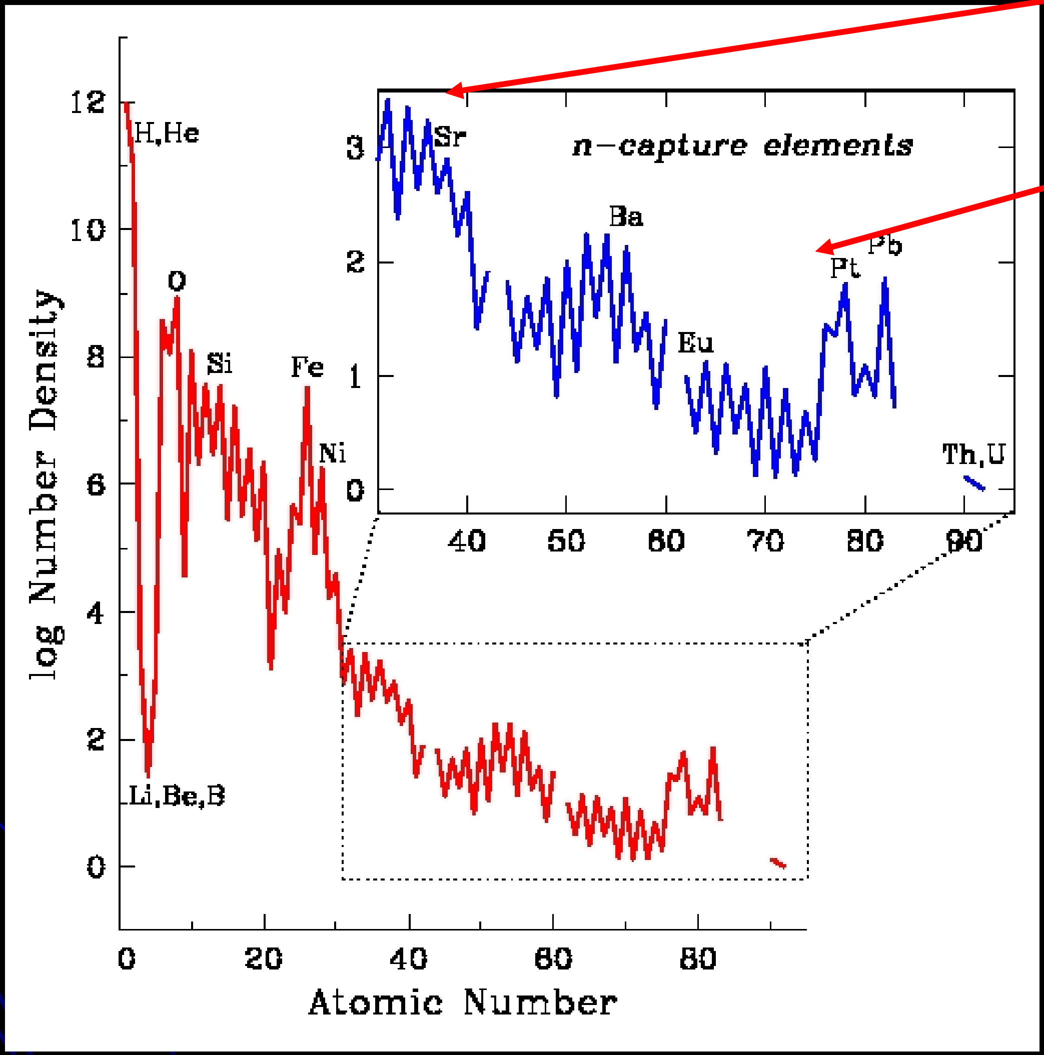


- Metal-poor Halo Stars are ``fossils'' of the Early Universe
- These Stars are Relatives of the First Stars in the Universe

``Near Field Cosmology''

back

Solar System (``Cosmic") Abundances



Ge, Zr

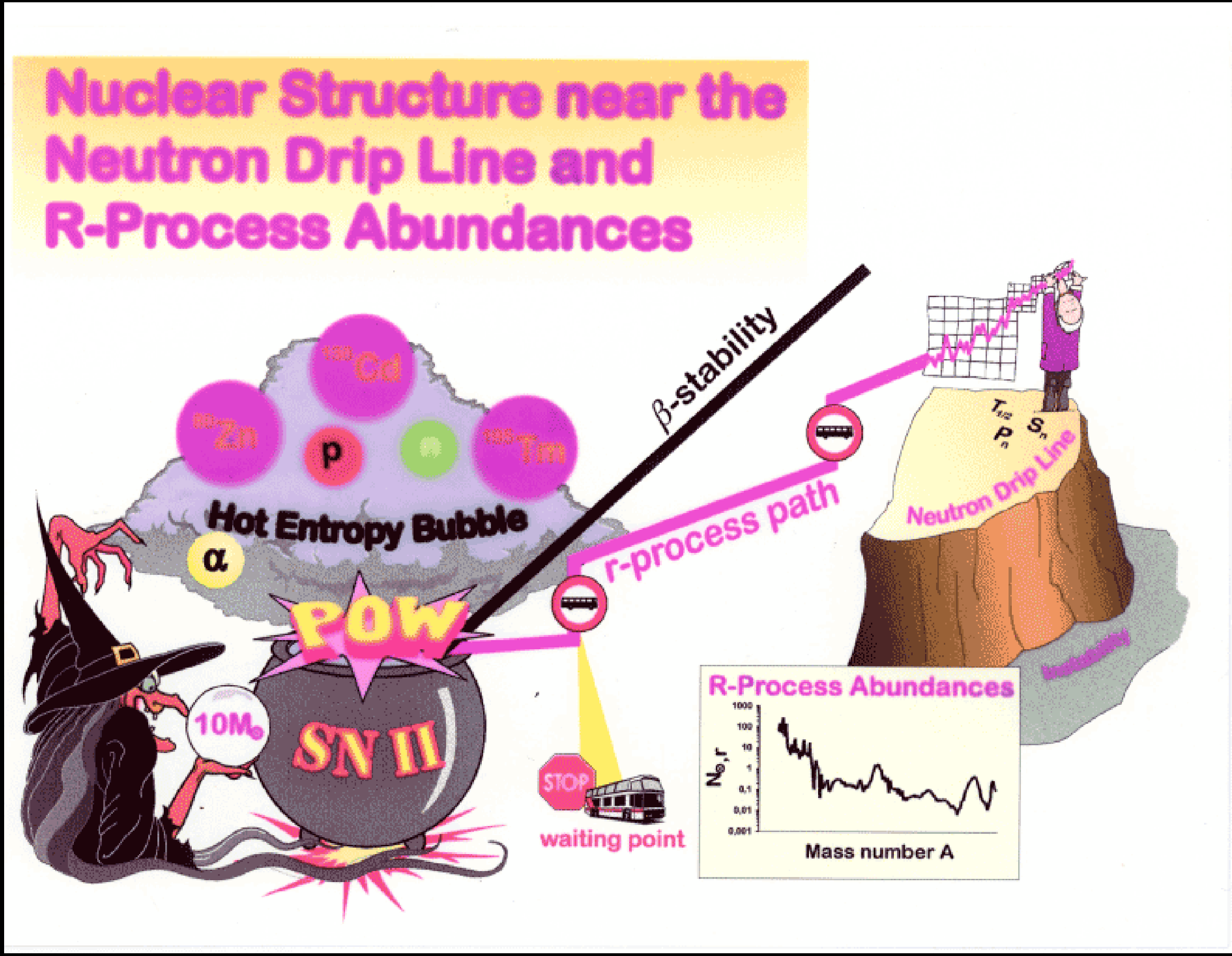
Os, Pt

Jewelry store items

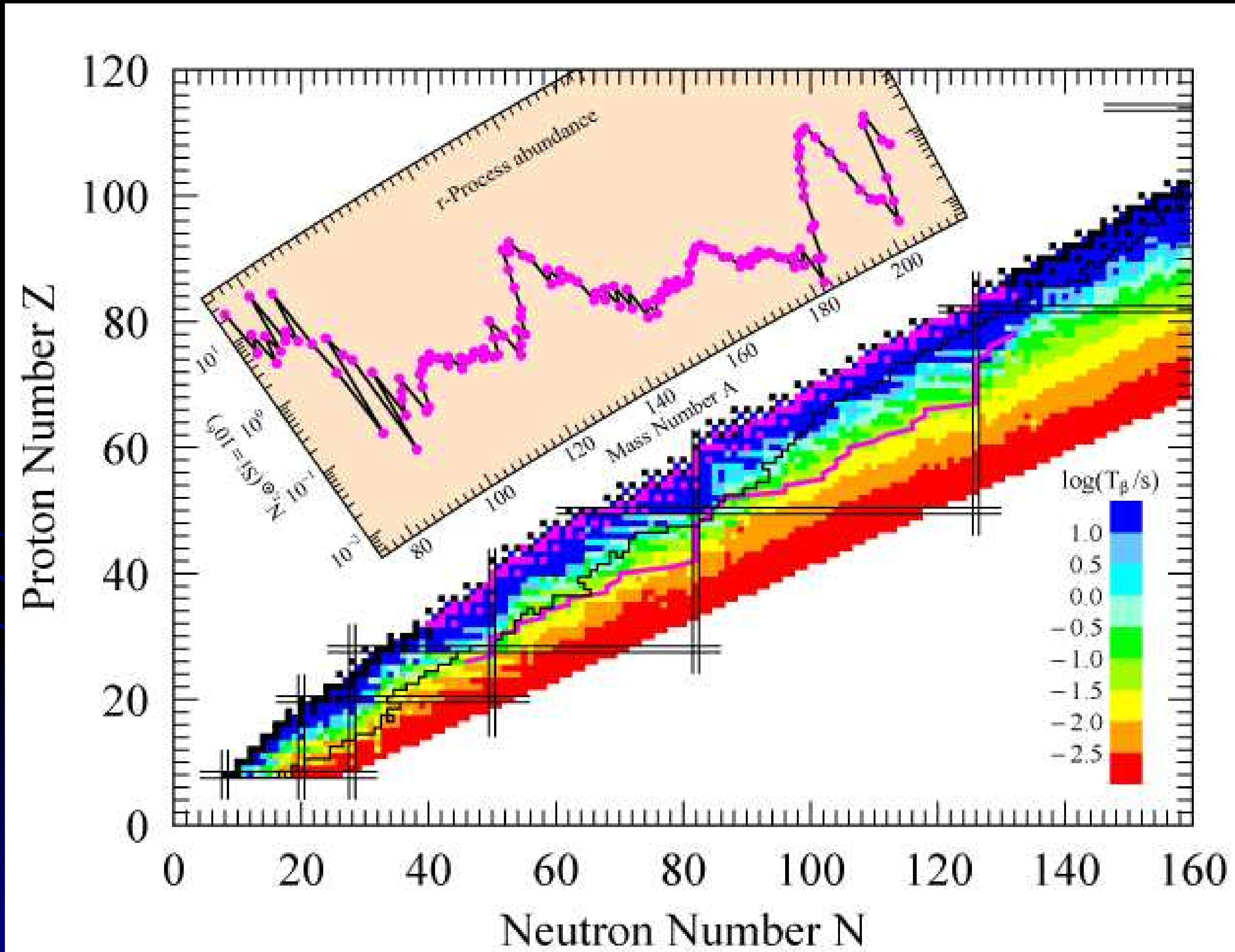
Sneden & JC (2003)

