# STELLAR ABUNDANCE OBSERVATIONS AND HEAVY ELEMENT FORMATION

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# Top 11 Greatest Unanswered Questions of Physics

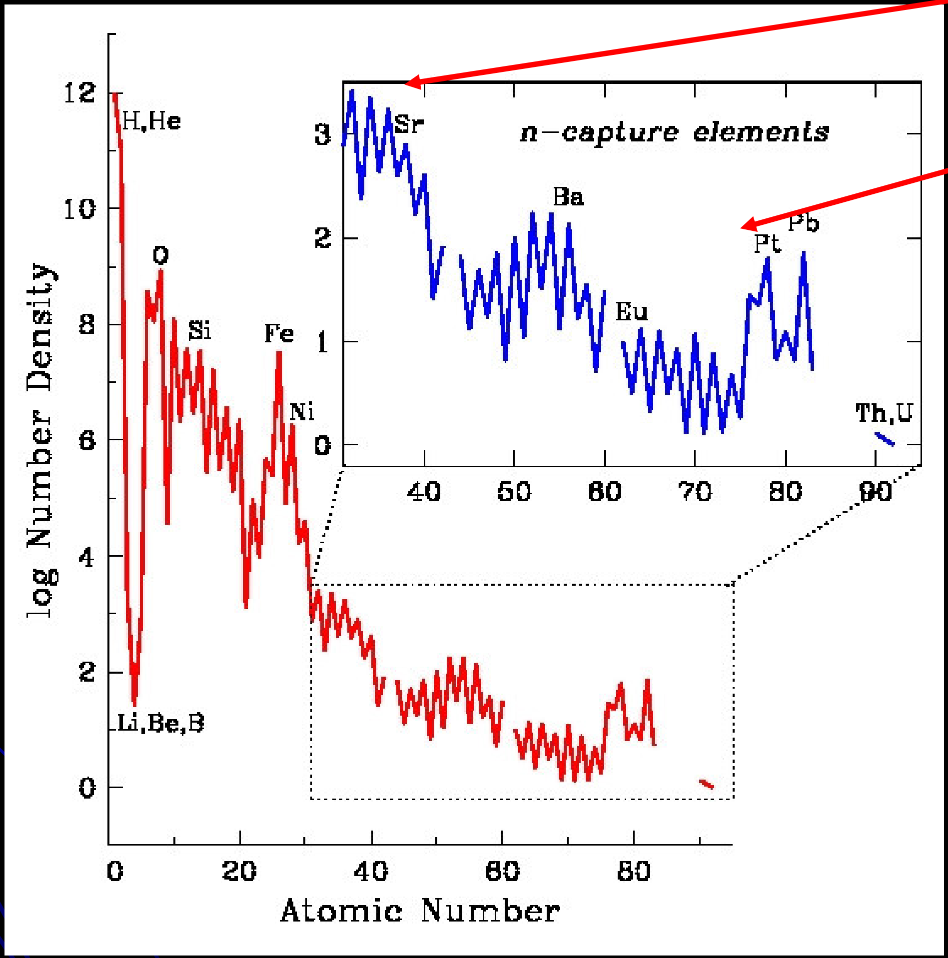
1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there 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?

National Research Council Report, Discover Magazine (2002).

# 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

# Solar System Abundances




Ge, Zr

Os, Pt

Jewelry store items

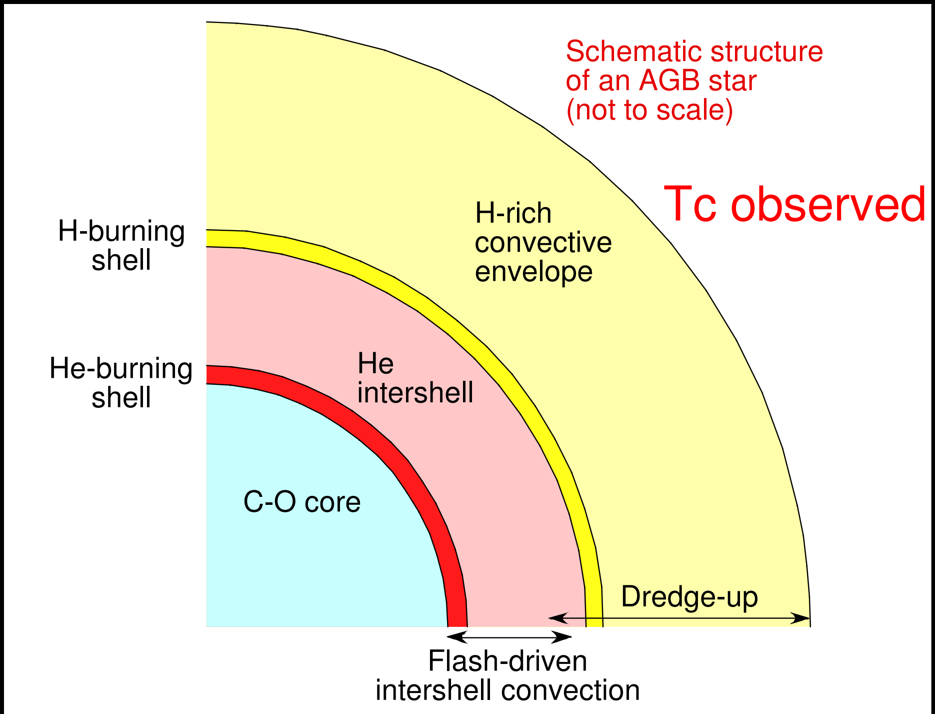
Sneden & JC (2003)

# Heavy Element Synthesis

- About ½ of nuclei above iron formed in the slow (s) neutron capture process
- The other half of the nuclei formed in the rapid (r) neutron capture process
- Timescale (slow or fast) with respect to radioactive decay time of unstable nuclei produced by the neutron capture

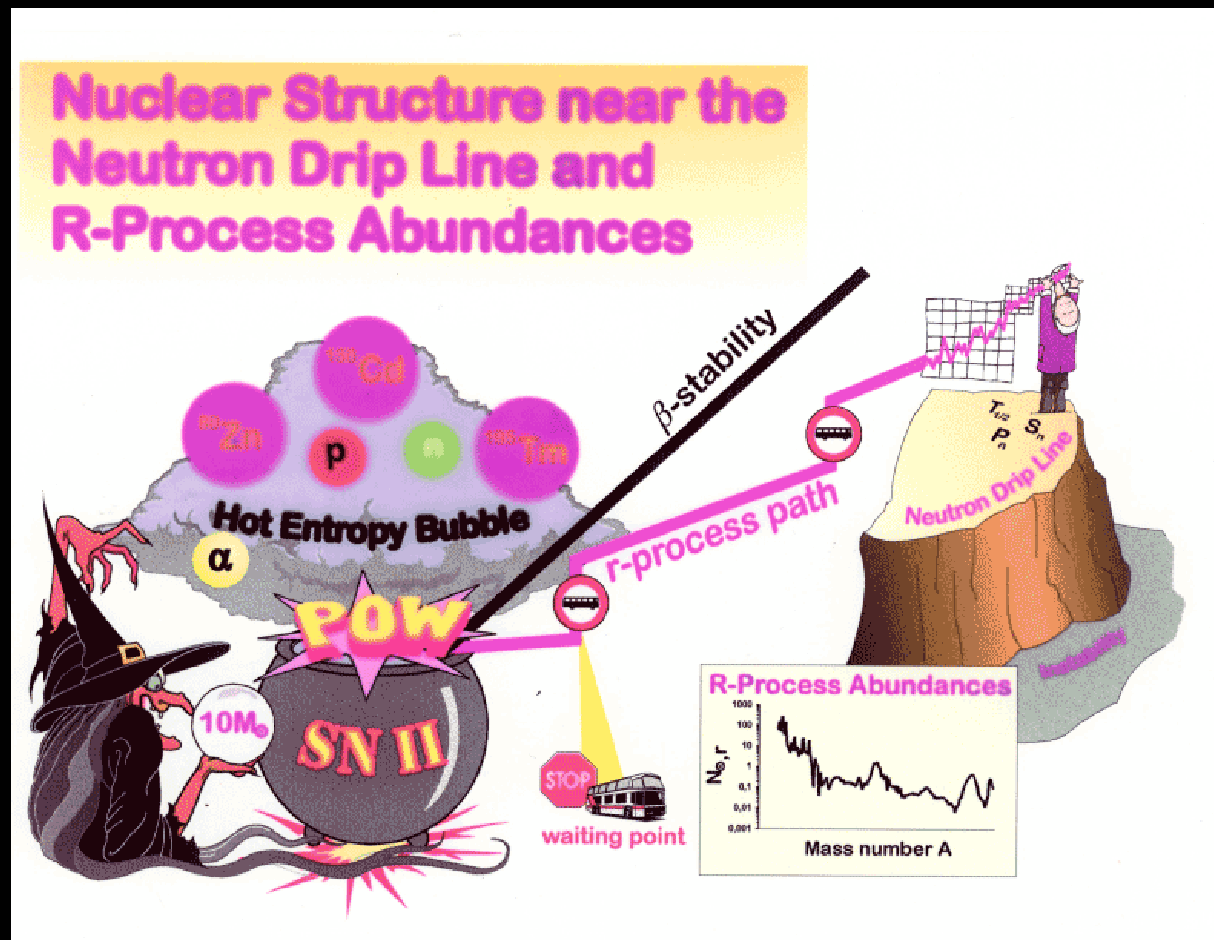
# s-Process Nucleosynthesis

- For the s-process:
- $\tau_{nc} >> \tau_{\beta}$ decay (typically hundreds to thousands of years)
- Site for the s-process well identified as AGB (red giant) stars

