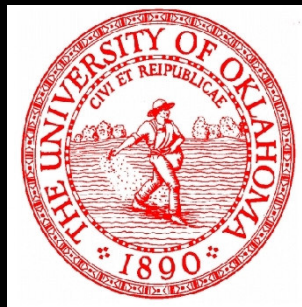


# NEUTRON-CAPTURE ELEMENTS IN ULTRA-METAL-POOR STARS

J. J. COWAN

University of Oklahoma



FRANZ (Frankfurt) -- May 22, 2007

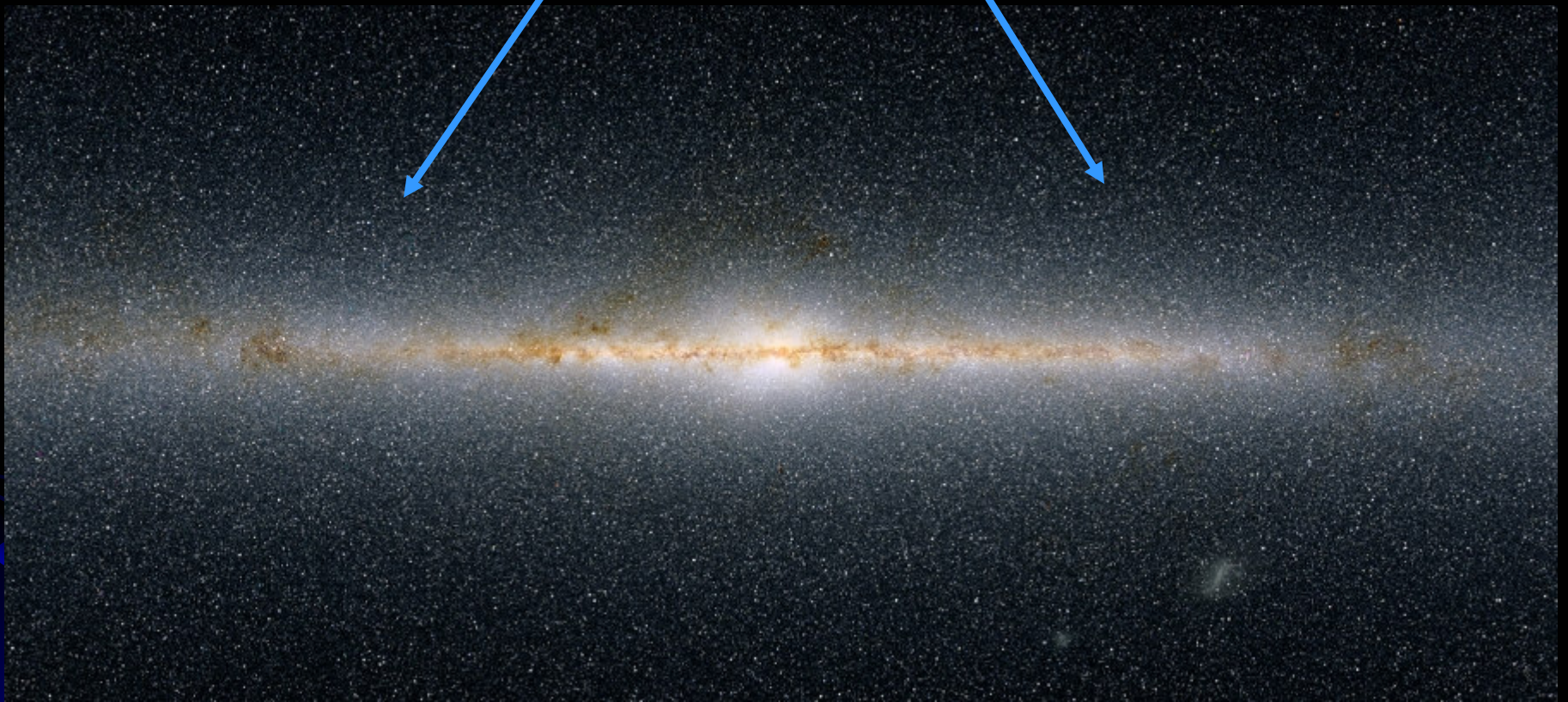