r-Process Nucleosynthesis

- For the r-process:
- $\tau_{nc} << \tau_{\beta}$ decay (typically 0.01–0.1 s)
- Site for the r-process still not still not identified

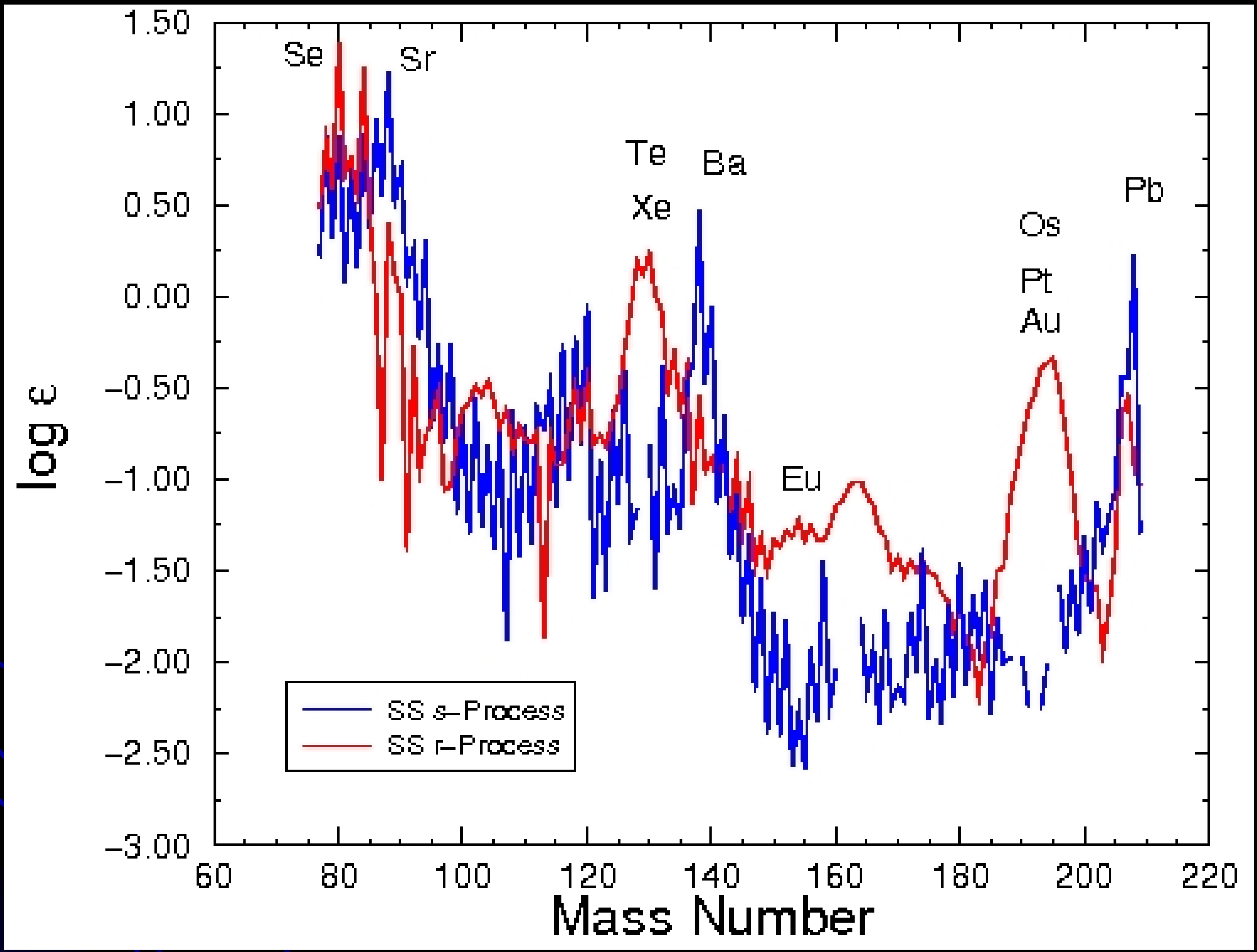


The Nuclear Isotopes in Nature



details

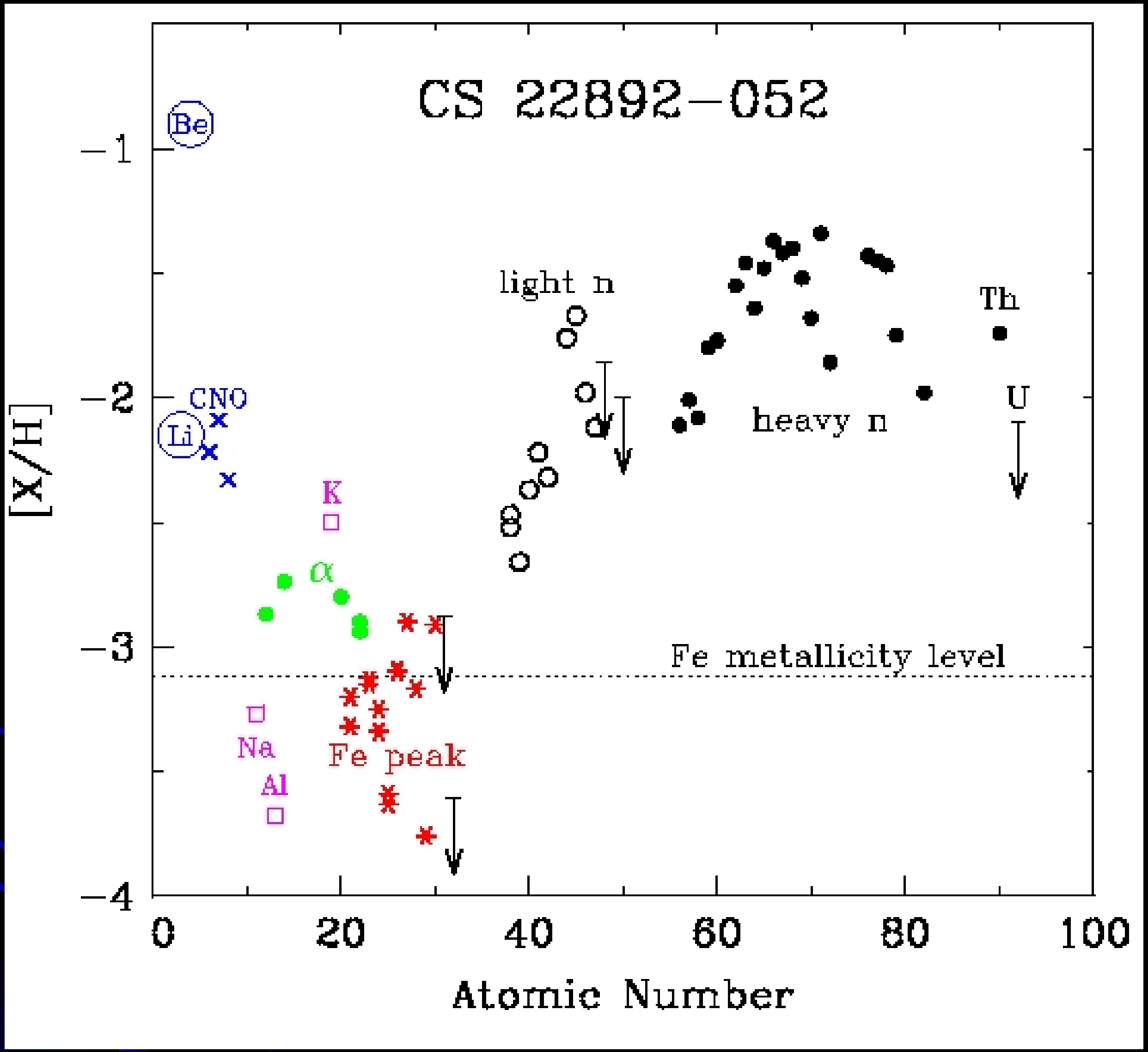
Solar System s- and r-Process Abundance Peaks



SS isotopic deconvolution by s- and r-process

$\text{Log } \varepsilon(A) = \log_{10}(N_A/N_H) + 12$

Total Abundances in CS 22892-052: A Metal-Poor Halo Star



Heavy n-capture elements greatly enhanced (≈ 40-50) over iron abundance.