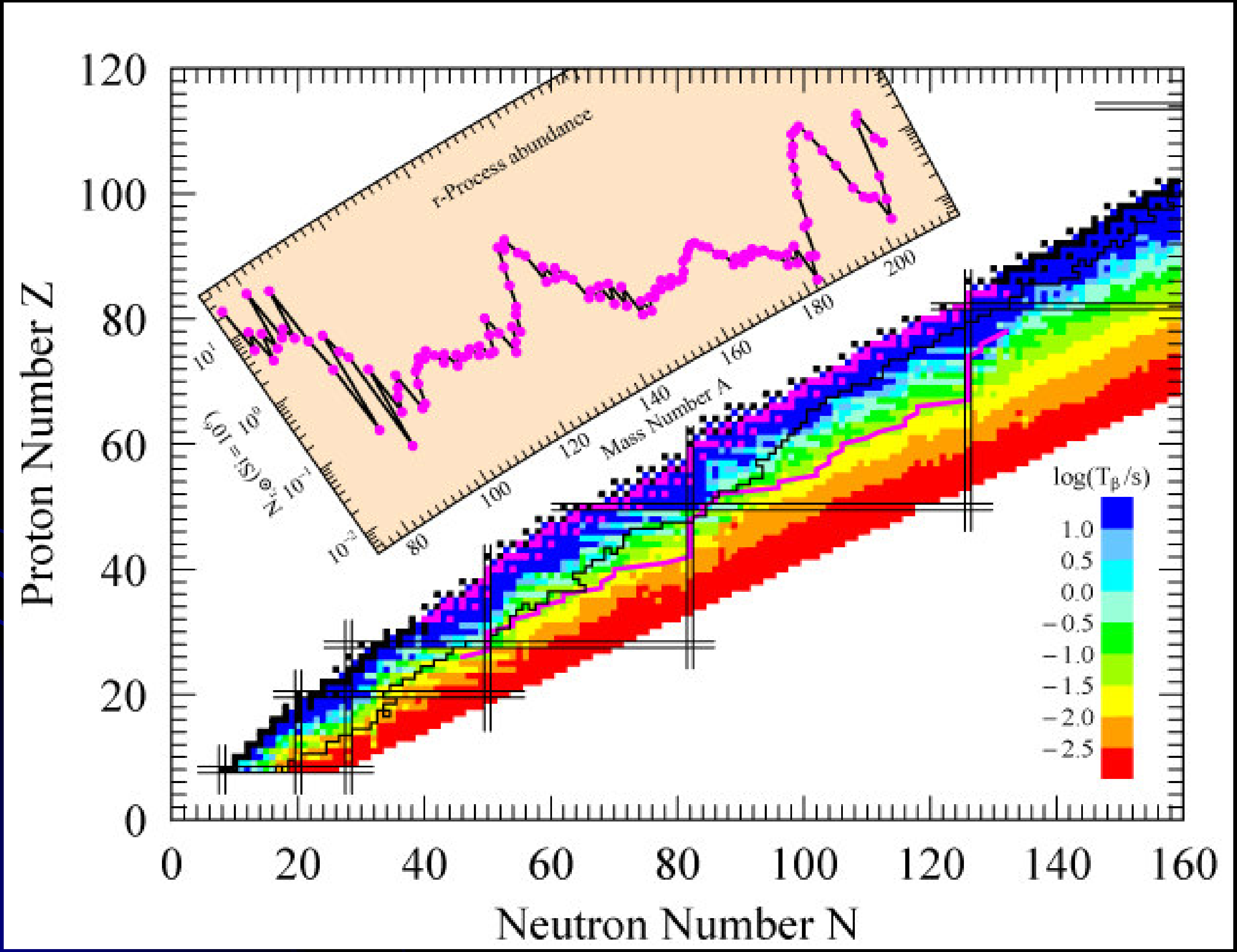


# r-Process Nucleosynthesis

- 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

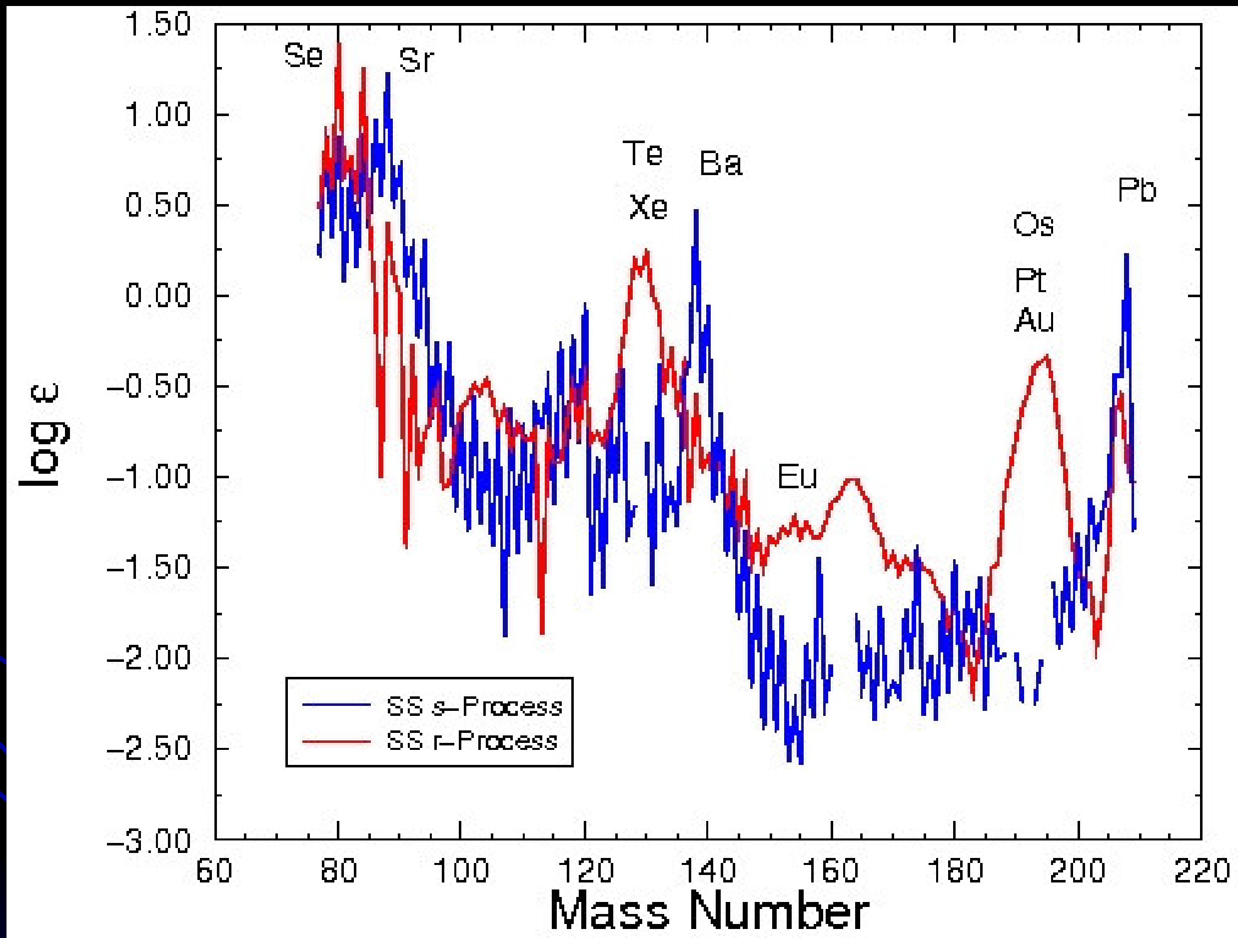


# The Nuclear Isotopes in Nature




details

# Solar System s- and r-Process Abundance Peaks




SS isotopic deconvolution by s- and r-process

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

# Most Likely Site(s) for the r-Process

- Supernovae: The Prime Suspects

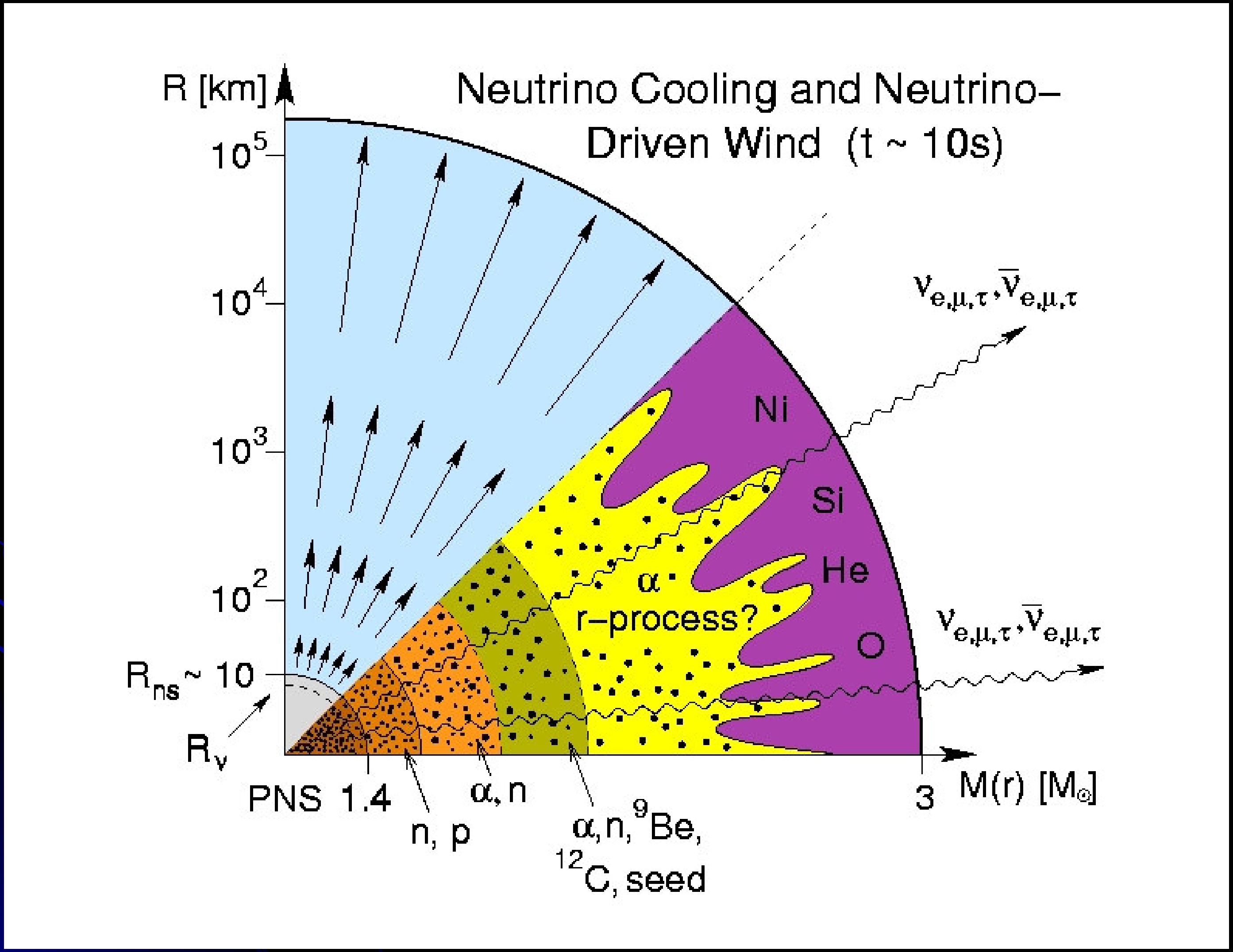
  → Regions just outside neutronized core: 1957 (Woosley et al. 1994; Wanajo et al. 2002)

  → Prompt explosions of low-mass Type II SNe (Wheeler, JC, Hillebrandt 1998)

  → Jets and bubbles (Cameron 2001)

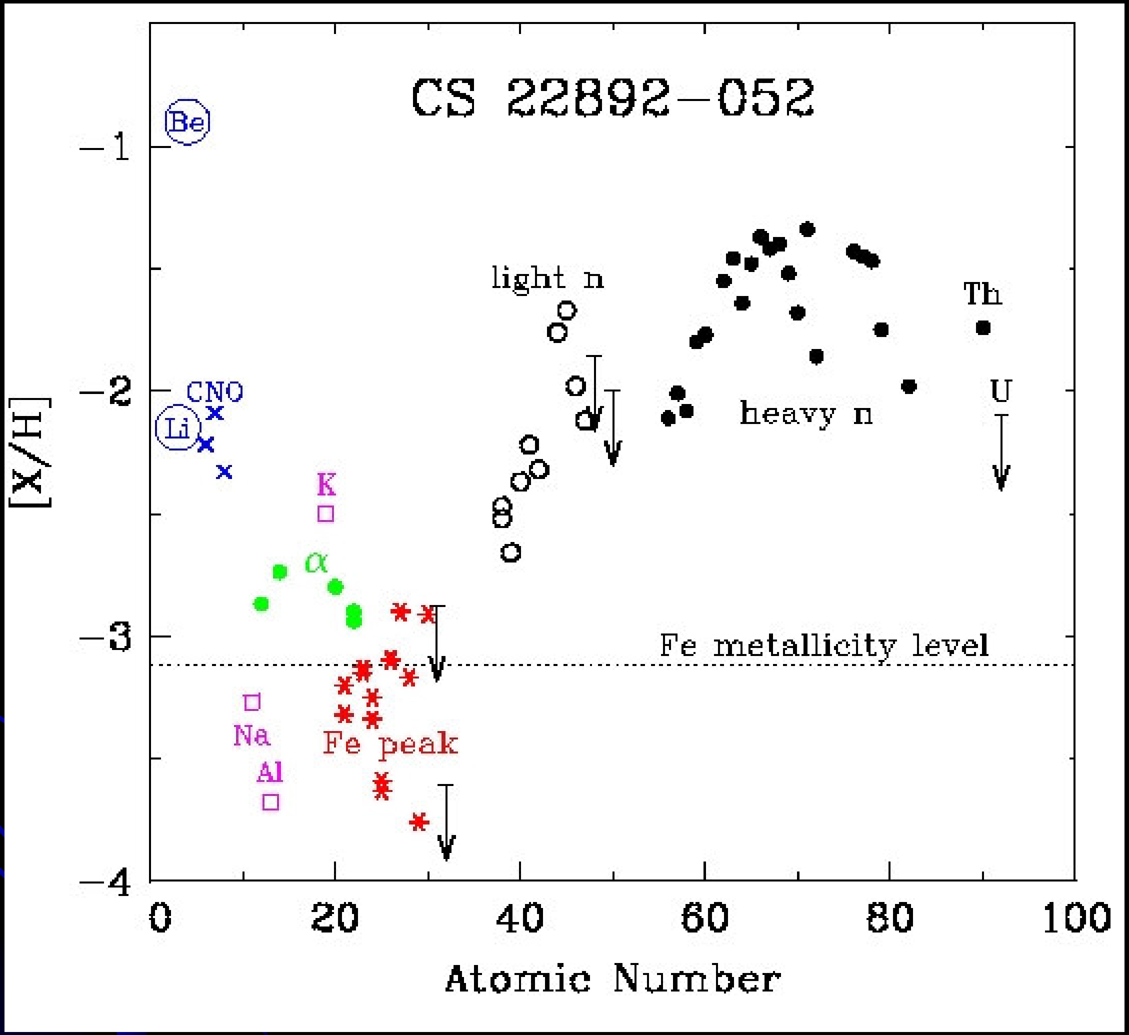
- NS & NS-BH mergers (Rosswog et al. 1999; Freiburghaus et al. 1999)

# Rapid Neutron Capture in Type II SNe ?



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

Light elements mostly scale with [Fe/H].