# Abundance Clues and Constraints

- 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

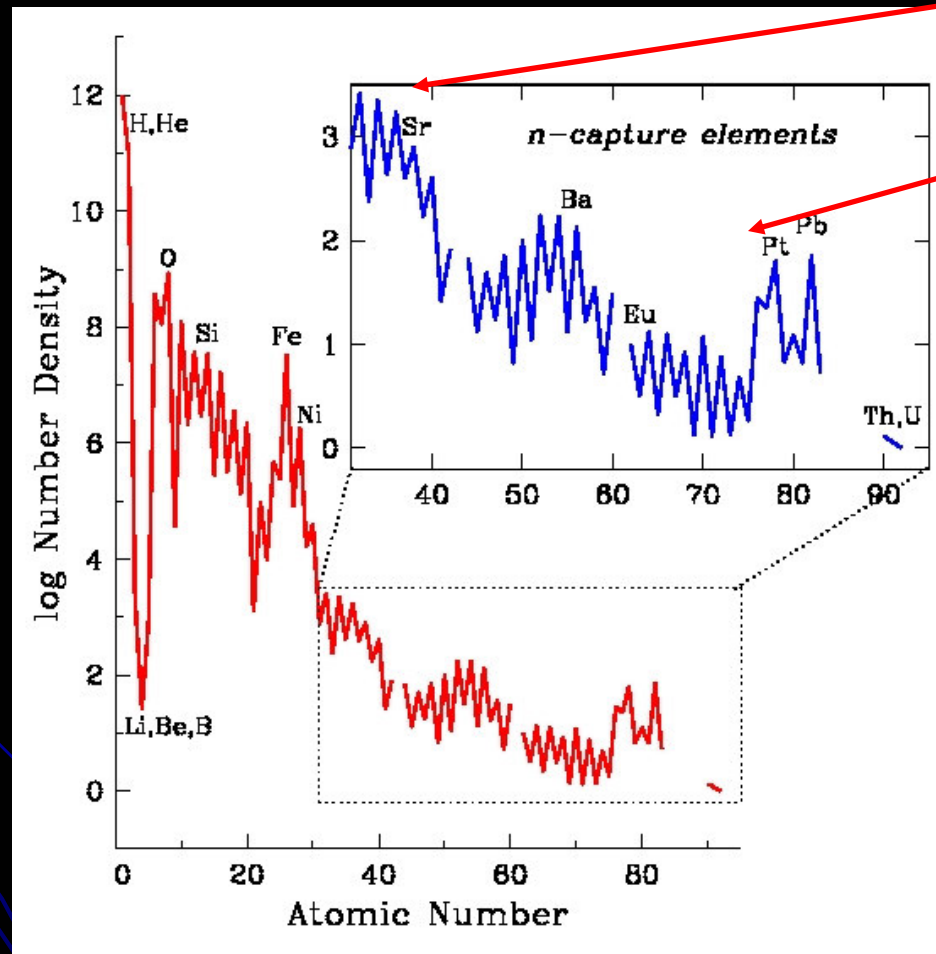
Galactic Halo Stars



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

[back](#)