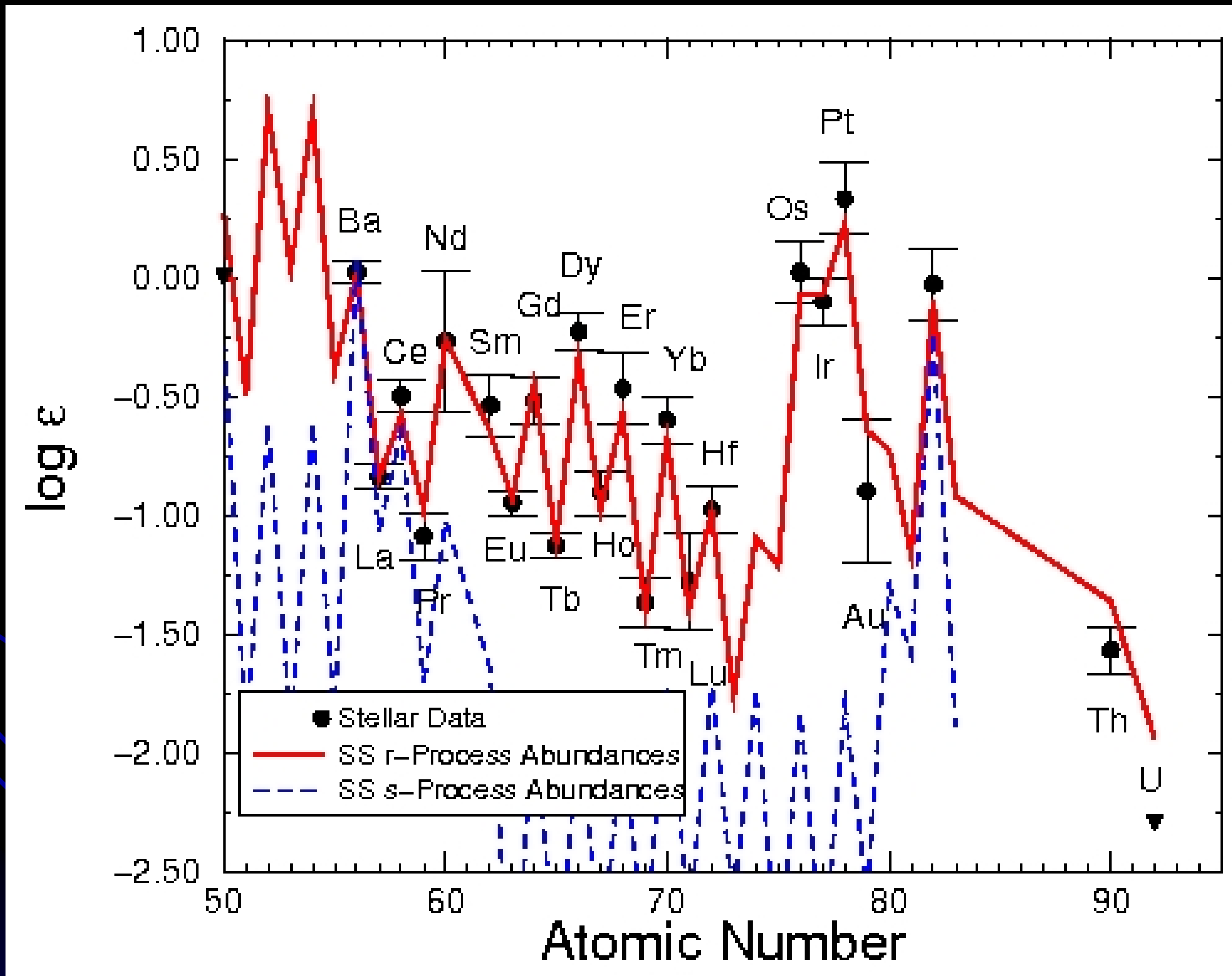
Light elements mostly scale with [Fe/H].

[Fe/H] = -3.1

$[A/B] = \log_{10}(A/B)_{star} - \log_{10}(A/B)_{sun}$

n-Capture Abundances in CS 22892-052

Even s-process elements like Ba made in r-process early in the Galaxy.



Historical (~ 1996)

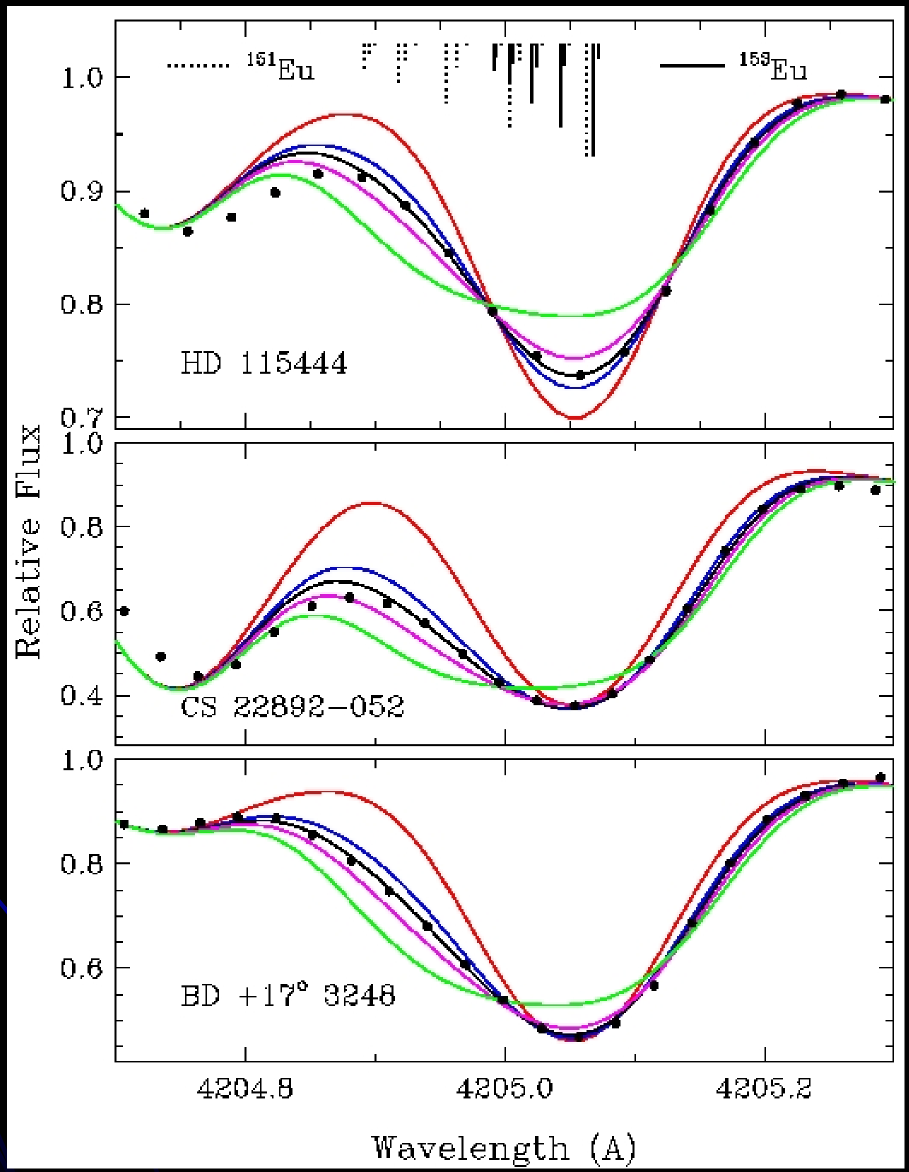
Very old star. Robust r-process over the history of the Galaxy.

Stellar elemental abundances consistent with scaled SS r-process only

Eu Isotopic Abundances in Three Metal-Poor Halo Stars

^{151}Eu:
- → 100%
- → 65%
- → 48%
- → 35%
- → 0%

Sneden et al. (2002)