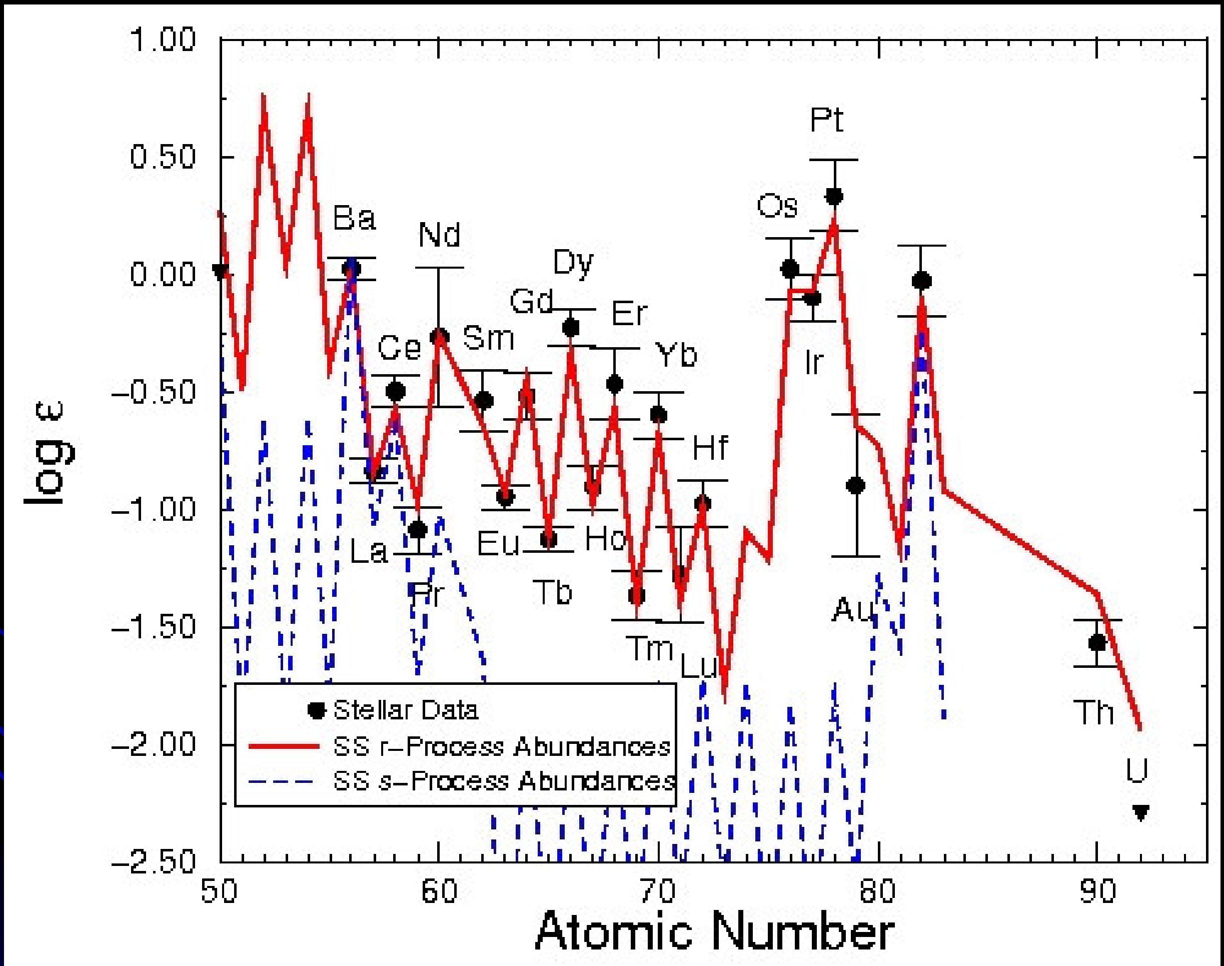

Heavy n-capture elements greatly enhanced (≈ 40-50) over iron abundance.

[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.

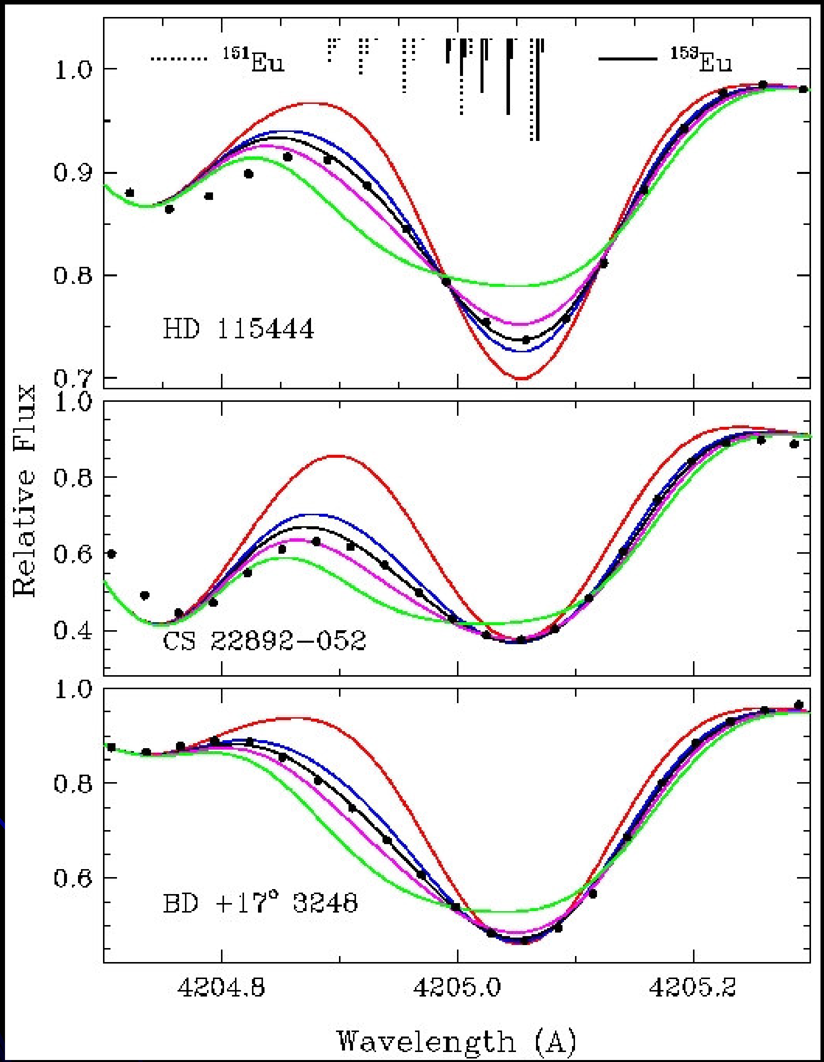



Very old star. Robust r-process over the history of the Galaxy.

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%



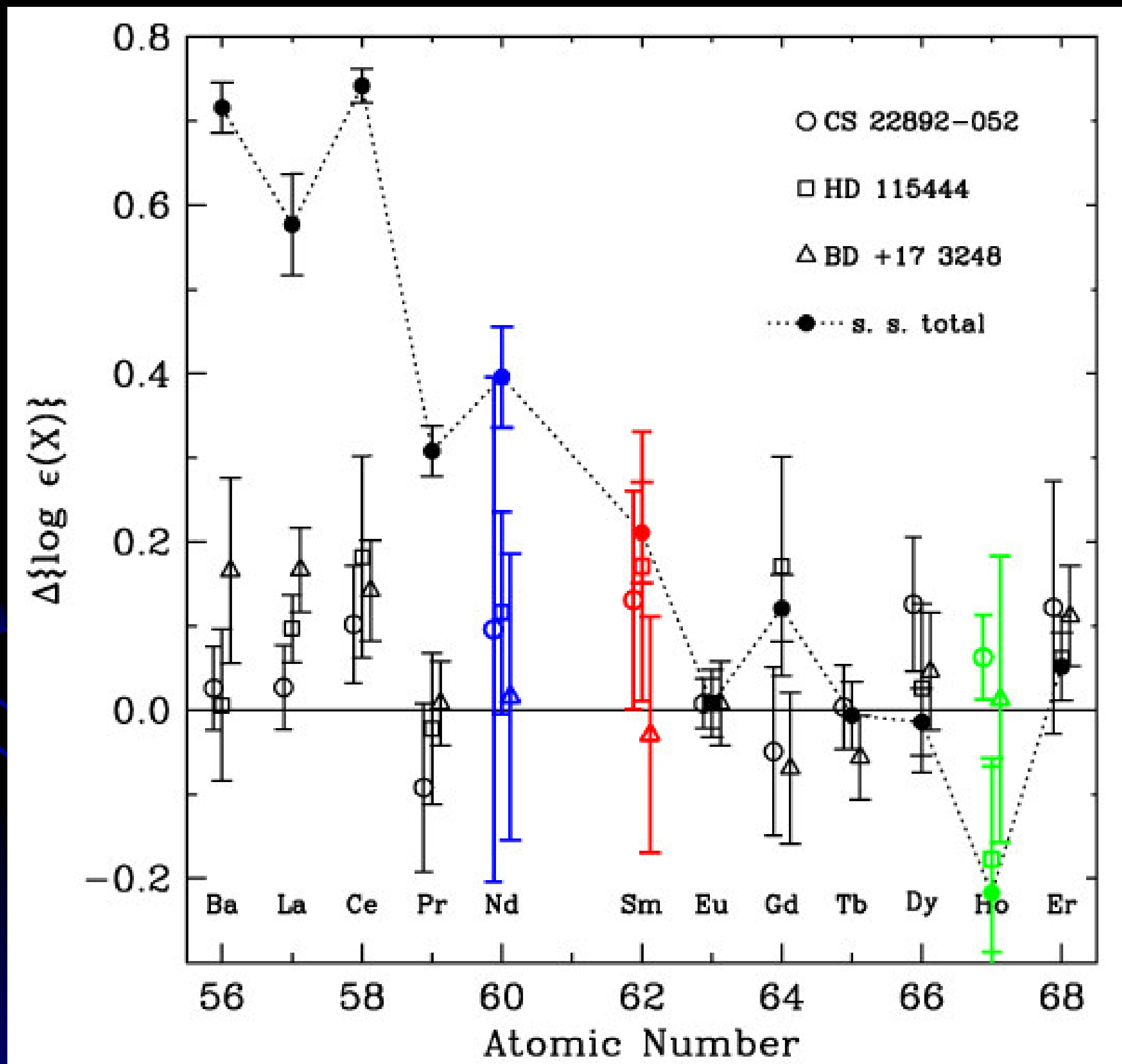

Sneden et al. (2002)

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.

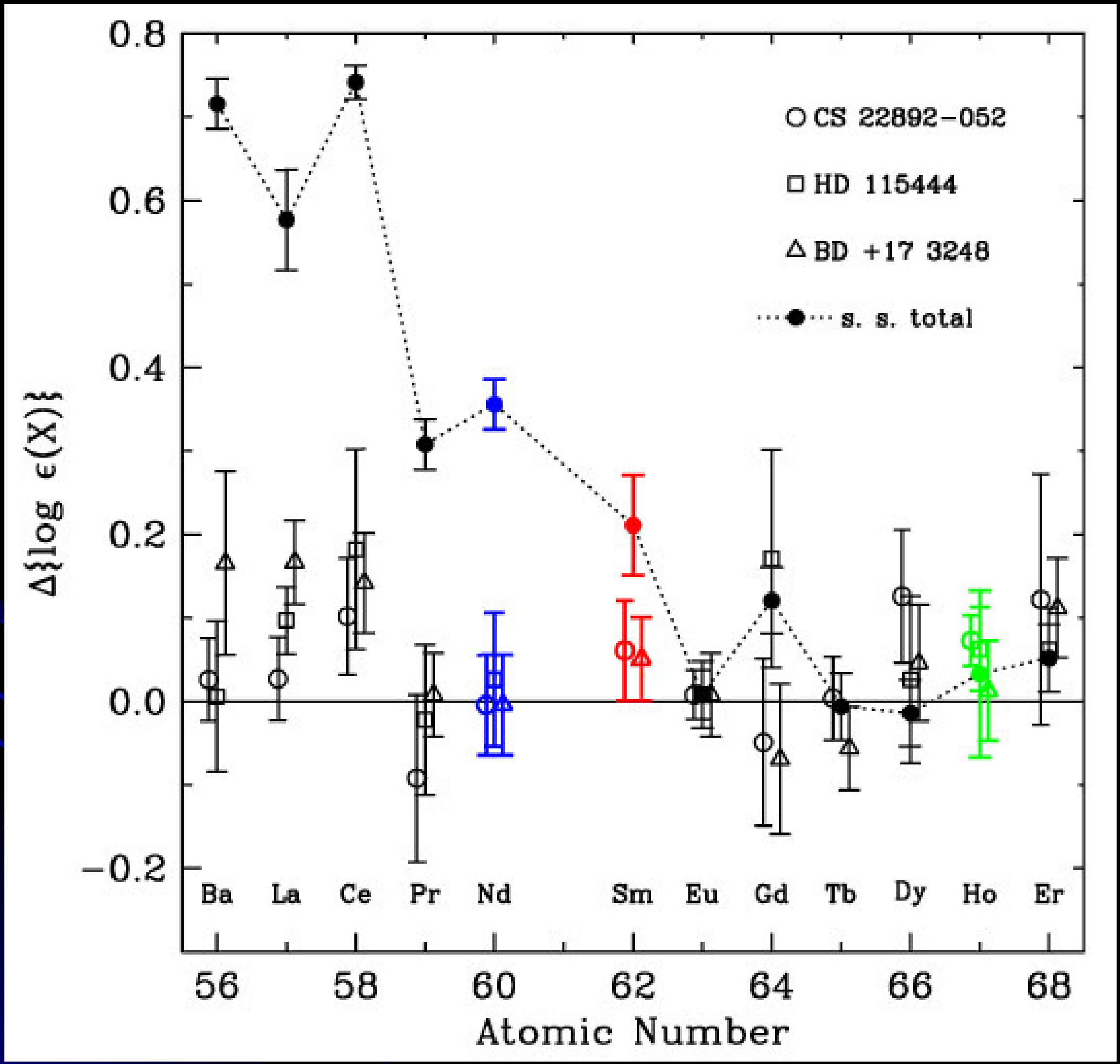
More lines in the same star

# Focus On Individual Elements: Nd, Ho & Sm




Reduce abundance uncertainties with new experimental atomic physics data.