# Solar System ("Cosmic") Abundances



Ge, Zr

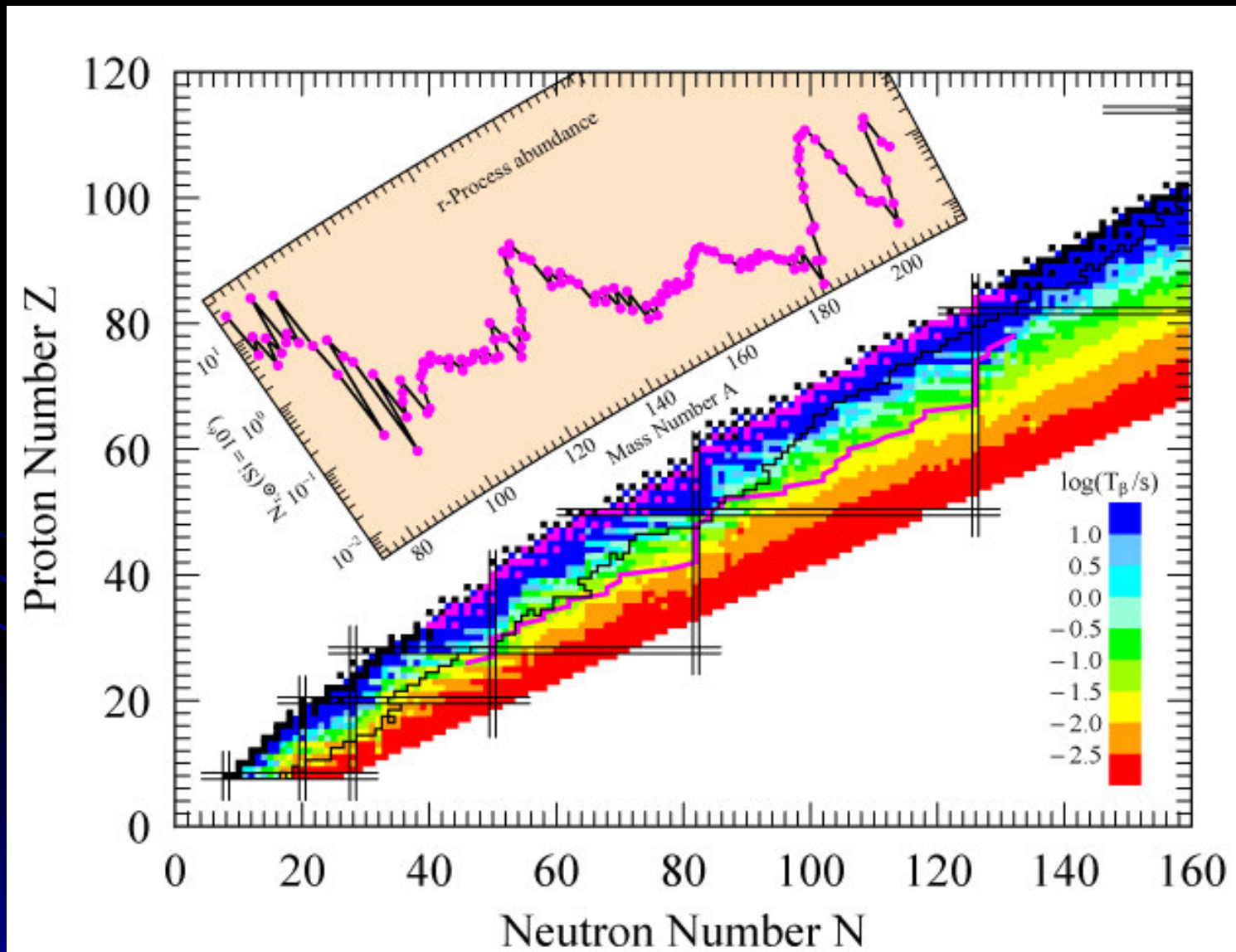
Os, Pt

Jewelry store  
items

Snedden & JC (2003)