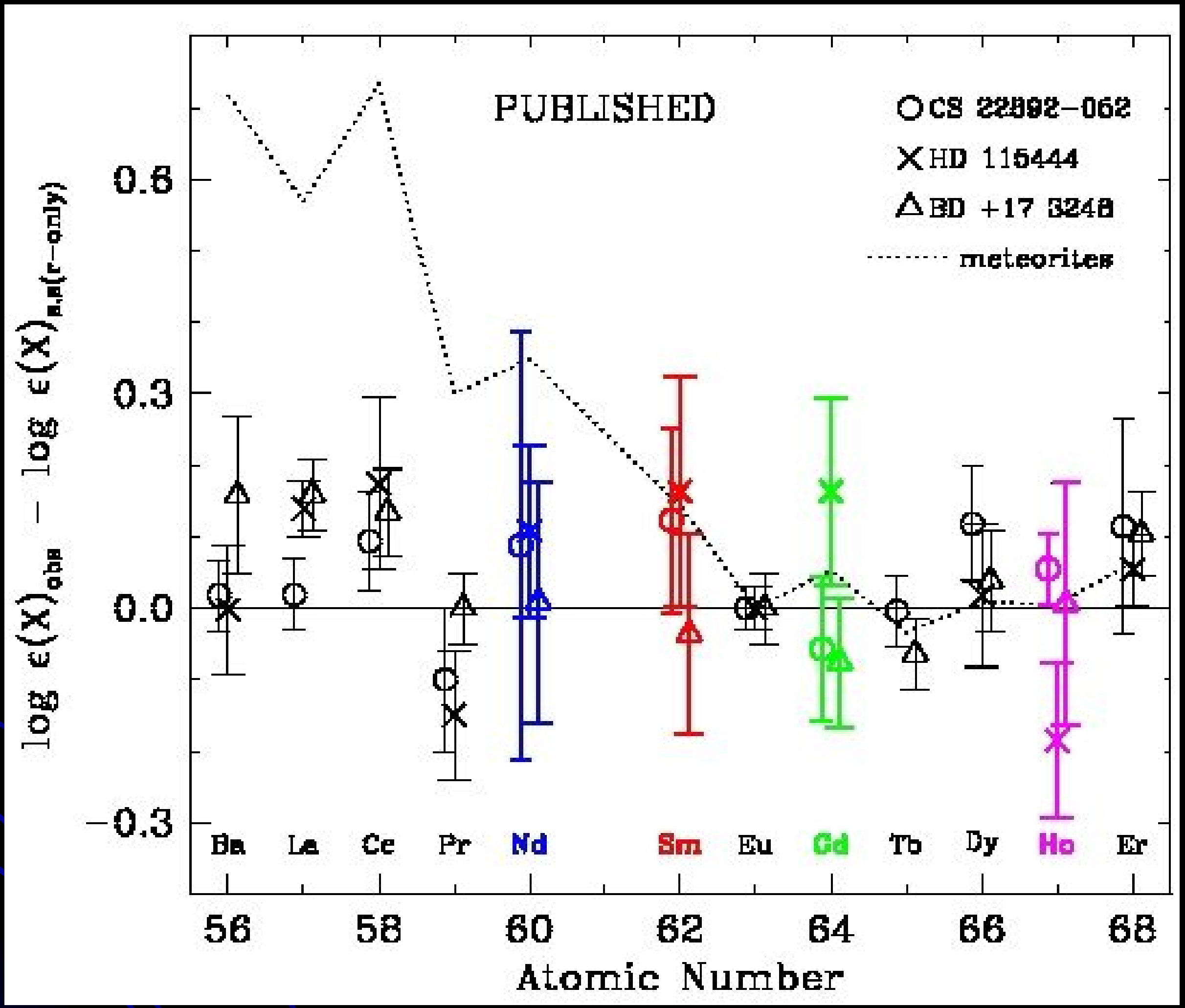
More lines in the same star

Many more examples of Eu isotopes in other stars. Same ratio found.

Ba now seen as well in one star: isotopes appears to be consistent with SS ratios.

Sm & others in progress

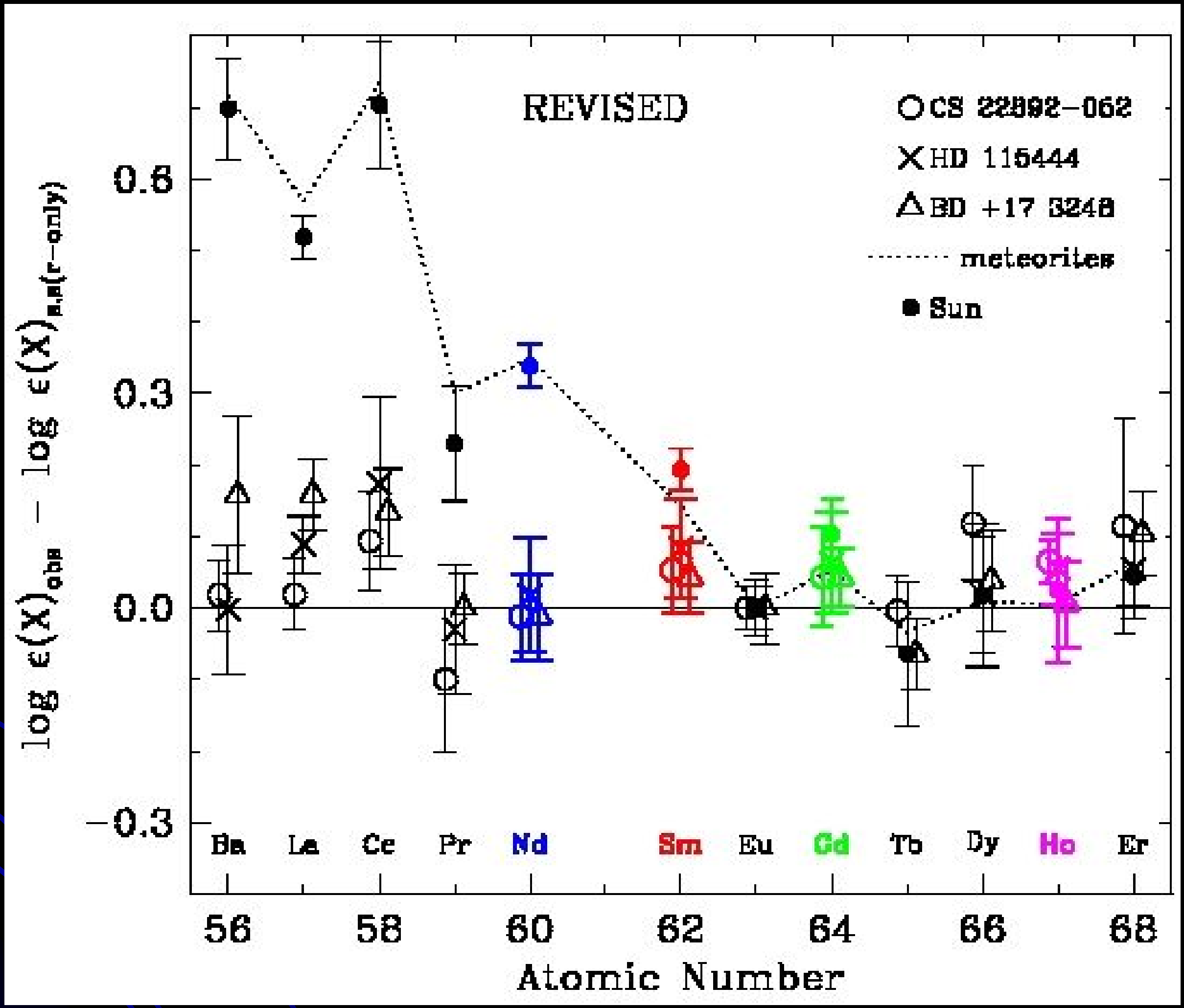
Focus On Individual Elements: Nd, Sm, Gd & Ho



Previous abundance determinations based upon older atomic data.

Reduce abundance uncertainties with new experimental atomic physics data.

Focus On Individual Elements: Nd, Sm, Gd & Ho



New experimental atomic physics data:

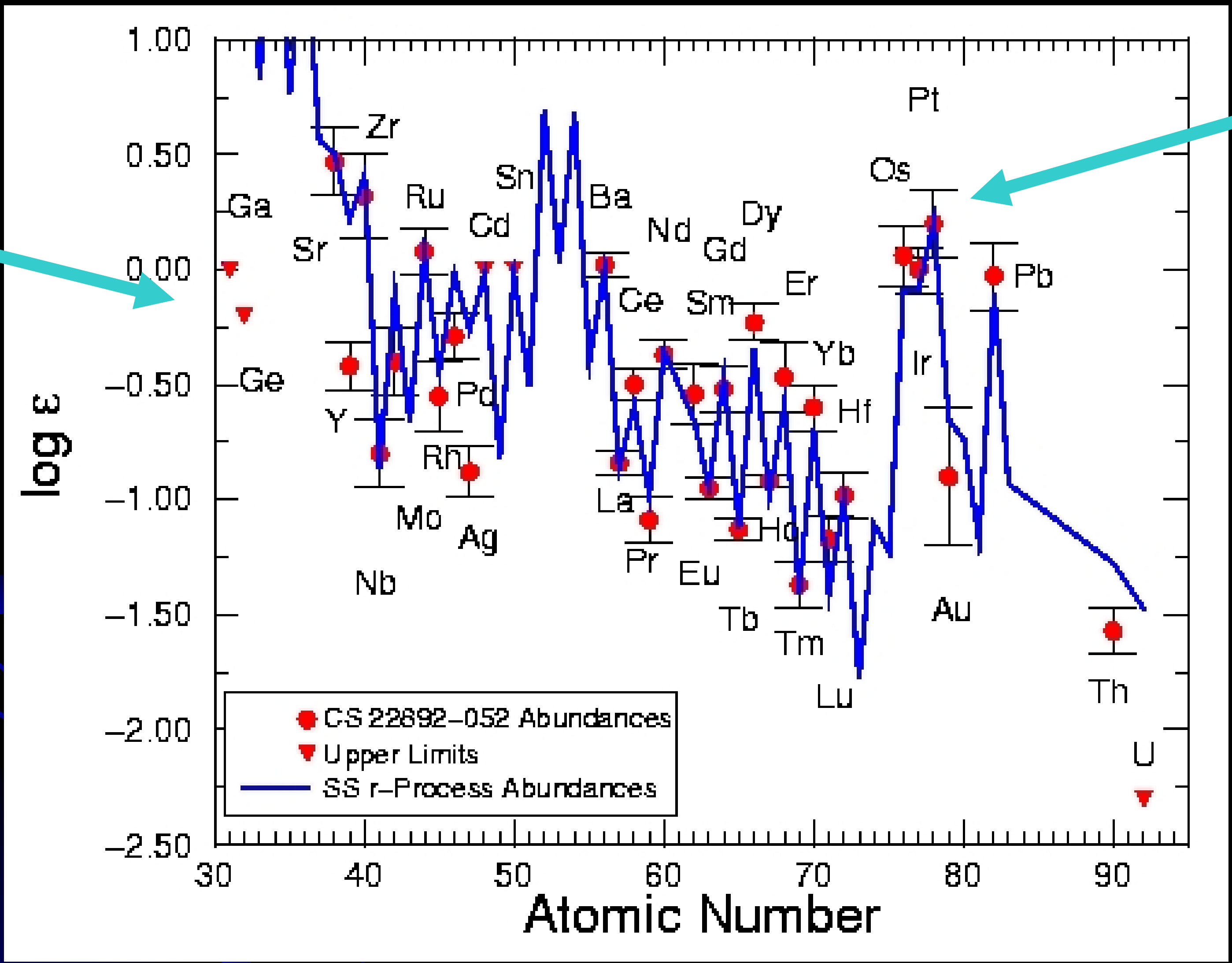
- Nd done (Den Hartog et al. 2003)
- Ho done (Lawler et al. 2004)
- Pt done (Den Hartog et al. 2005)
- Sm done (Lawler et al. 2006)
- Gd done (Den Hartog et al 2006)
- Hf done (Lawler et. al. 2007)