# Focus On Individual Elements: Nd, Ho & Sm




New experimental atomic physics data:

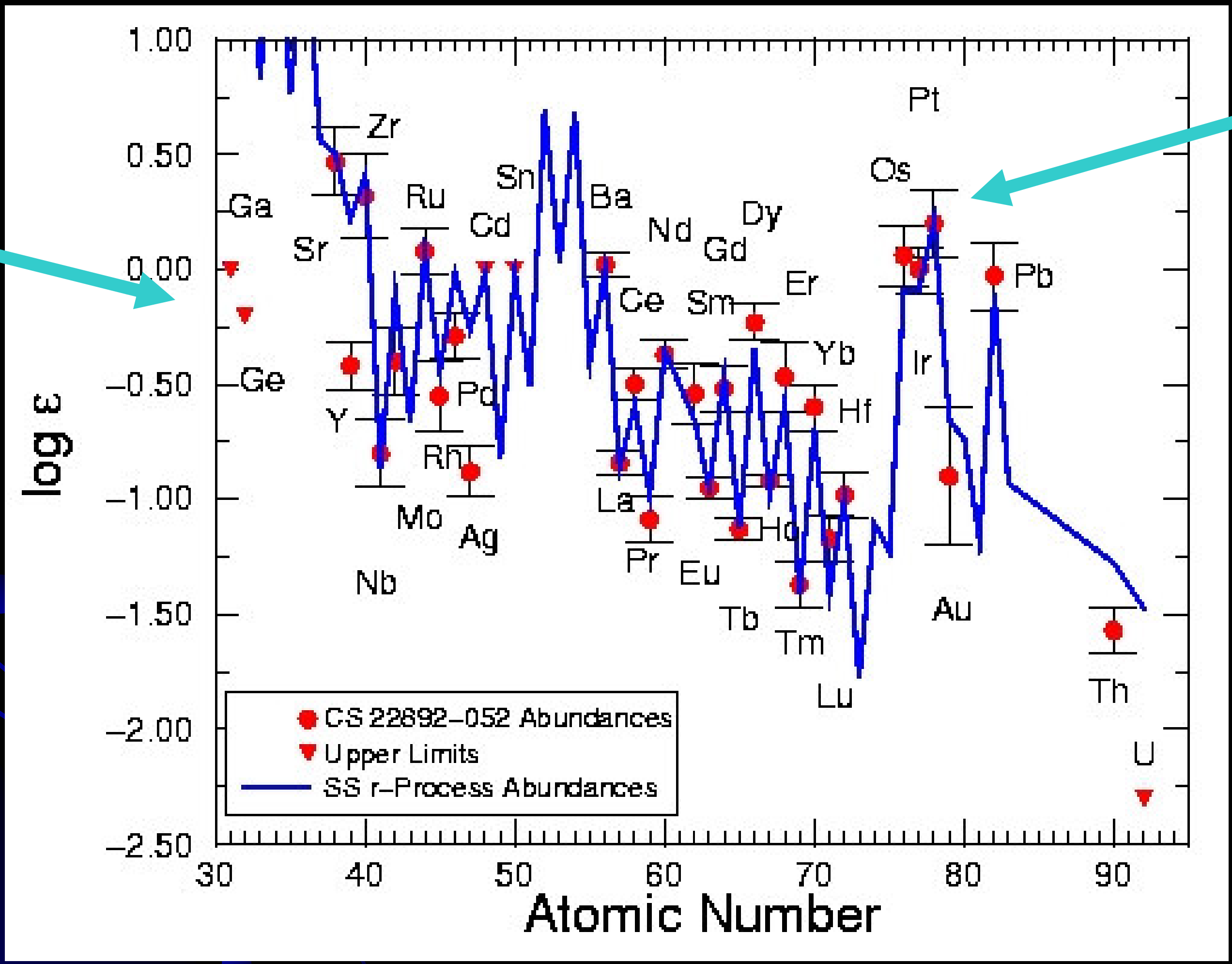
- Nd done (Den Hartog et al. 2003)
- Ho done (Lawler et al. 2004)
- Pt done (Den Hartog et al. 2005)
- Sm in progess

Working our way through the Periodic Table!

# CS 22892-052 Abundances

Cowan et al. (2005)

Germanium



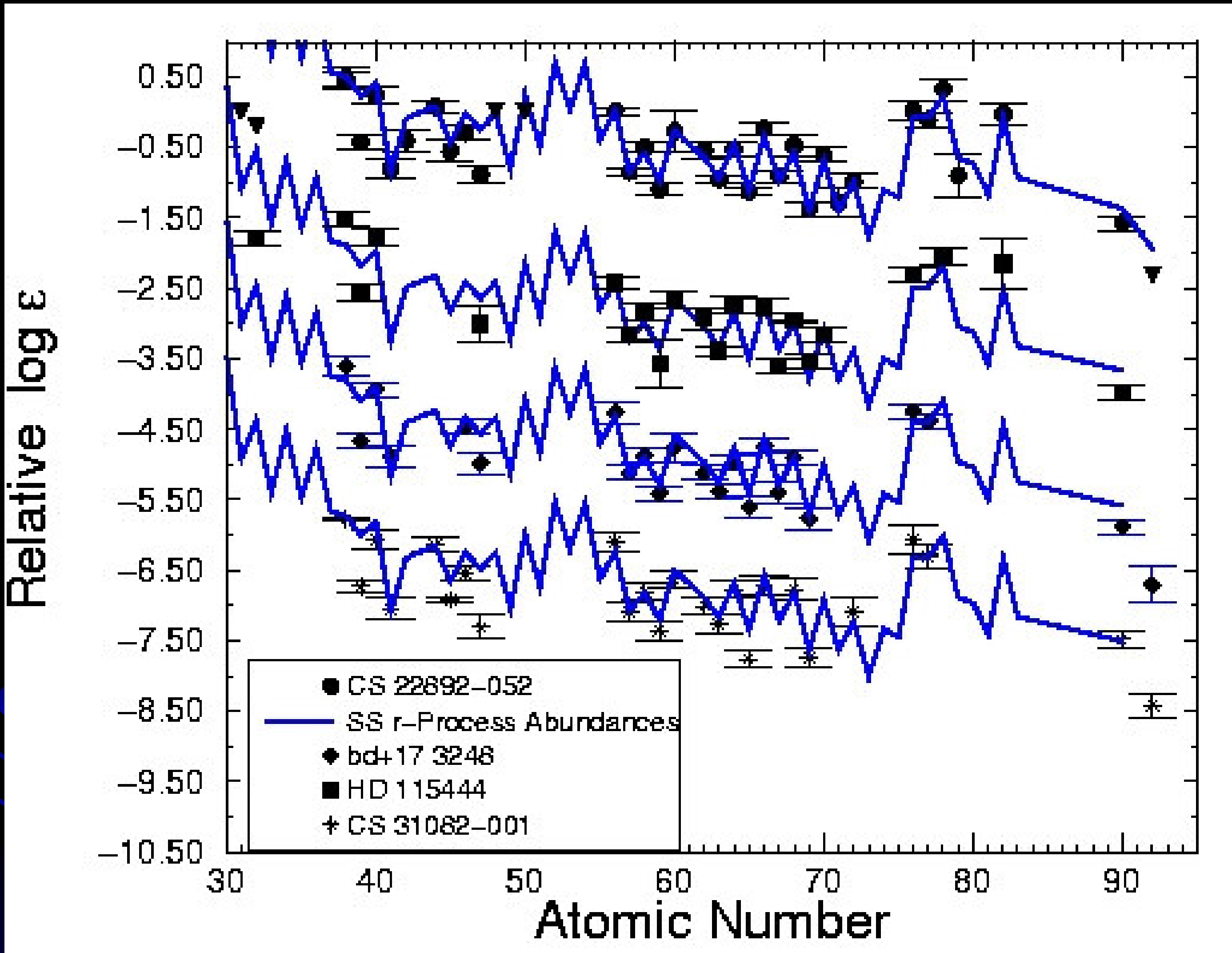

Platinum

(64 HST Orbits)

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

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

# Halo Star Abundances




4 r-process rich stars

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

# Light n-Capture Elements: Evidence for a Second r-process ?

- Only recently any detections of elements, Z = 40-50
  - → Best evidence CS 22892-052
- Heavier element (Z ≥ 56) abundances seem to follow SS r-process curve, not so for the lighter elements
  - → Same pattern appears in several other r-process rich stars
- Two separate sites (Wasserburg, Busso & Gallino): strong and weak r-process (two types of SNe or SNe and NS mergers) or
- One site (different epochs or regions)

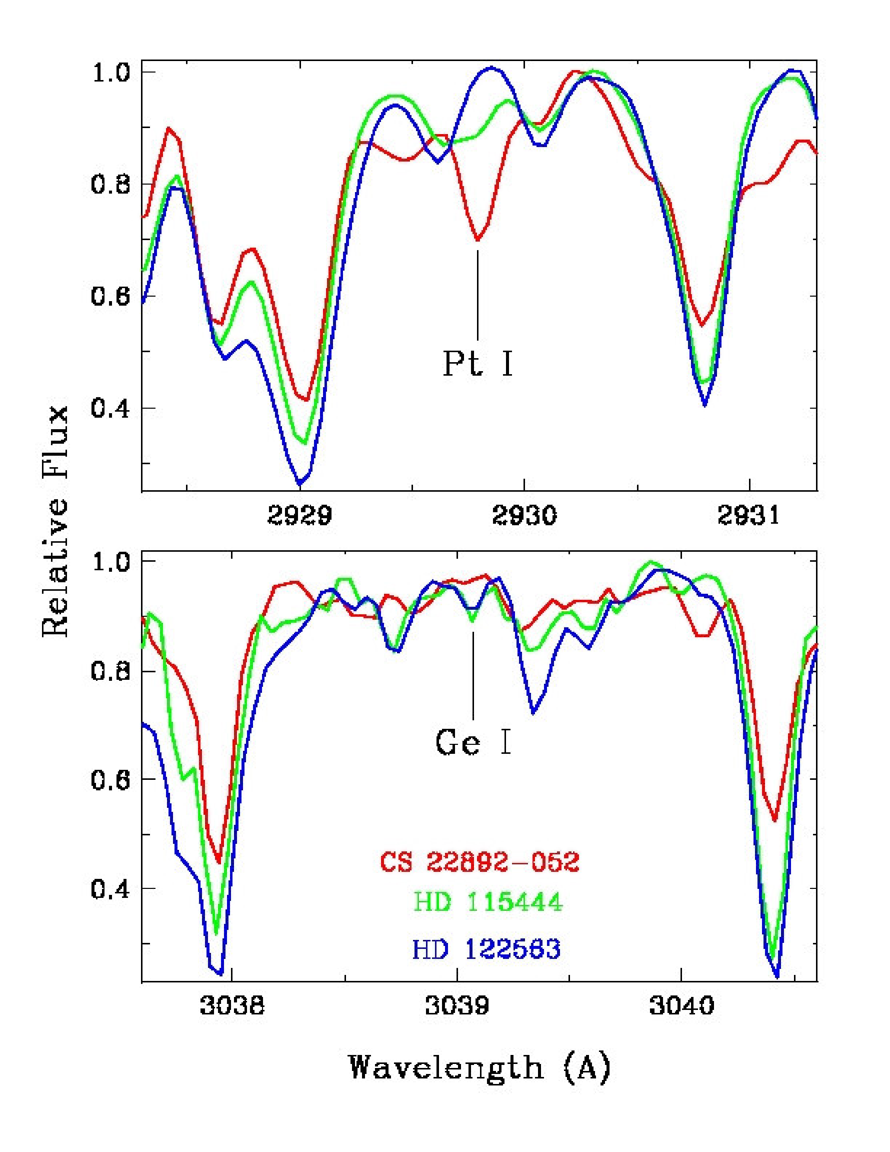
More evidence?

# New 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

# NUV HST STIS Spectra

Heavy n-capture elements do not scale with iron.