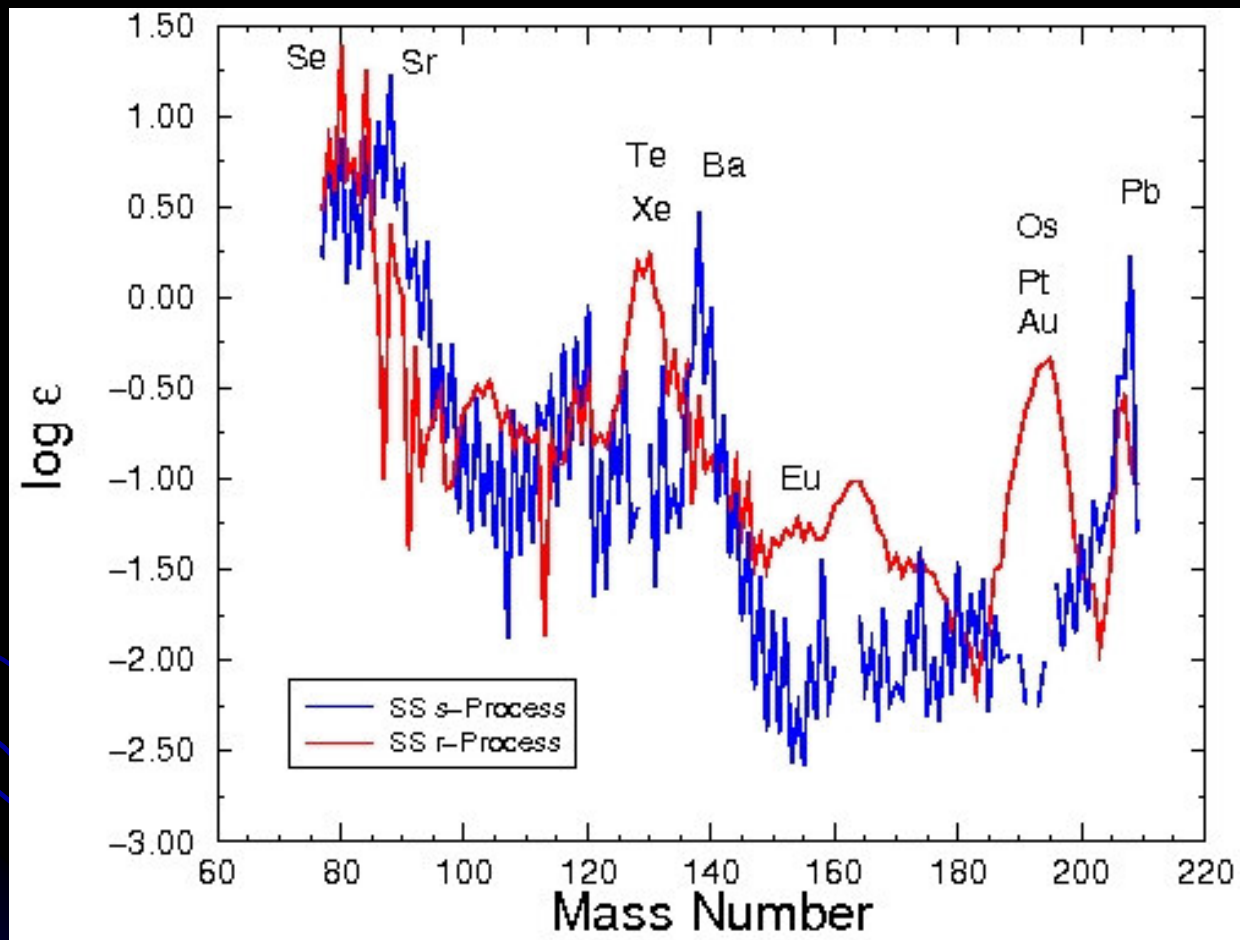


# The Nuclear Isotopes in Nature



[details](#)