Working our way through the Periodic Table! (Ce, Dy, Er)

CS 22892-052 Abundances

(with new atomic and stellar data, JC et al. 2005)

Germanium



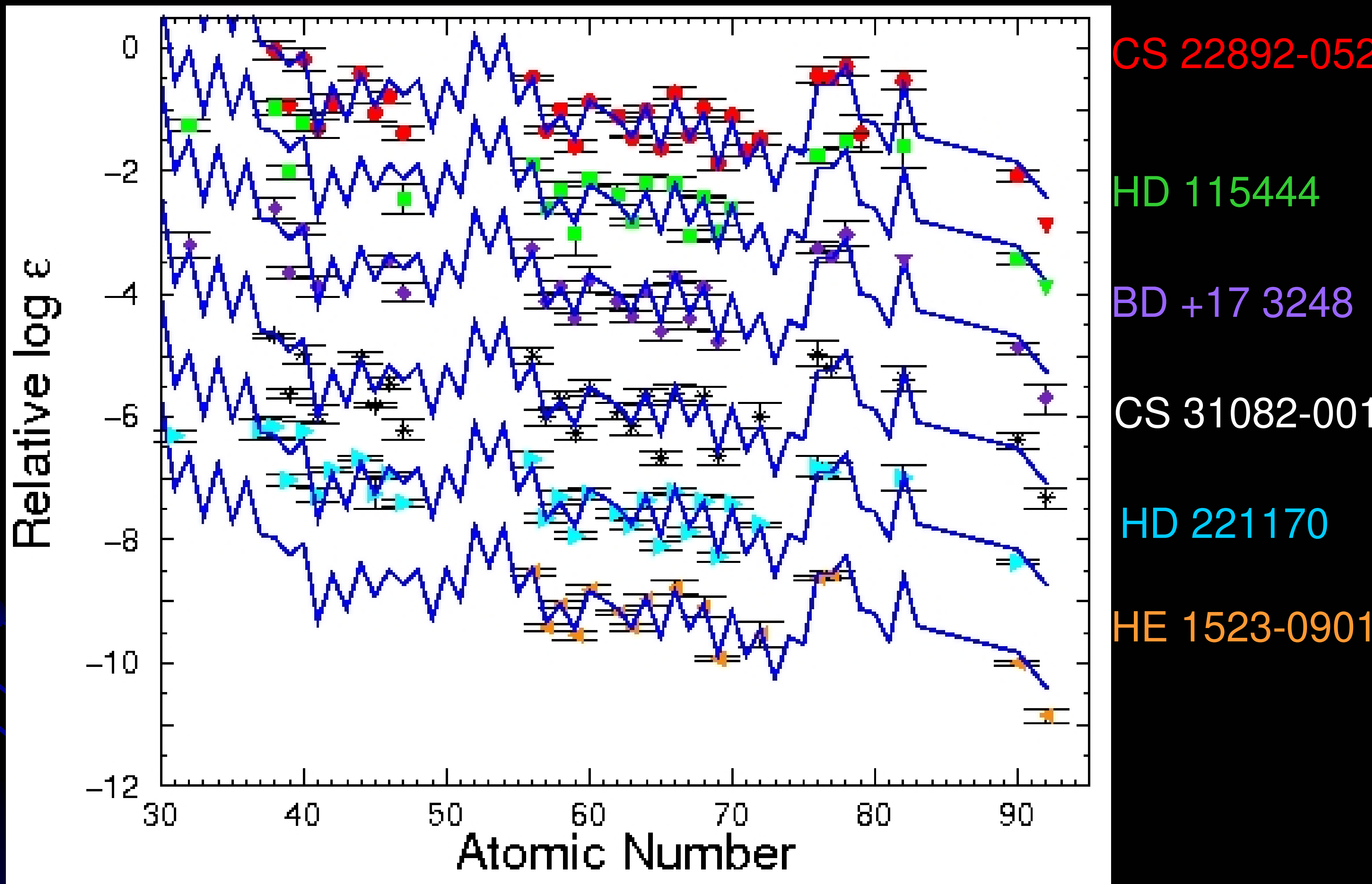
Platinum

(64 HST Orbits)

57 elements observed. More than any star except the Sun.

$$\text{Log } \varepsilon(A) = \text{Log}_{10}(N_A/N_H) + 12$$

Observational Summary of Total Abundances



6 r-process rich stars

Same abundance pattern at the upper end and ? at the lower end.

Observational Evidence for a Second (Weak) r-process ?

- Only recently any detections of elements, Z = 40-50

→ Best previous evidence CS 22892-052

- Heavier element (Z ≥ 56) abundances seem to follow SS r-process curve, not so for the lighter elements

→ Now seeing (?) similar pattern for light n-capture elements in several other r-process rich stars

What about new observations of HD 221170?

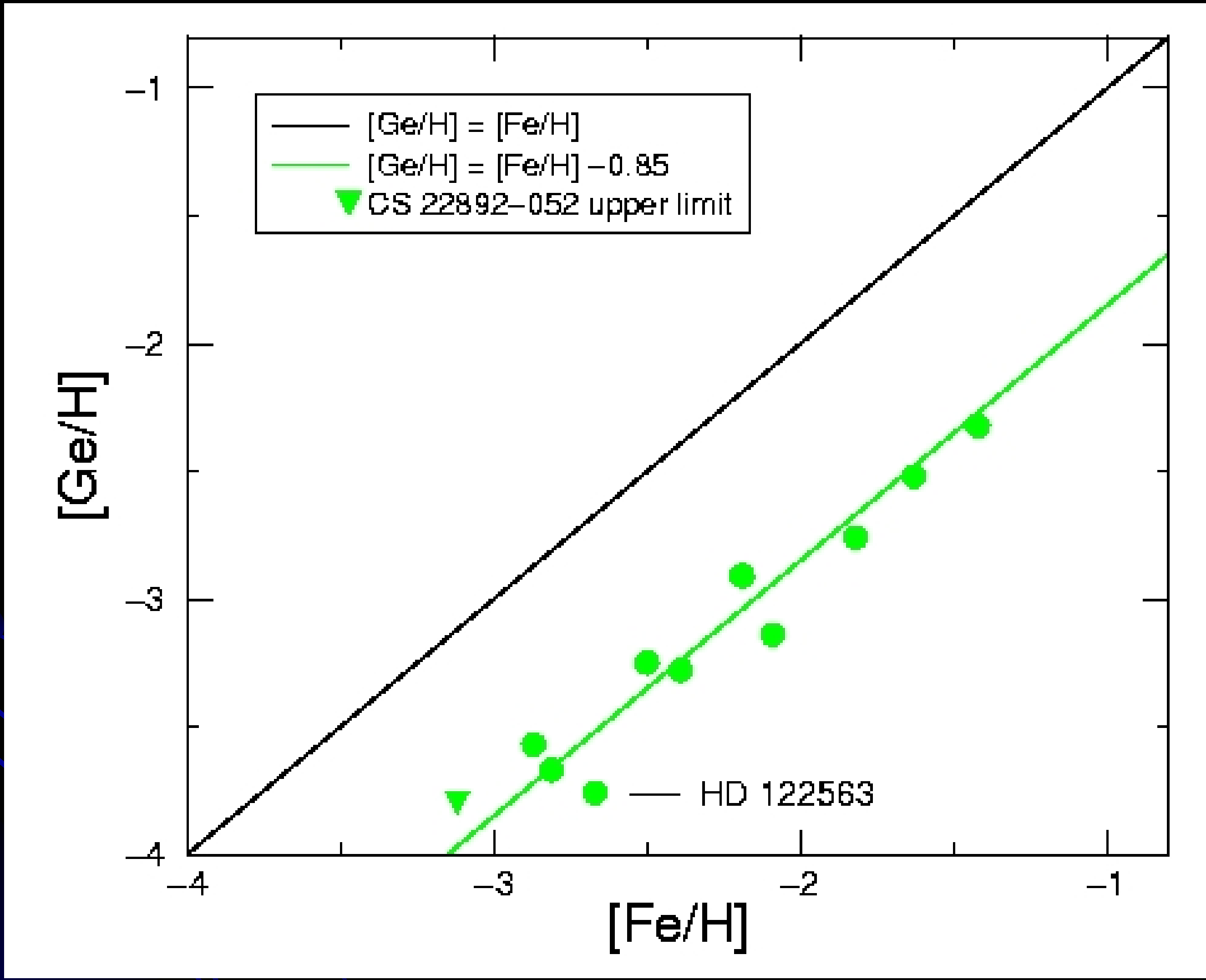
- Two separate sites based upon SS meteoritic data (Wasserburg, Busso & Gallino): strong and weak r-process (two types of SNe or SNe and NS mergers) or
- One site (different epochs or regions)

More evidence?

HST Abundance Observations

- Dominant transitions for elements such as Ge, Os and Pt in NUV requires HST
- New abundance determinations of these elements (and Zr) in 11 metal-poor halo stars
- Attempt to identify abundance trends and correlations

Ge Abundances in Halo Stars



Ge ∝ Fe

Challenge to theorists.
vp-process?