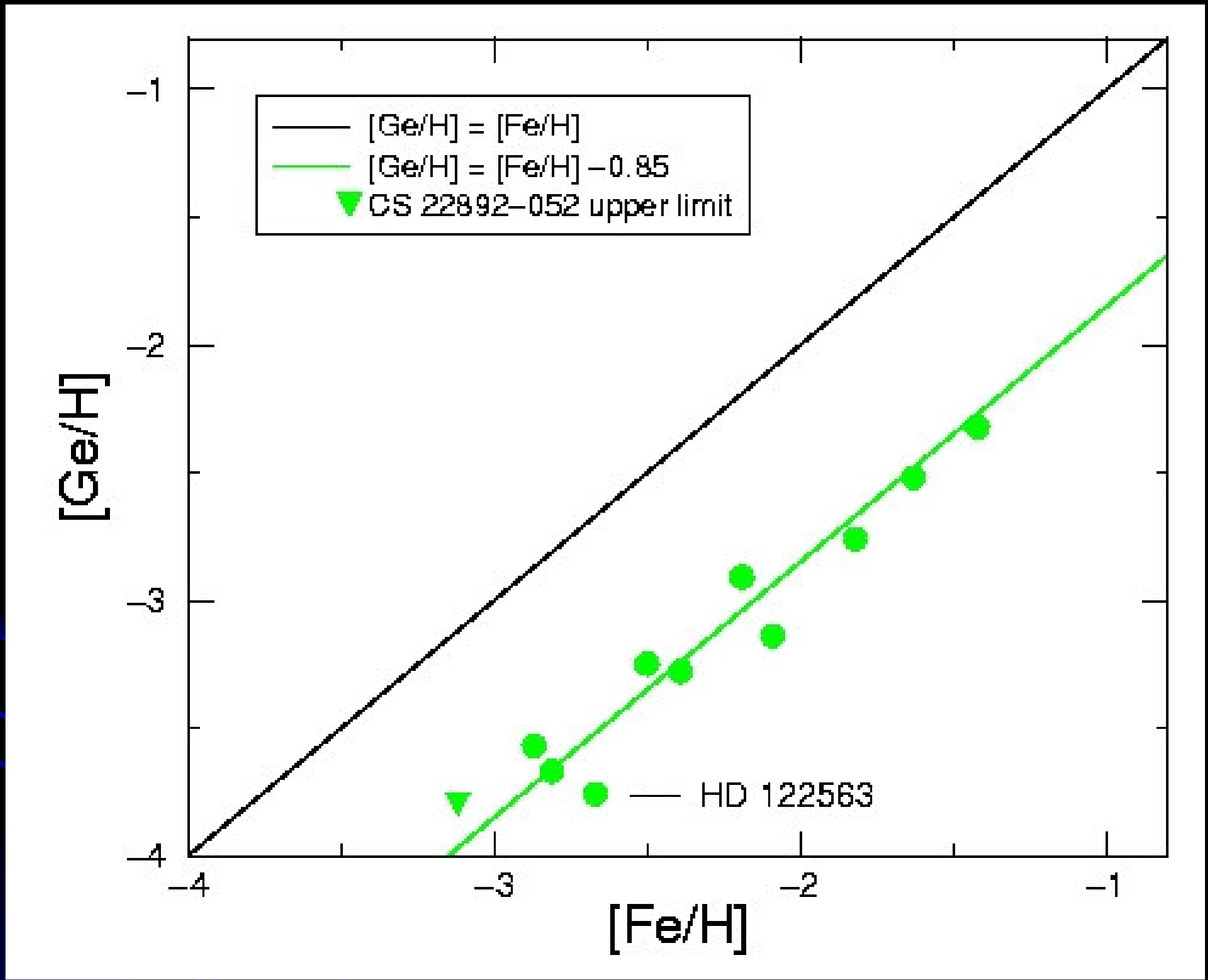



Ge scales with Fe.

More spectra

Note the resolution.

# Ge Abundances in Halo Stars




Ge ∝ Fe

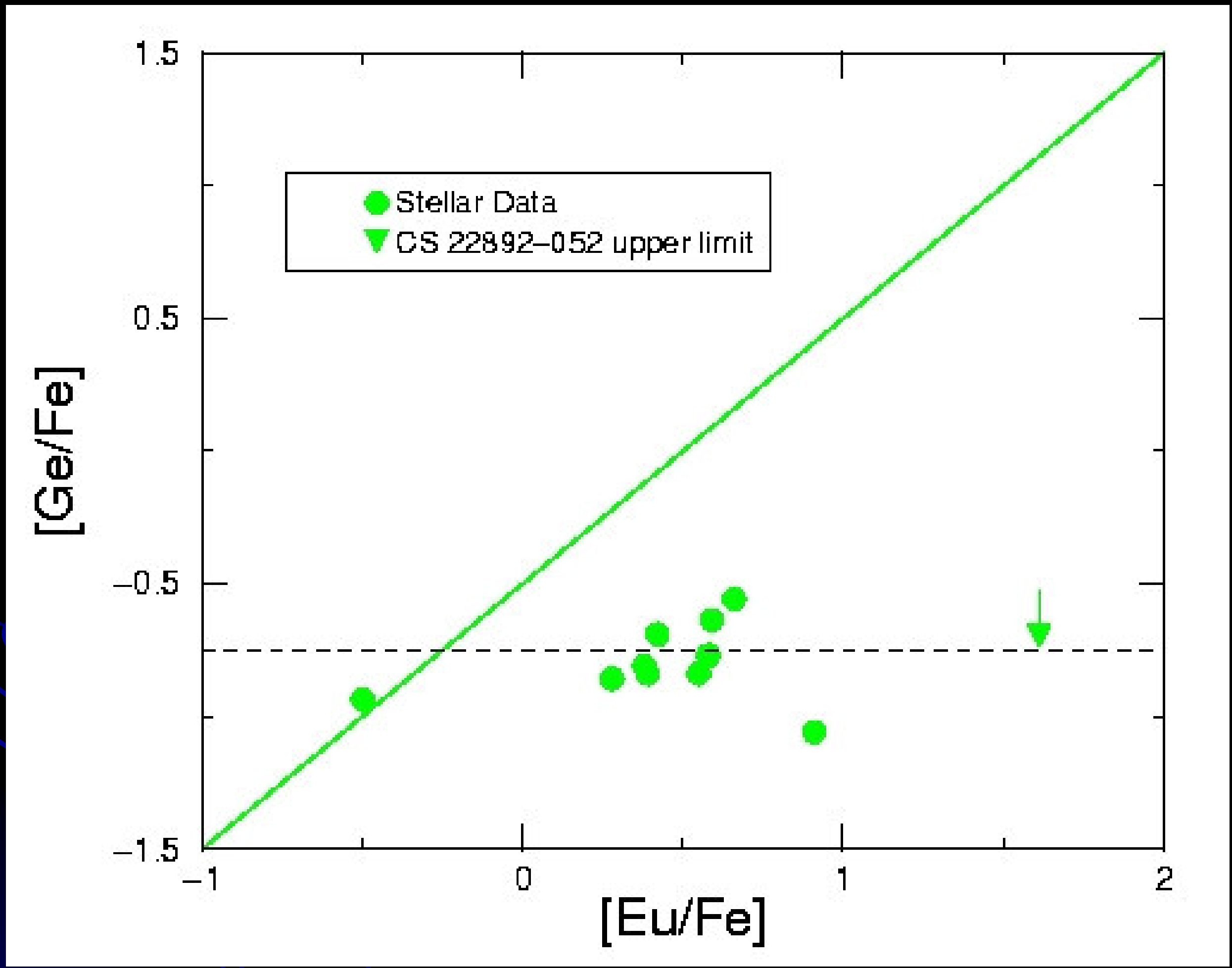
Challenge to theorists.

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

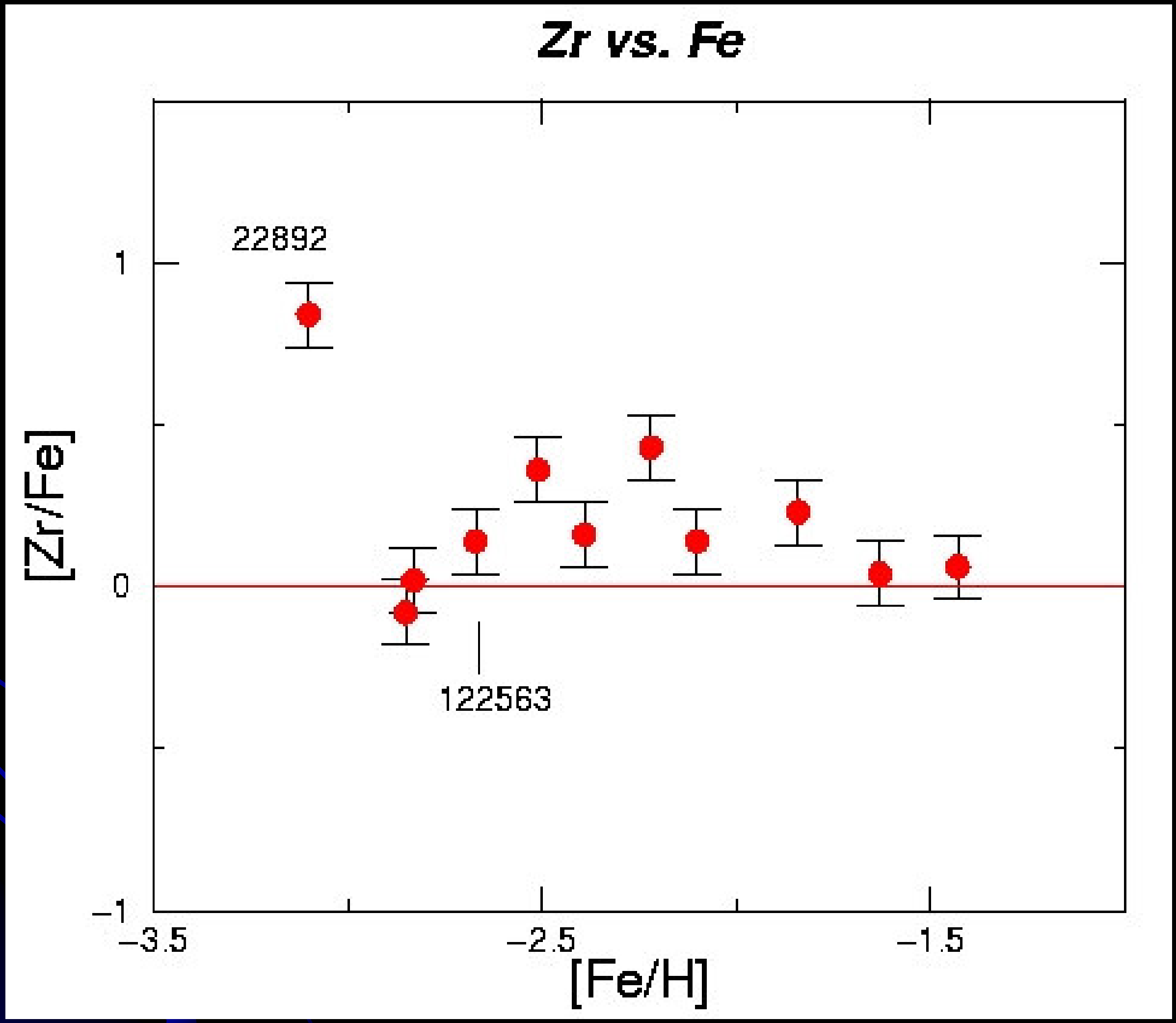



Ge $\not\propto$ Eu

JC et al. (2005)