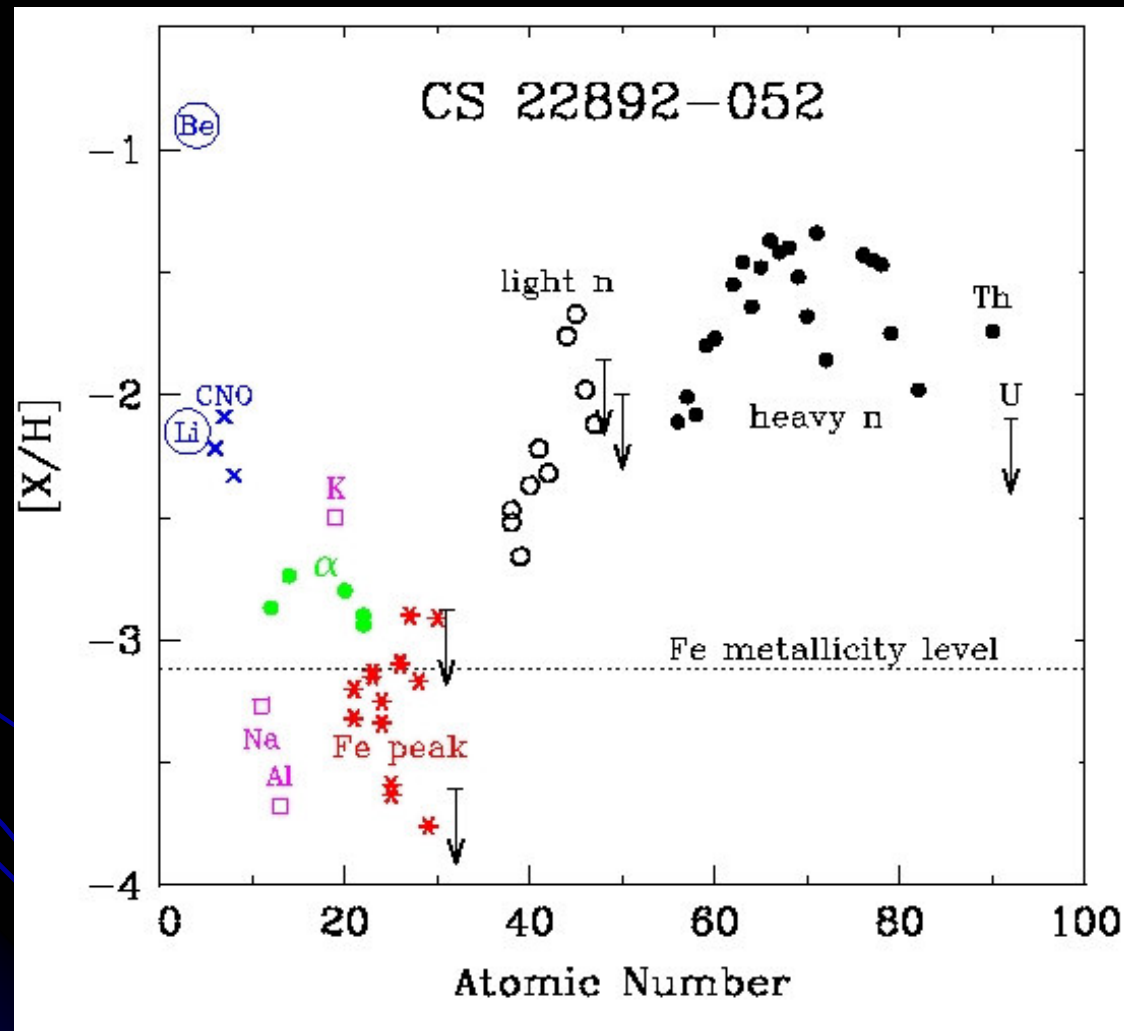
# Solar System s- and r-Process Abundance Peaks



SS isotopic deconvolution by s- and r-process

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

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



Light elements  
mostly scale  
with  $[Fe/H]$ .