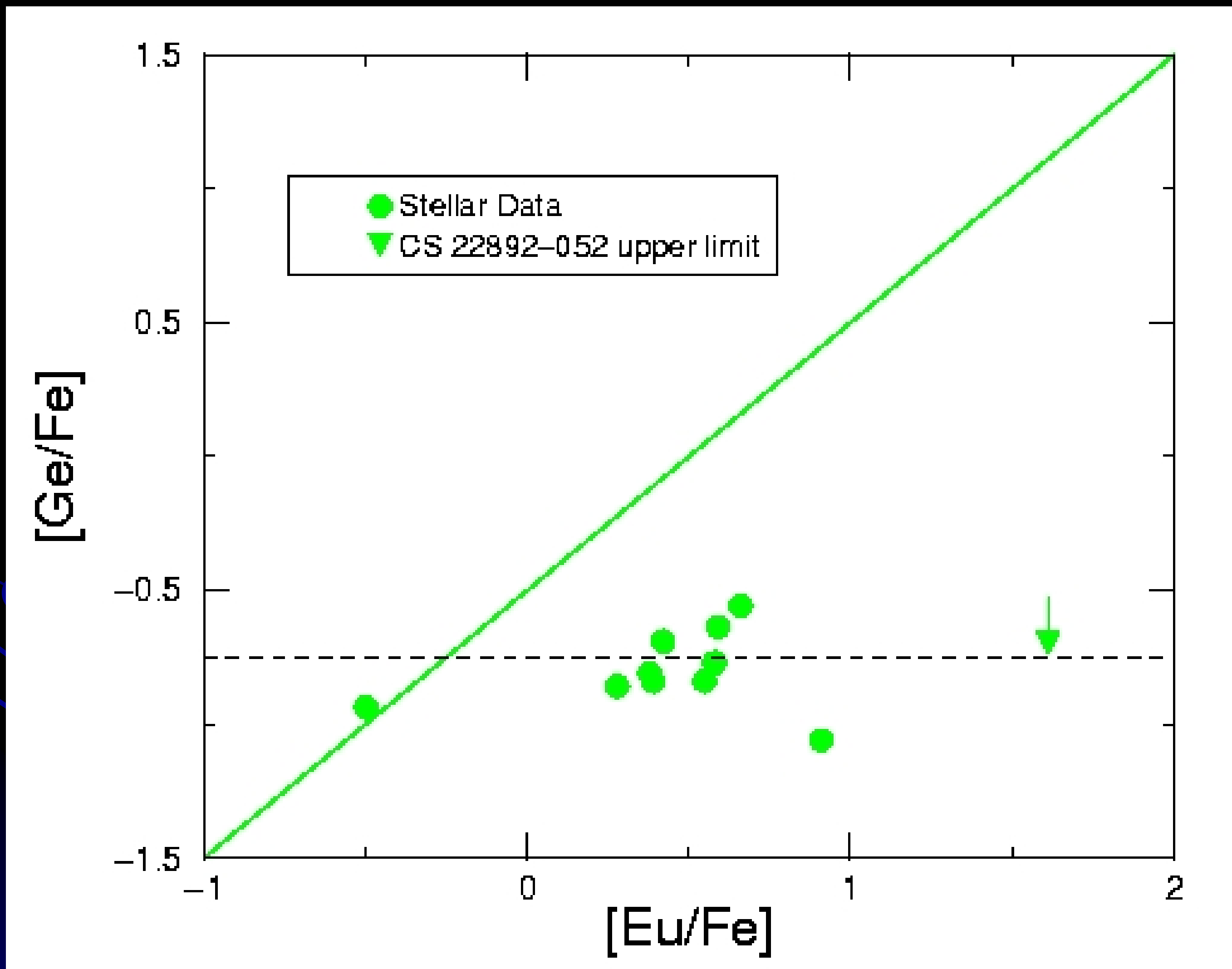
What happens at higher [Fe/H] with the s-process?

JC et al. (2005)

$$[A/B] = \log_{10}(A/B)_{star} - \log_{10}(A/B)_{sun}$$

Ge vs. Eu in Halo Stars

If Ge and Eu are both n-capture elements and both synthesized in same process they should be correlated?

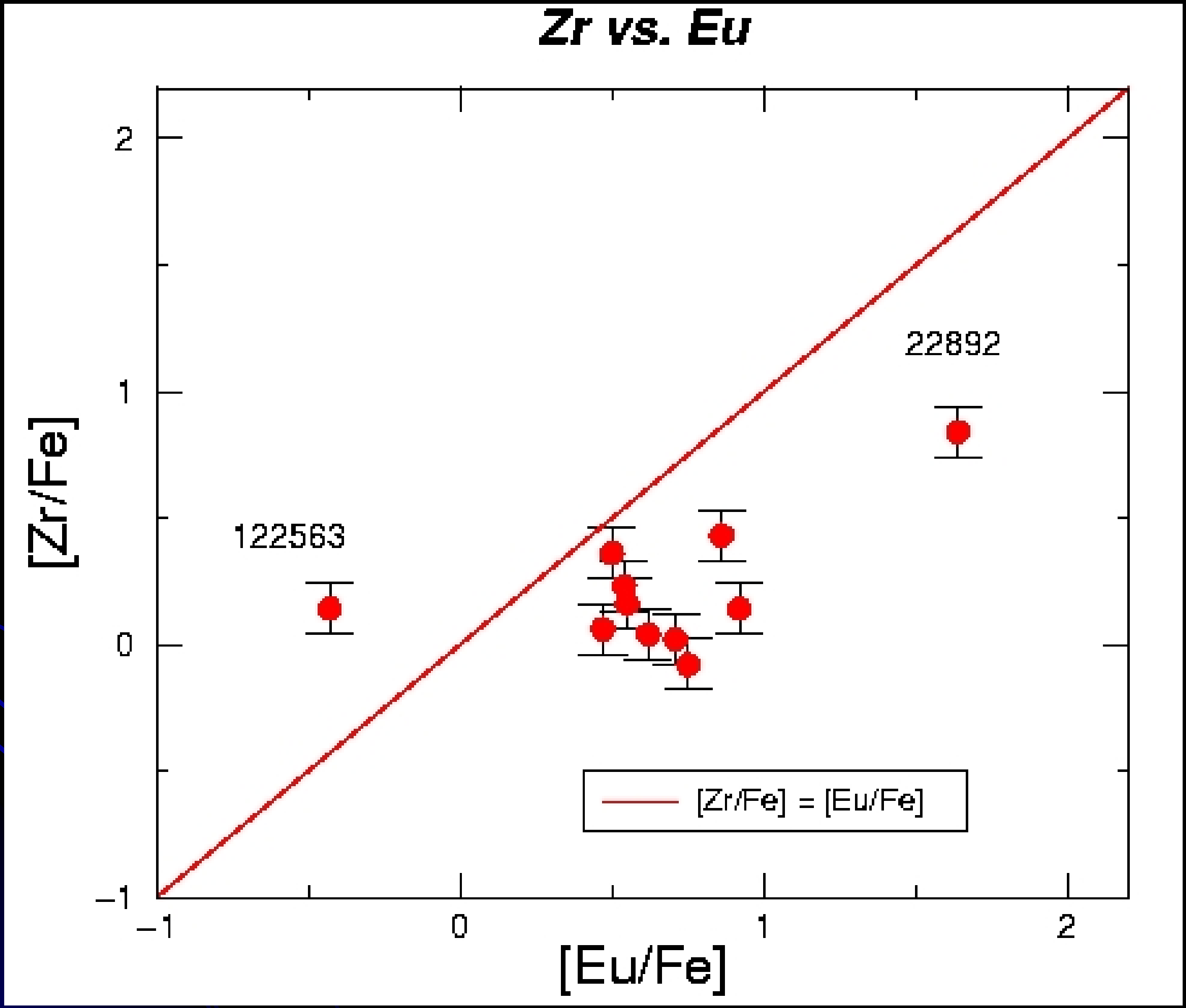


Ge $\not\propto$ Eu

JC et al. (2005)