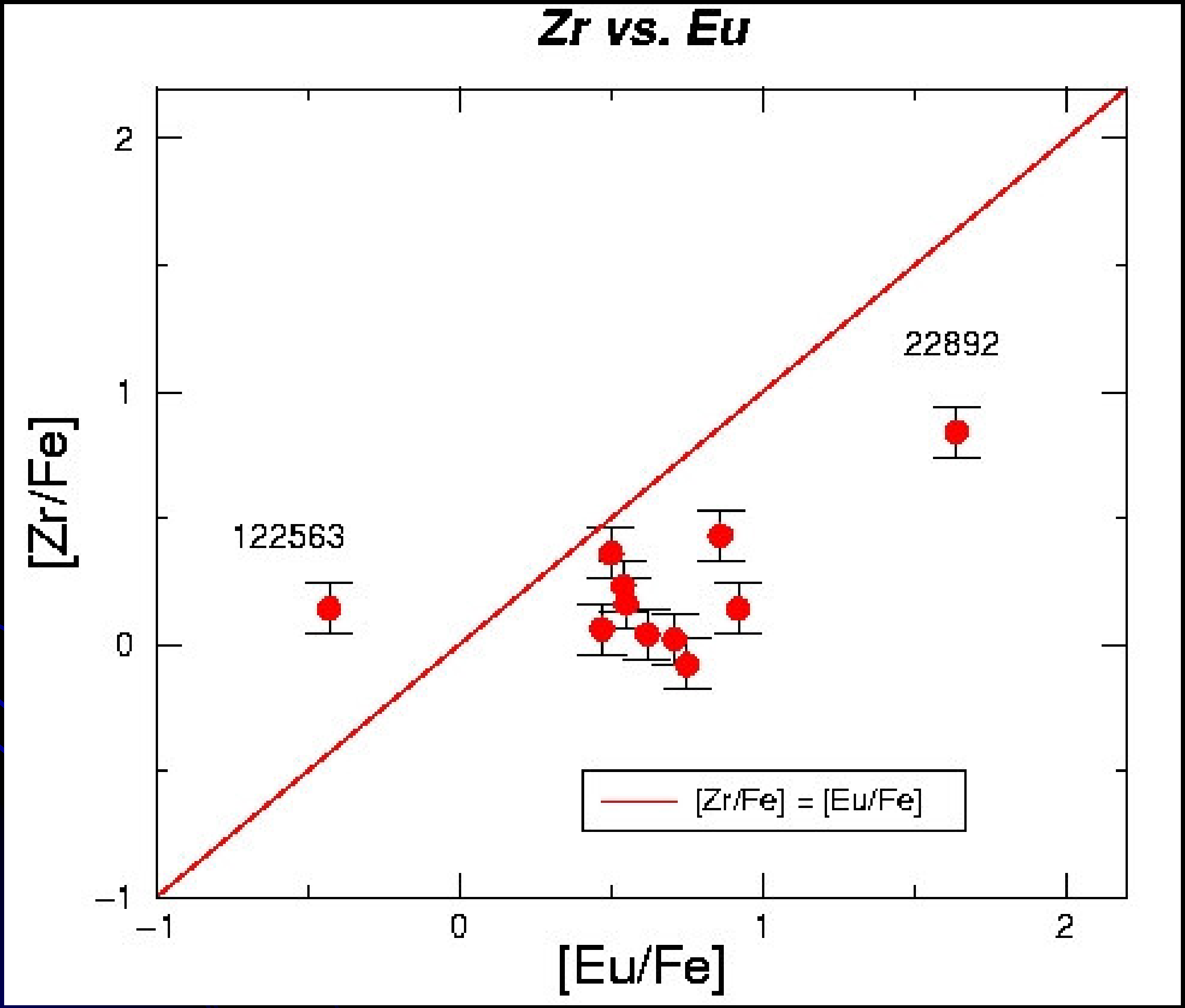
$[A/B] = \log_{10}(A/B)_{star} - \log_{10}(A/B)_{sun}$

# Zr as a Function of Metallicity




Zr independent of [Fe/H], as shown already by Travaglio et al. (2004).

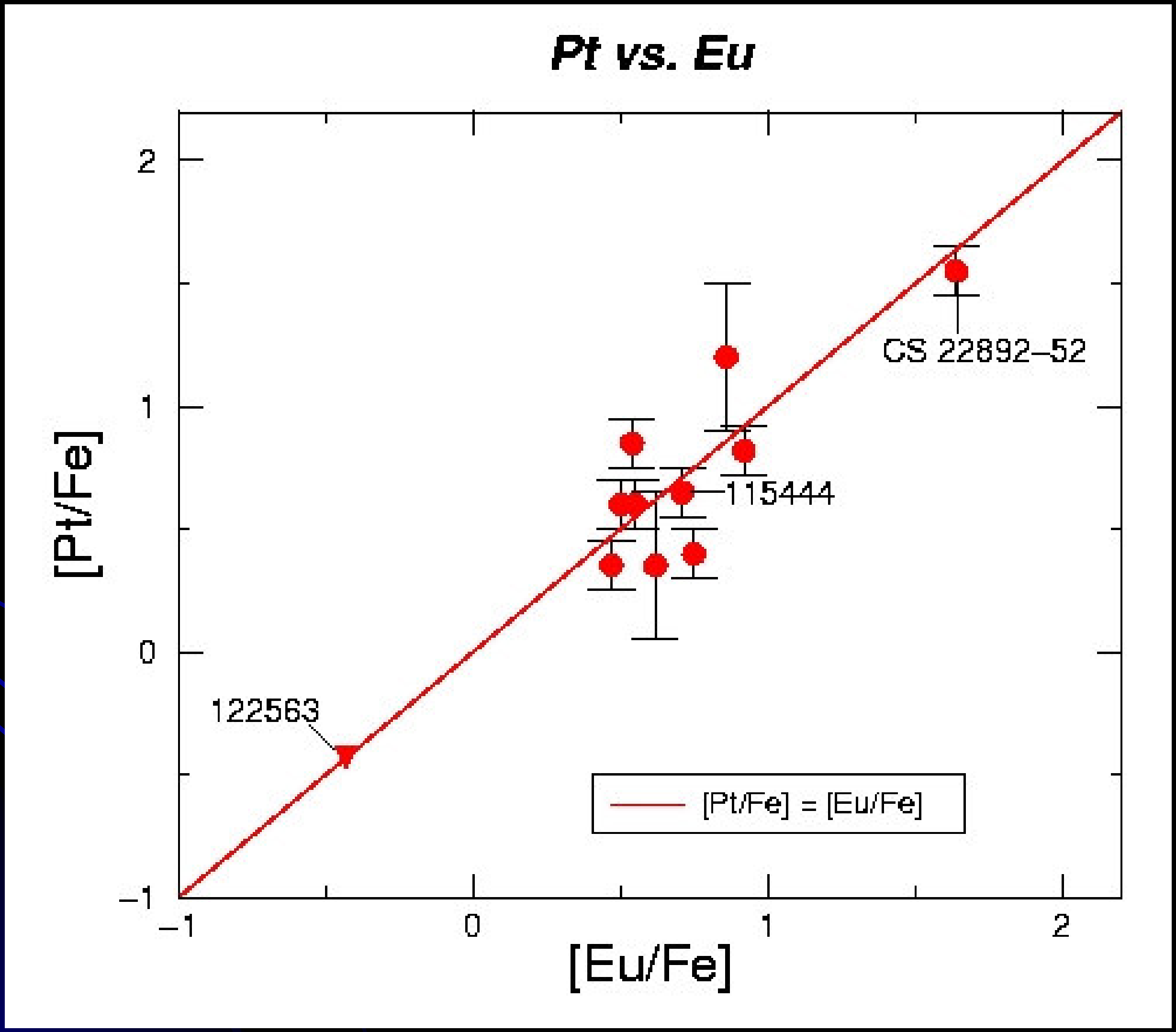
# Zr and Eu Abundances in Halo Stars




Zr ∝̸ Eu

Both n-cap elements but not from same source?

# n-Capture Element Correlations

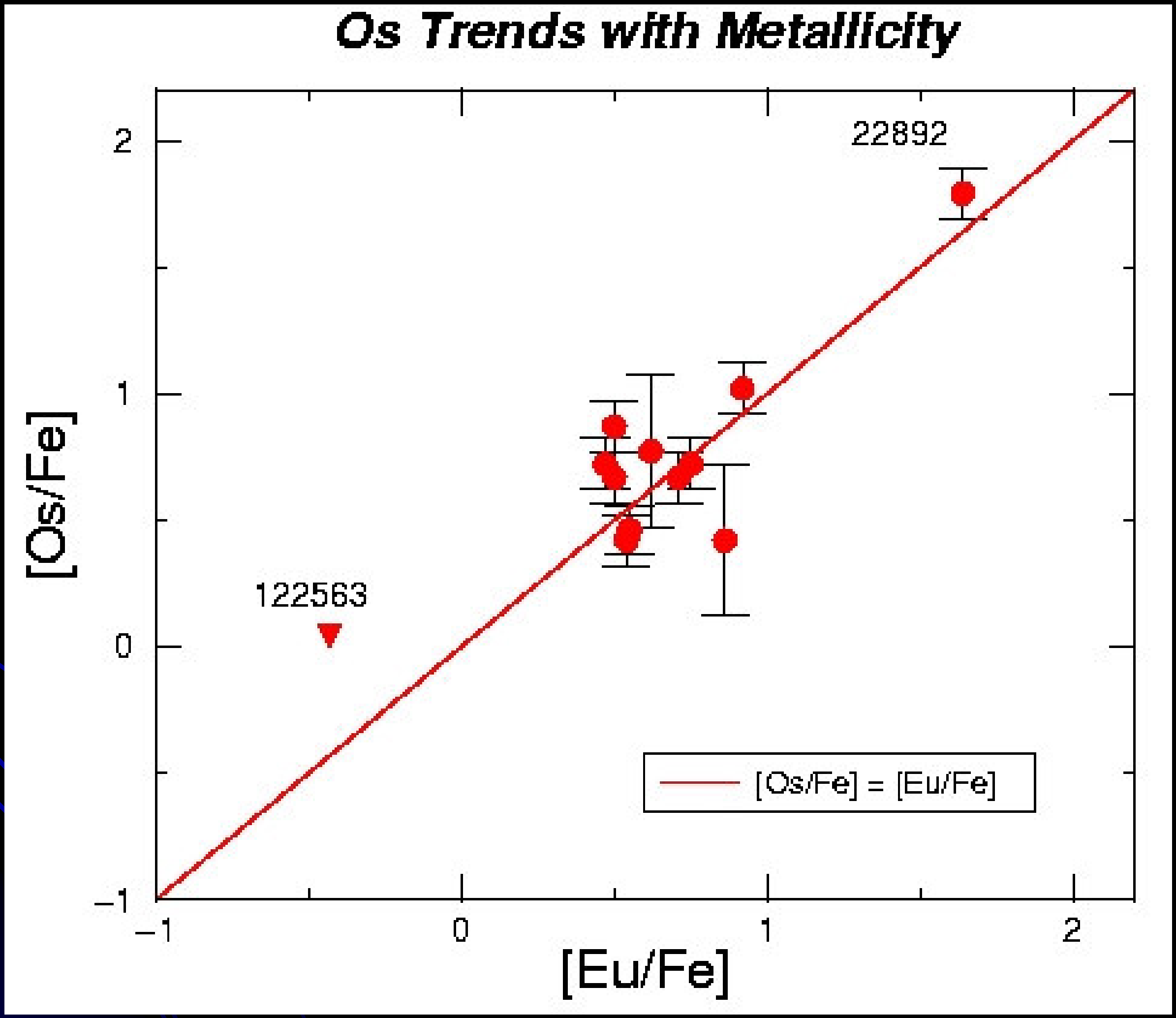



Pt ∝ Eu

[Os shows the same trends.]()

[Correlations]()