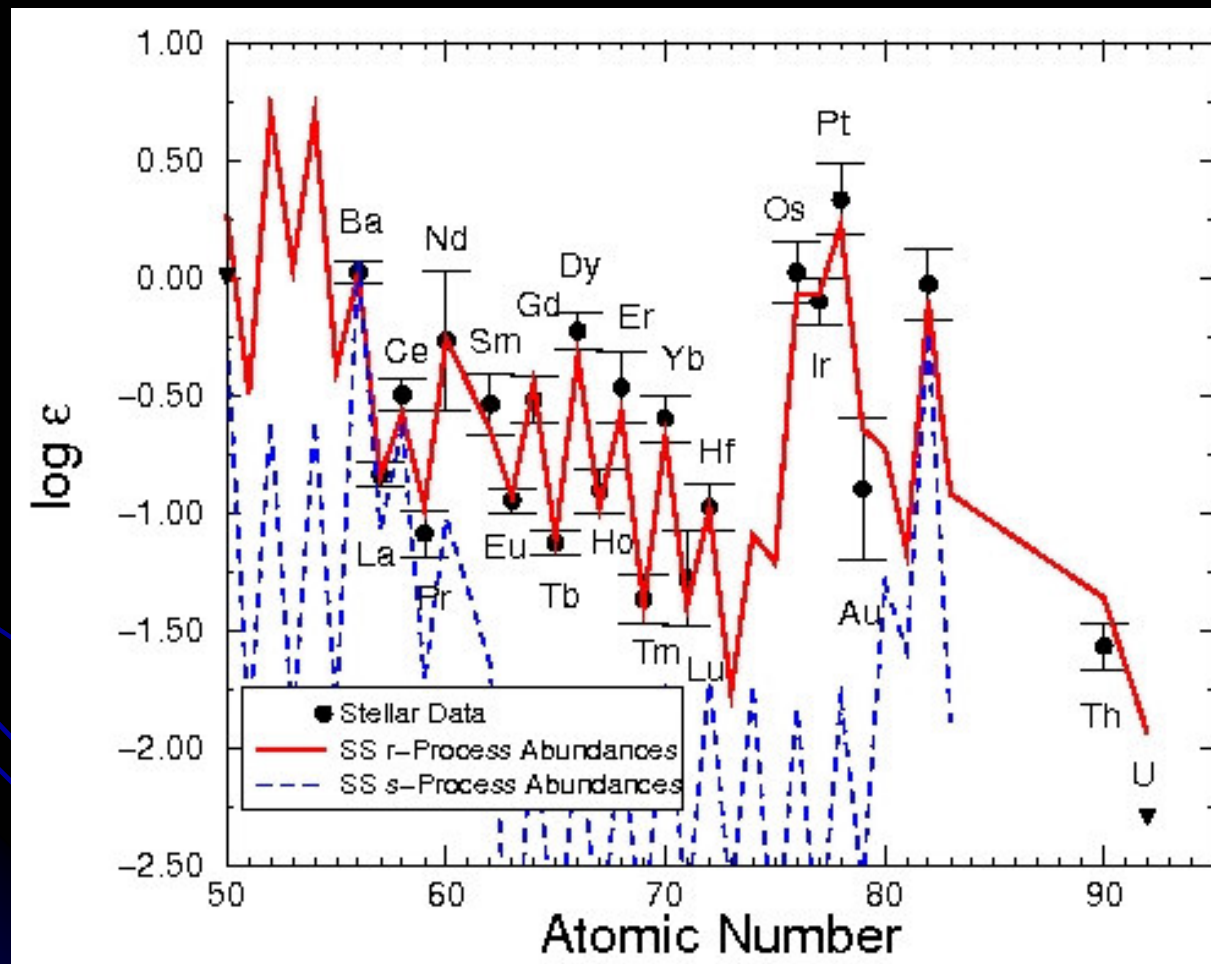
Heavy  
n-capture  
elements  
greatly  
enhanced  
( $\approx 40$ -50)  
over  
iron abundance.

$[Fe/H] = -3.1$

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

# n-Capture Abundances in CS 22892-052

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



Historical  
(~ 1996)



Major  
contribution  
by Franz et al

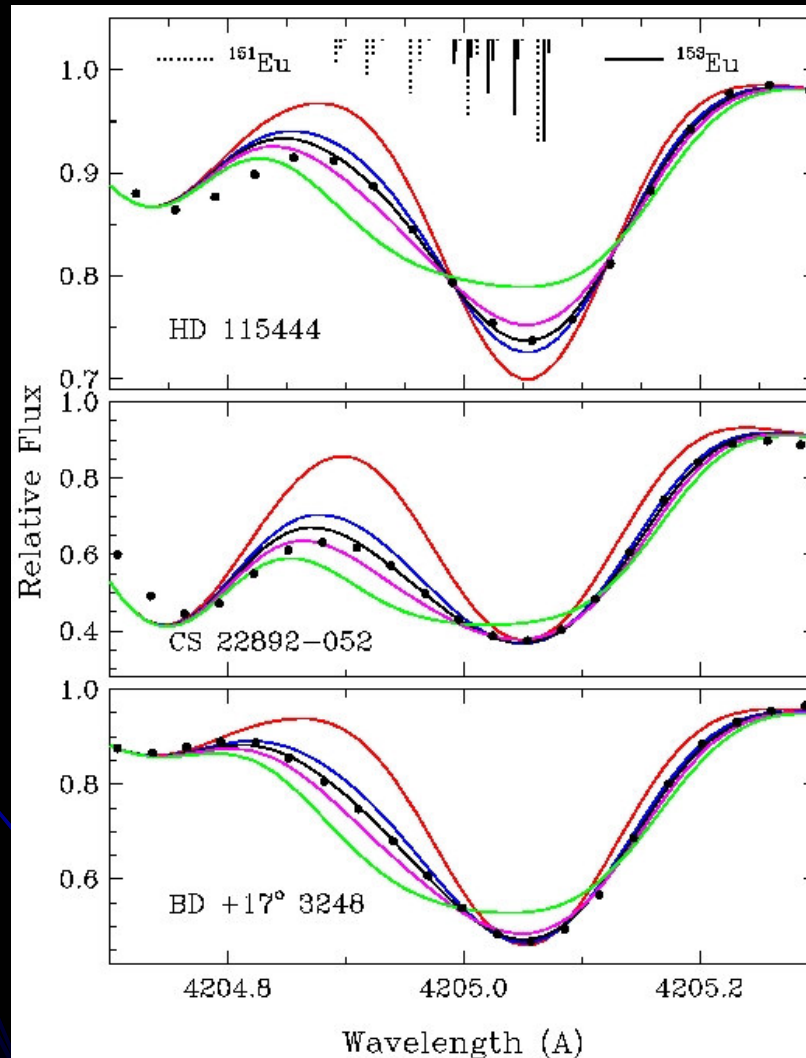
Very old star.  
Robust  
r-process over  
the history of  
the Galaxy.