$[A/B] = \log_{10}(A/B)_{star} - \log_{10}(A/B)_{sun}$

Zr and Eu Abundances in Halo Stars



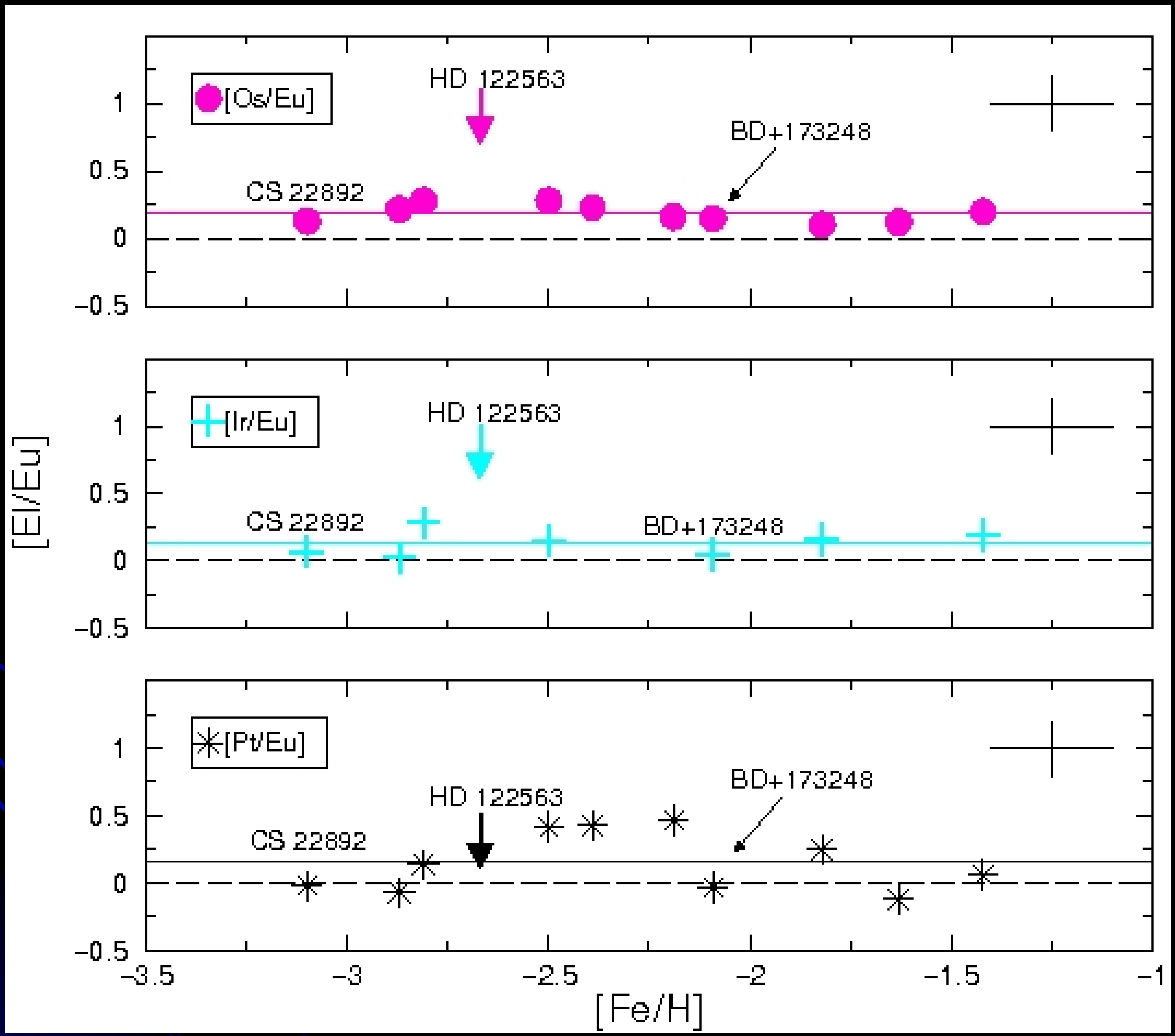
Zr ∝̸ Eu

Both n-cap elements but not from same source?

LEPP?
SN models?

n-Capture Element Correlations: 3rd r-Process Peak

3rd r-process peak elements correlate with Eu.

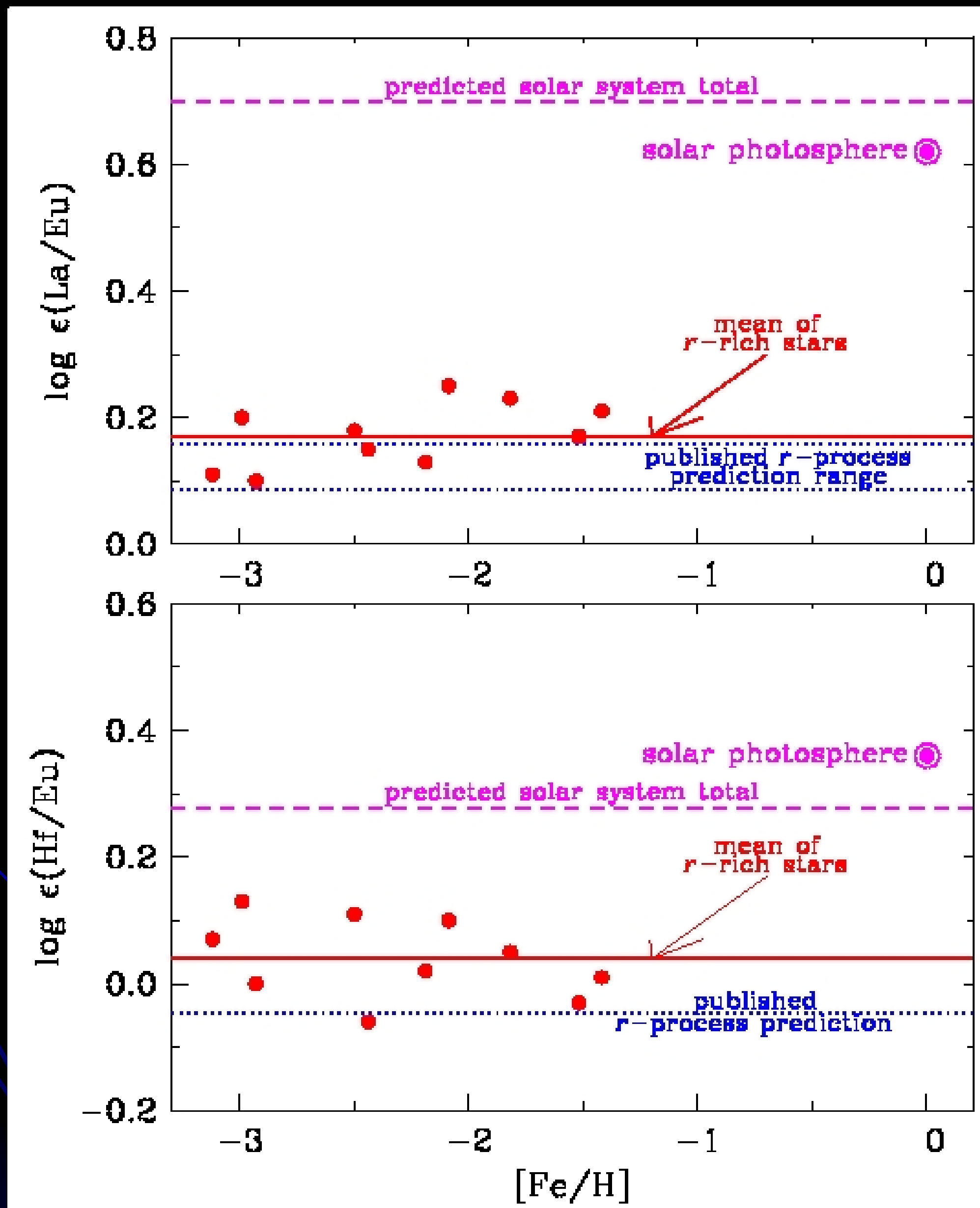


= typical error

ave.
SS r-pro

Observed La/Eu & Hf/Eu Ratios in Metal-Poor Stars

New atomic data refines Hf and La abundances in Sun and 10 metal-poor stars.

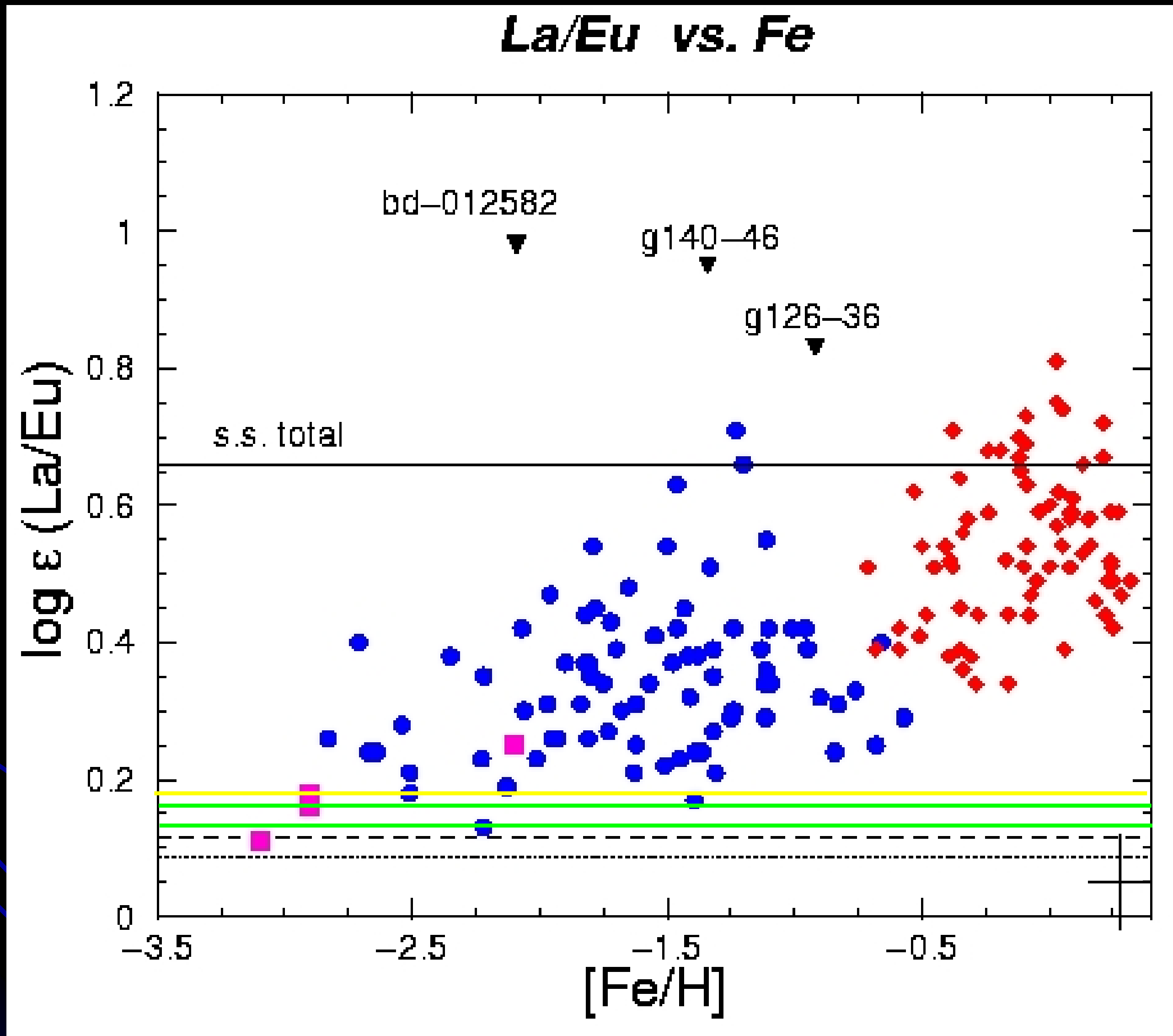


Observed ratios of La/Eu and Hf/Eu larger than previous estimates of SS r-only values

Suggests larger contribution to La and Hf from r-process

Lawler et al. (2007)

R- and S-Process Abundance Trends



Simmerer et al. (2004)

Trend is upward due to increasing s-process contribution to La

Arlandini et al.