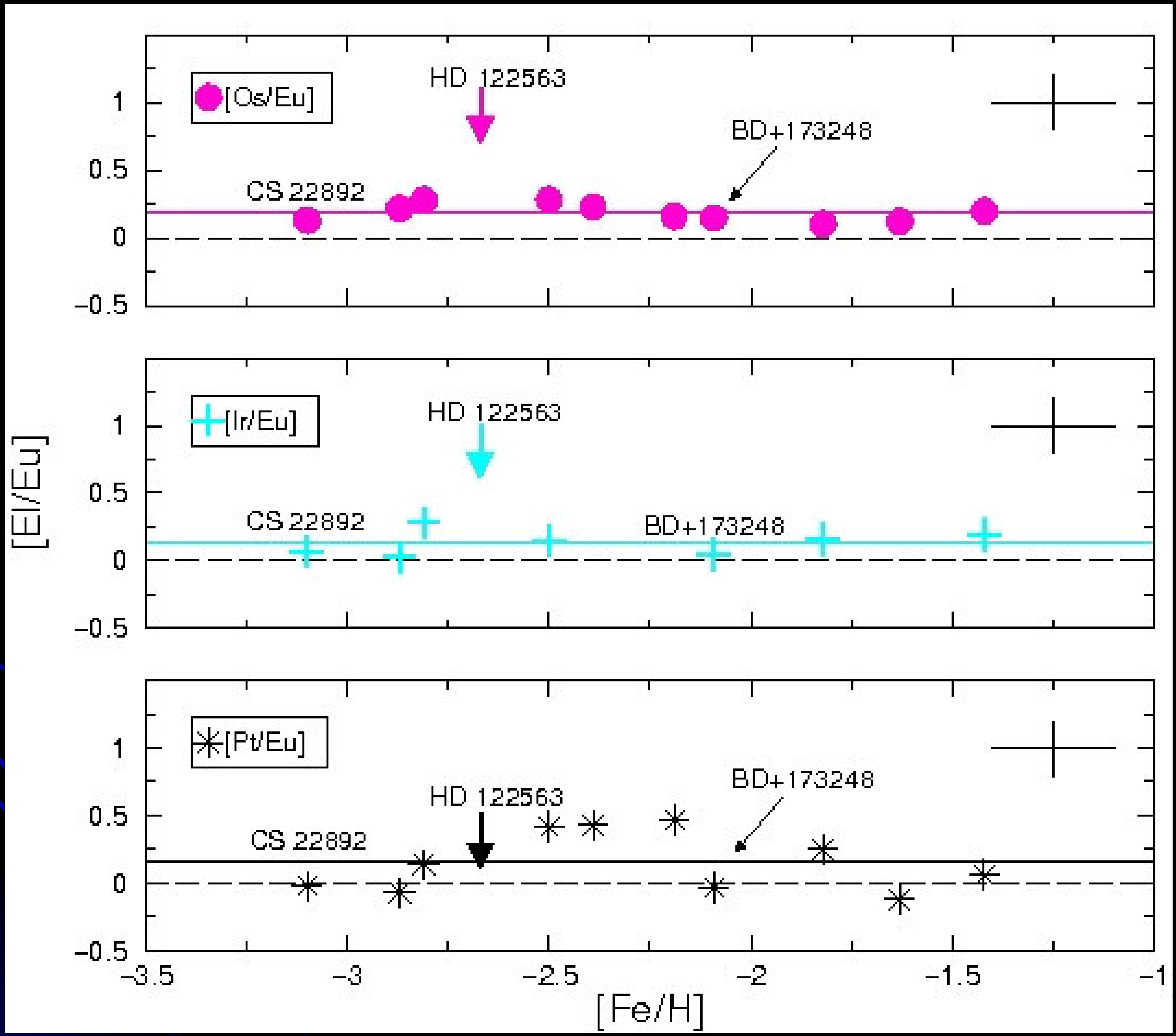
# n-Capture Element Correlations



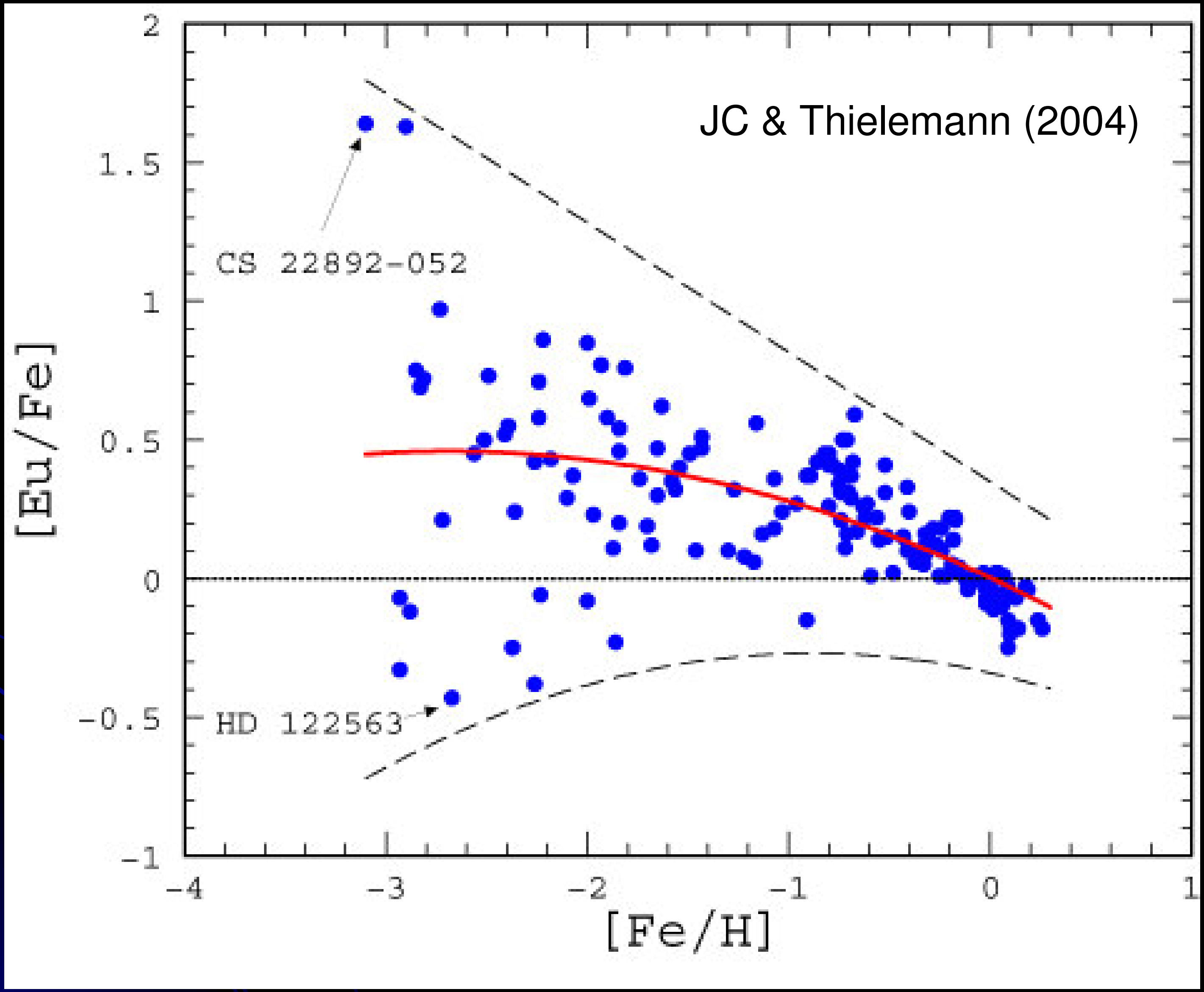

Os ∝ Eu

# n-Capture Element Correlations

$3^{rd}$ r-process peak elements correlate with Eu.



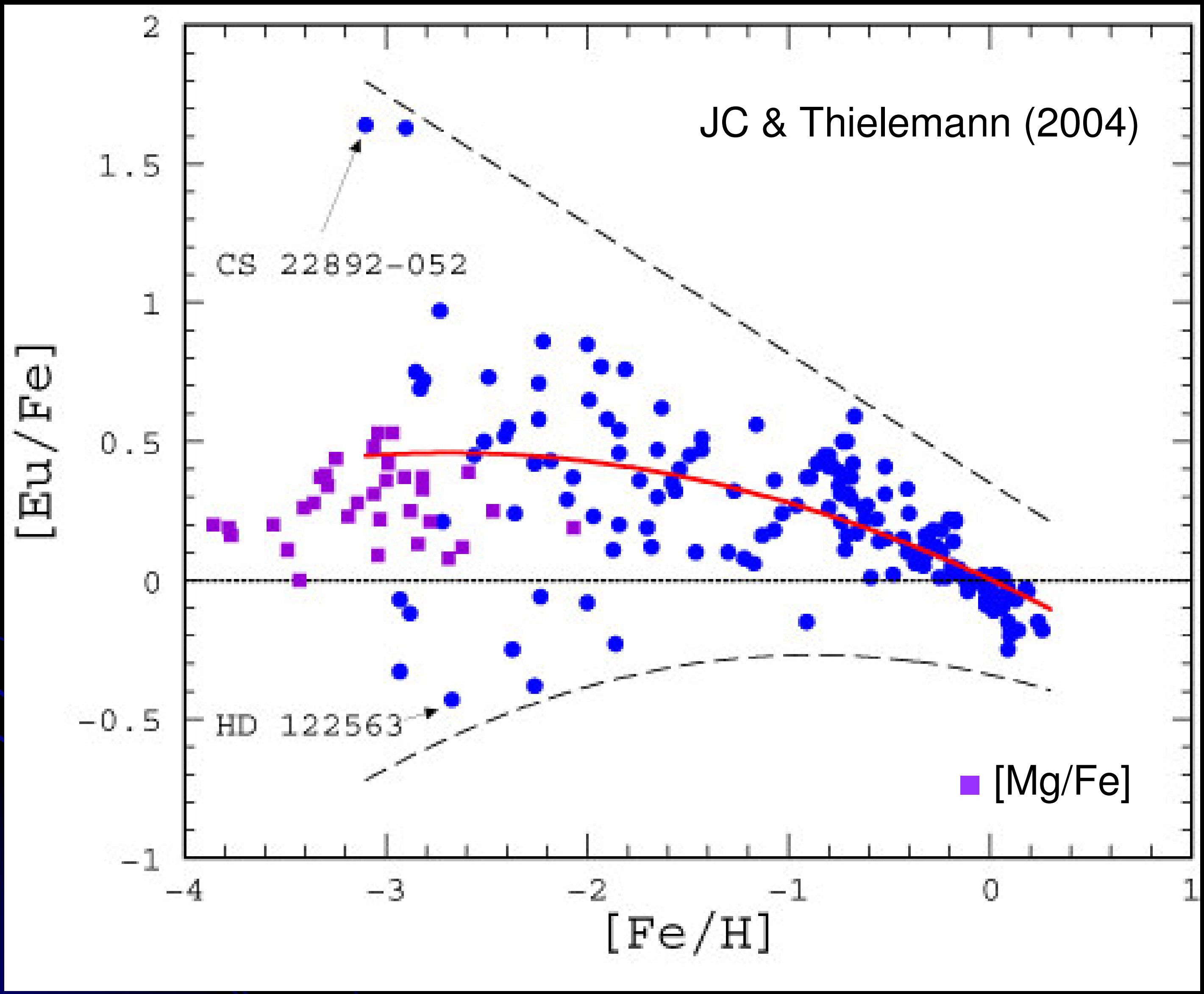
# Eu Abundance Scatter in the Galaxy




Single SNe at early times?

Early Galaxy chemically inhomogeneous and unmixed for r-process elements.

# Eu Abundance Scatter in the Galaxy

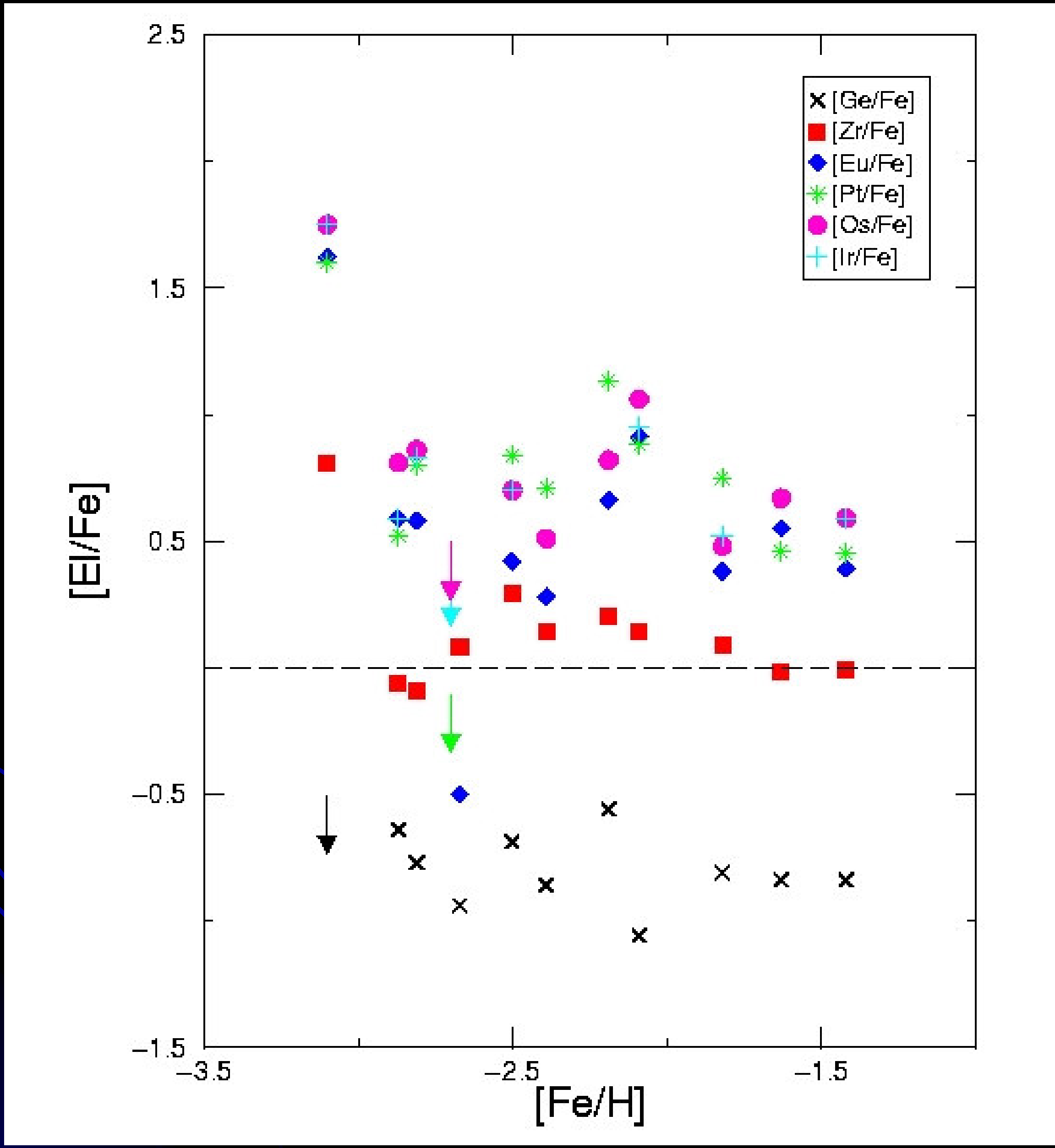



Early Galaxy chemically inhomogeneous and unmixed for r-process elements.