Stellar elemental abundances consistent with scaled SS r-process only



# Eu Isotopic Abundances in Three Metal-Poor Halo Stars

$^{151}\text{Eu}$ :  
→ 100%  
→ 65%  
→ 48%  
→ 35%  
→ 0%



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

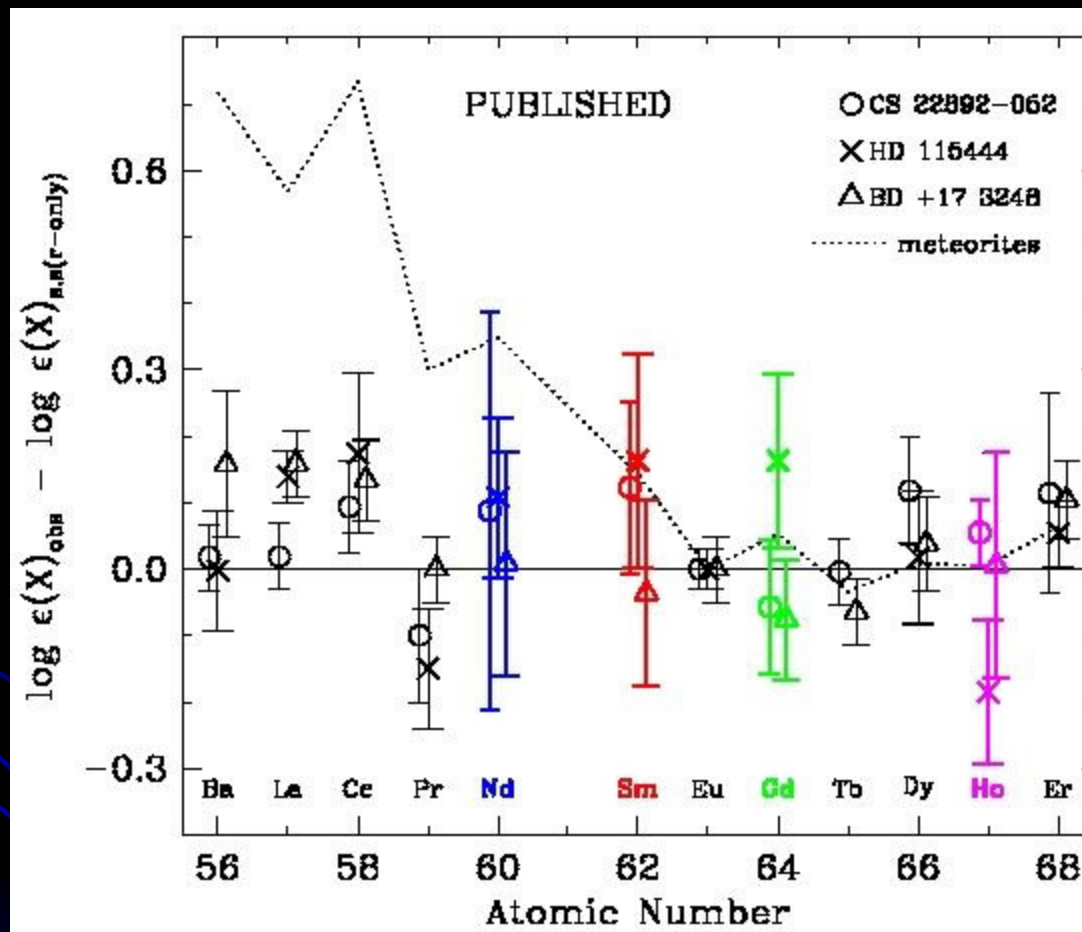
[Ba now seen as well in one star](#): isotopes appears to be consistent with SS ratios.