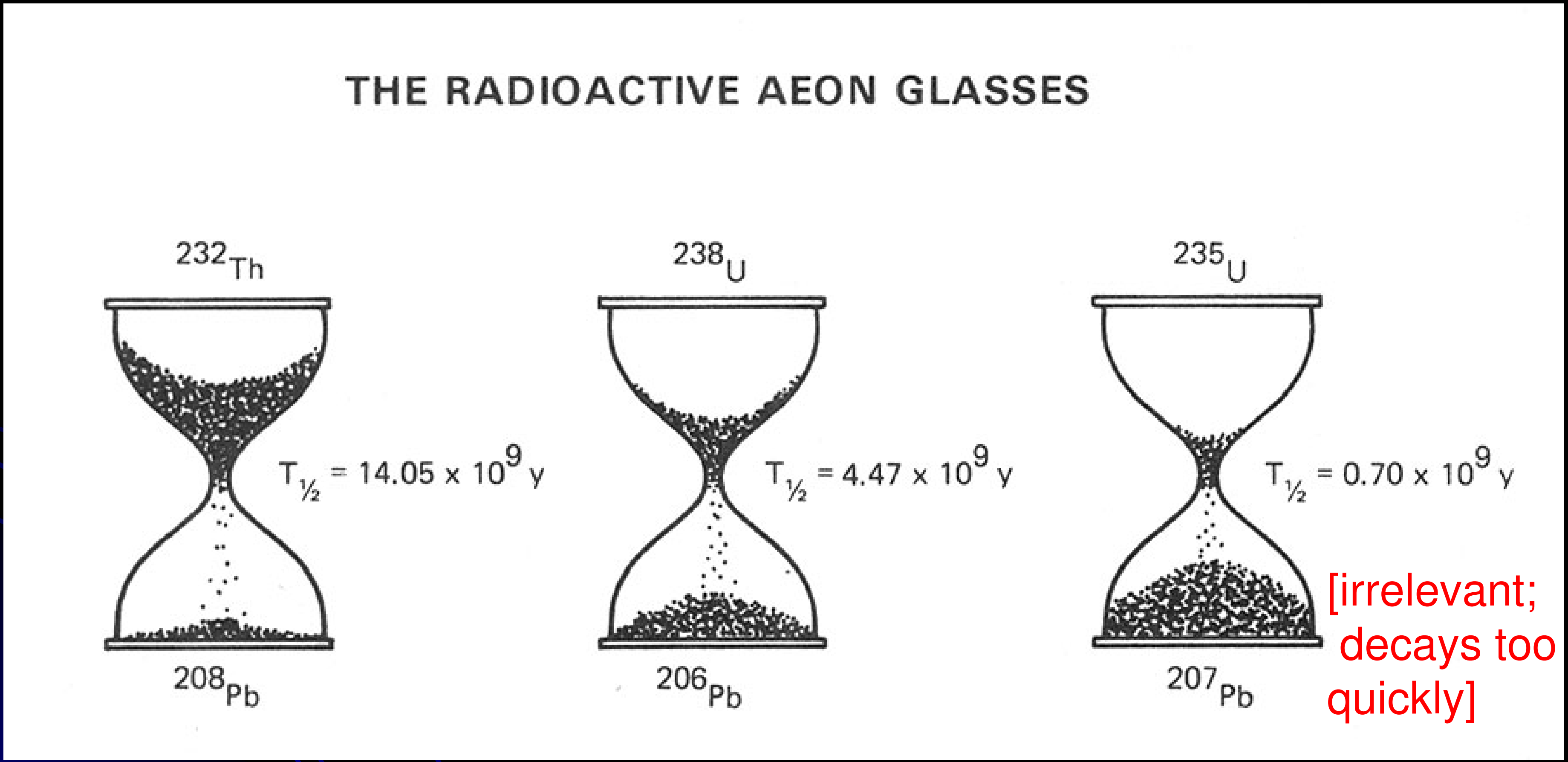
r-process only

O'Brien et al. (2003)

Burris et al. (2000)

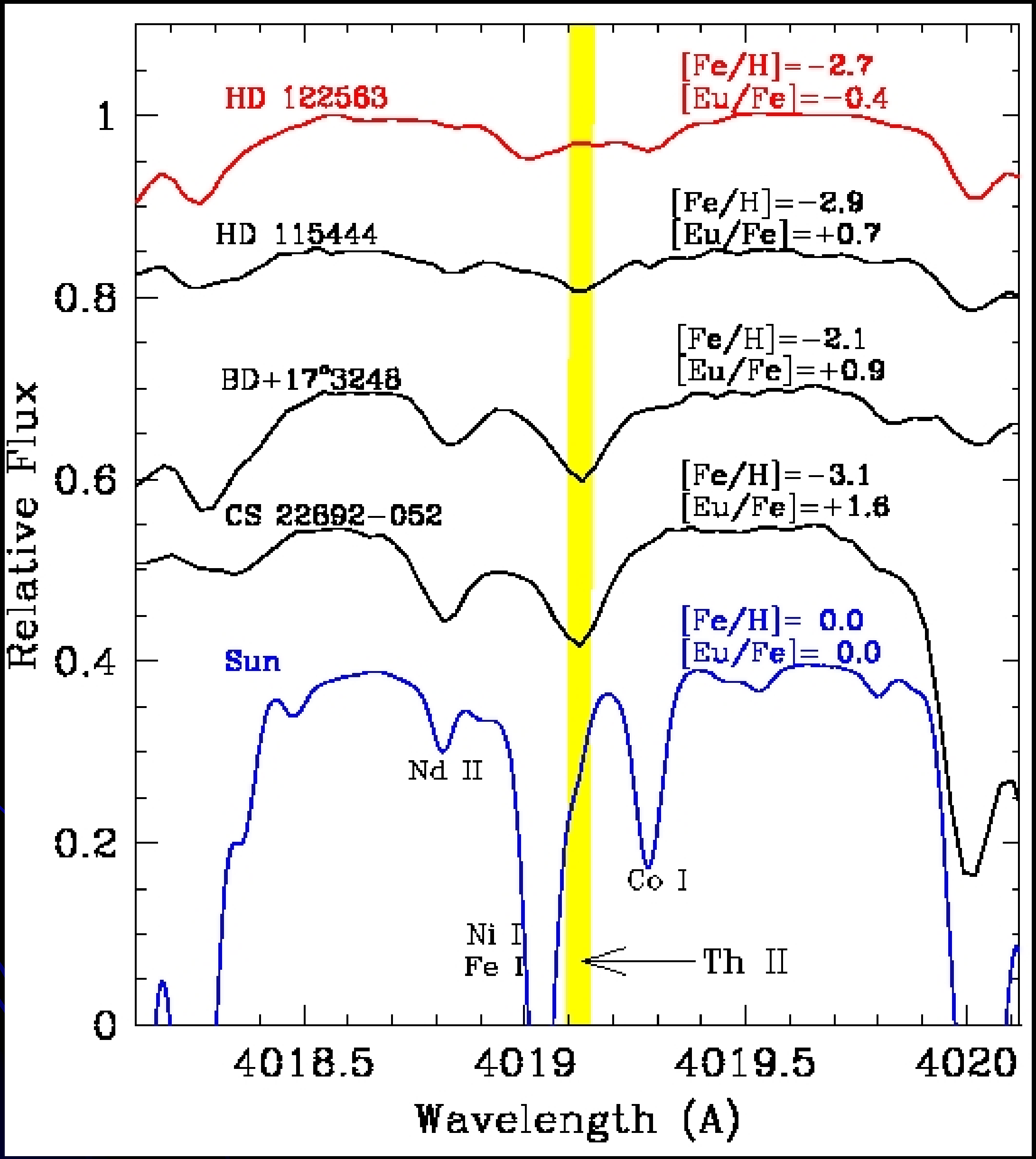
■ r-process enhanced, • halo stars, ♦ disk stars

Cosmochronometers



Rolfs & Rodney (1988)

Th Detections in Four Halo Stars and the Sun



Note the strength of the Th lines independent of metallicity

More Chronometers?

No

Yes

Some Concluding Thoughts on: Nucleosynthesis Early in the Galaxy

- r-process elements observed in very metal-poor (old) halo stars
- Implies that r-process sites, earliest stellar generations

→ rapidly evolving: live and die, eject r-process material into ISM prior to formation of halo stars

- Elements (even s-process ones like Ba) produced in r-process early in Galaxy
- Robust for heavy end:

→ places constraints on sites for the r-process

More Deep Thoughts on: Element Synthesis

- Ge and Zr complicated element formation: challenge to theorists
- Evidence for a second r-process? LEPP?
- Os, Ir & Pt correlated (and scatter) with Eu
- s-process onset at low [Fe/H]: how?
- Detections of radioactive elements (Th & U) allow age estimates for oldest stars: putting limits on the age of the Galaxy & Universe

With Collaborators at:

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