# n-Capture Element Abundance Trends

Os-Pt & Eu correlated and show similar scatter with [Fe/H]

RARE

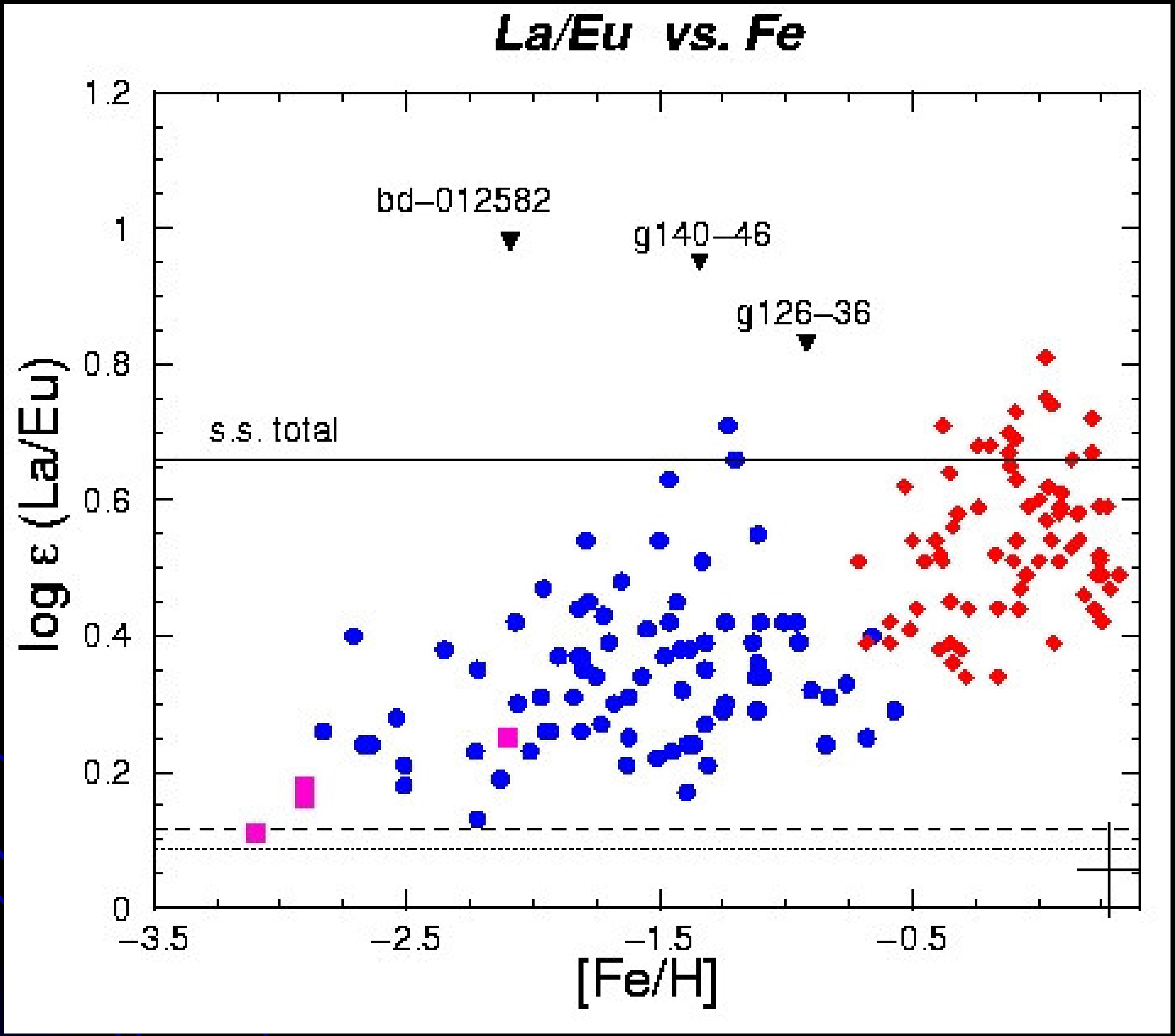



Ge & Zr Show little Scatter.

COMMON

# r- and s-Process Abundance Trends

Simmerer et al. (2004)

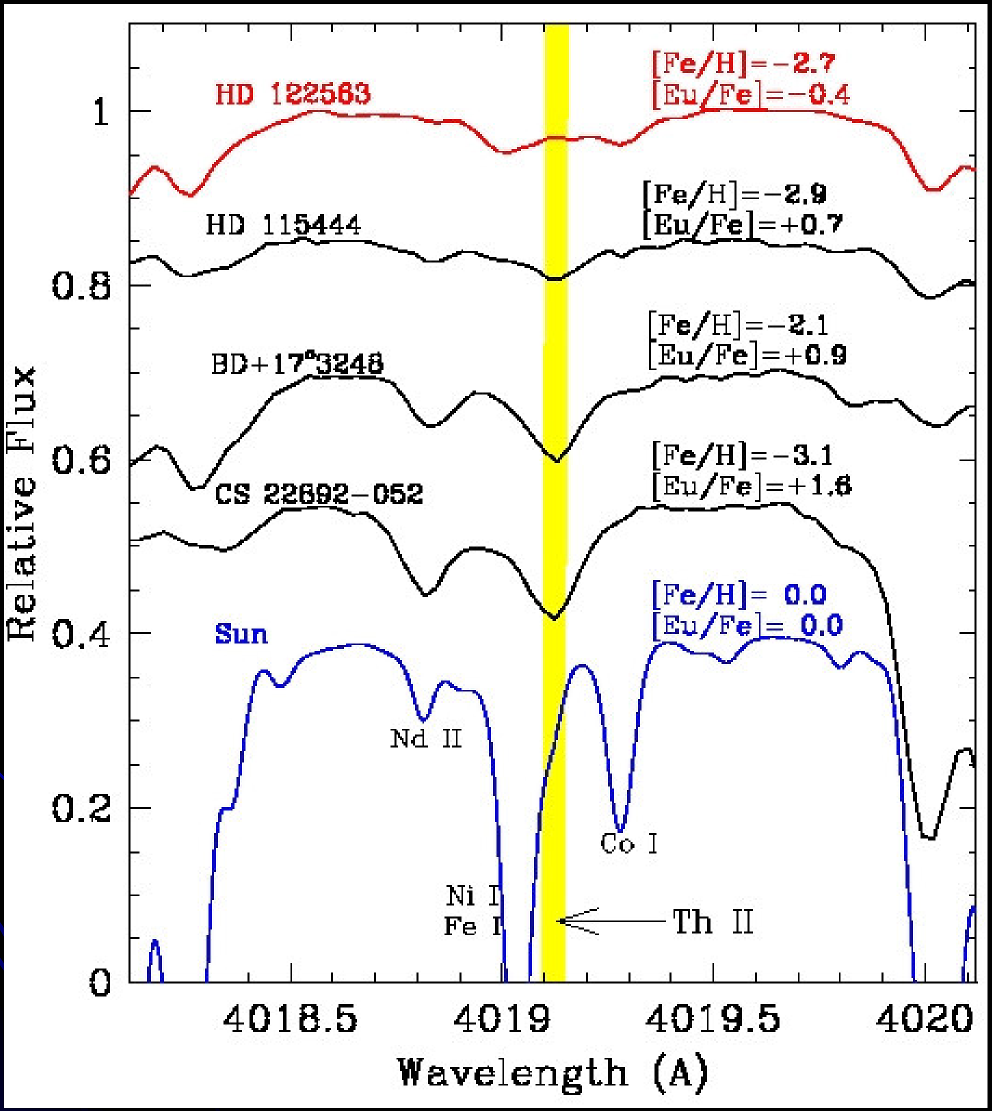



O'Brien et al. (2003)

Burris et al. (2000)

r-process only

# Th Detections in Four Halo Stars and the Sun




More Chronometers?

Yes

No

# R-Process Chronometers

- Use various radioactive abundance ratios: Th/Eu, Th/U, Th/Pt, etc. to predict initial time-zero values
- Compare with observed ratios
- Is independent of chemical evolution models
- A range of values depending upon uncertainties in nuclear physics predictions (i.e., mass formulae) and abundance uncertainties

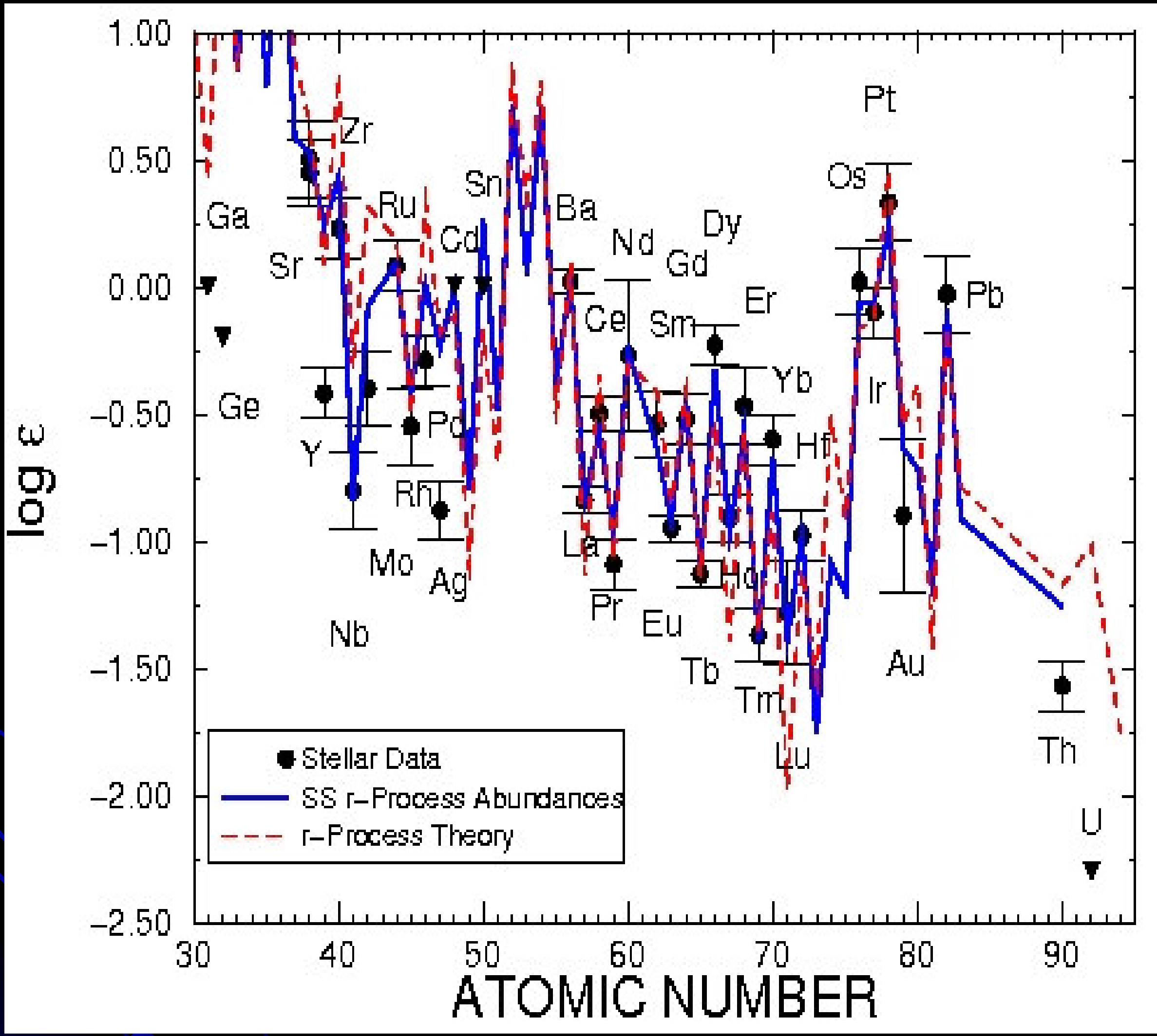
# Radioactive-Decay Age Estimates

- The measured abundance of Th in stars such as CS 22892-052 allows for age determinations using the long half-life of $^{232}$Th (14 Gyr).

→ $N_{Th(t)} = N_{Th(t0)} \exp(-t/\tau_{Th})$

- SS Th/Eu (today) = 0.344
- SS Th/Eu (at formation) = 0.463
- Measured Th/Eu in CS 22892-052 = 0.24

# Theoretical r-Process Predictions




More predictions

Calculate radioactive abundance ratios based upon fitting stable elemental & isotopic values.

# Chronometric and Other Ages

- For CS 22892-052 (latest values of Th/Eu, Th/Pt) give <14.2> +/- 3 Gyr
- For bd+17 3248 (with the detection of U) Th/U, Th/Eu, Th/Pt, etc. (<13.8> +/- 4 Gyr)
- Compare to globular values (M15 ≈ 14Gyr, from chronometers) & typically 13-15 Gyr
- WMAP of 13.7 Gyr
- SN Ia of 14.2 +/- ≈ 2  Gyr

# Problems and Uncertainties

- What about CS 31082-001? Th/Eu give unrealistic age – Th/U give 14.1 – 15.5 +/- ≈ 3 Gyr (from different groups)

→ Th & U very high: actinide boost?

fission recycling? What about low Pb?

Need more U detections and need better

Nuclear values.

# 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?
- 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: Galaxy & Universe

# With Collaborators at:

- U. of Texas
- MSU
- U. of Chicago
- Caltech
- MIT
- Carnegie Obs.
- U. of Wisconsin
- U. of Mainz
- Obs. de Paris
- U. of Basel
- U. di Torino
- ESO

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