Sm & others in progress

[More lines in the same star](#)

Sneden et al. (2002)

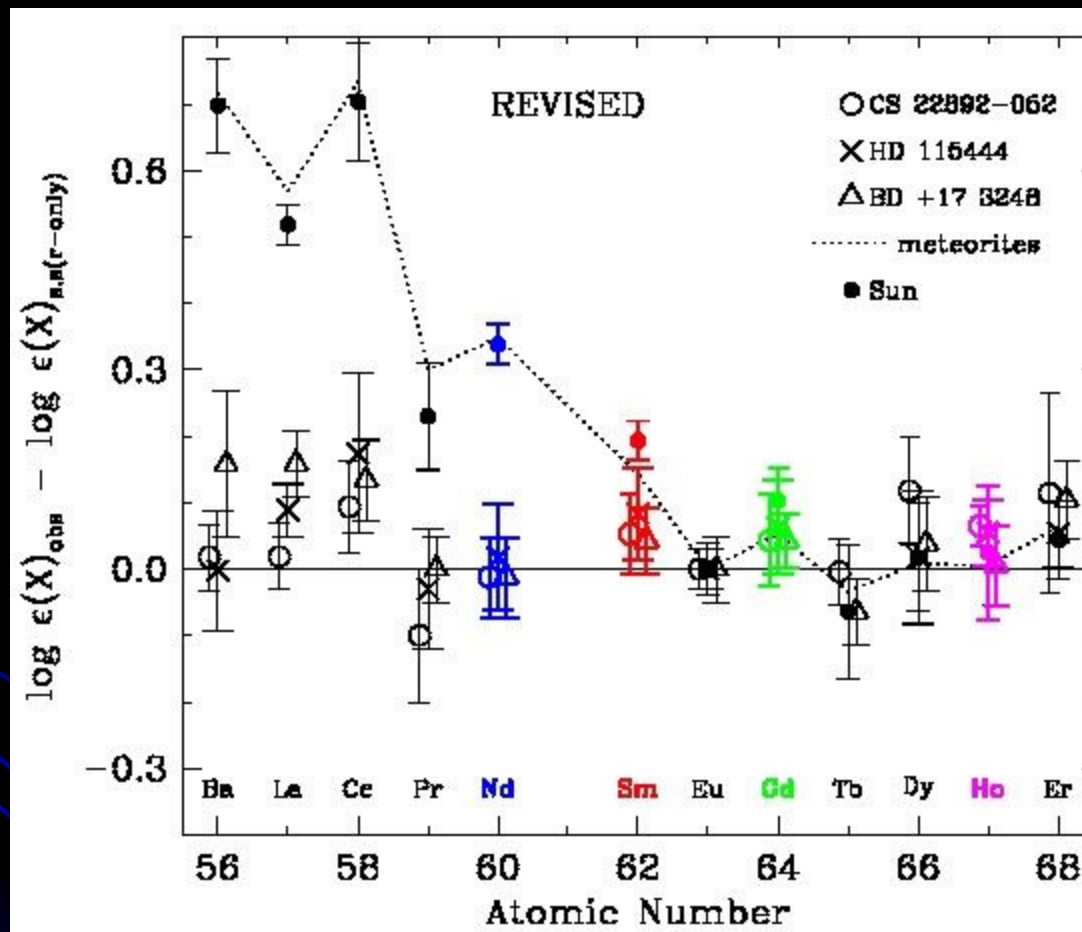
# Focus On Individual Elements: Nd, Sm, Gd & Ho



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)

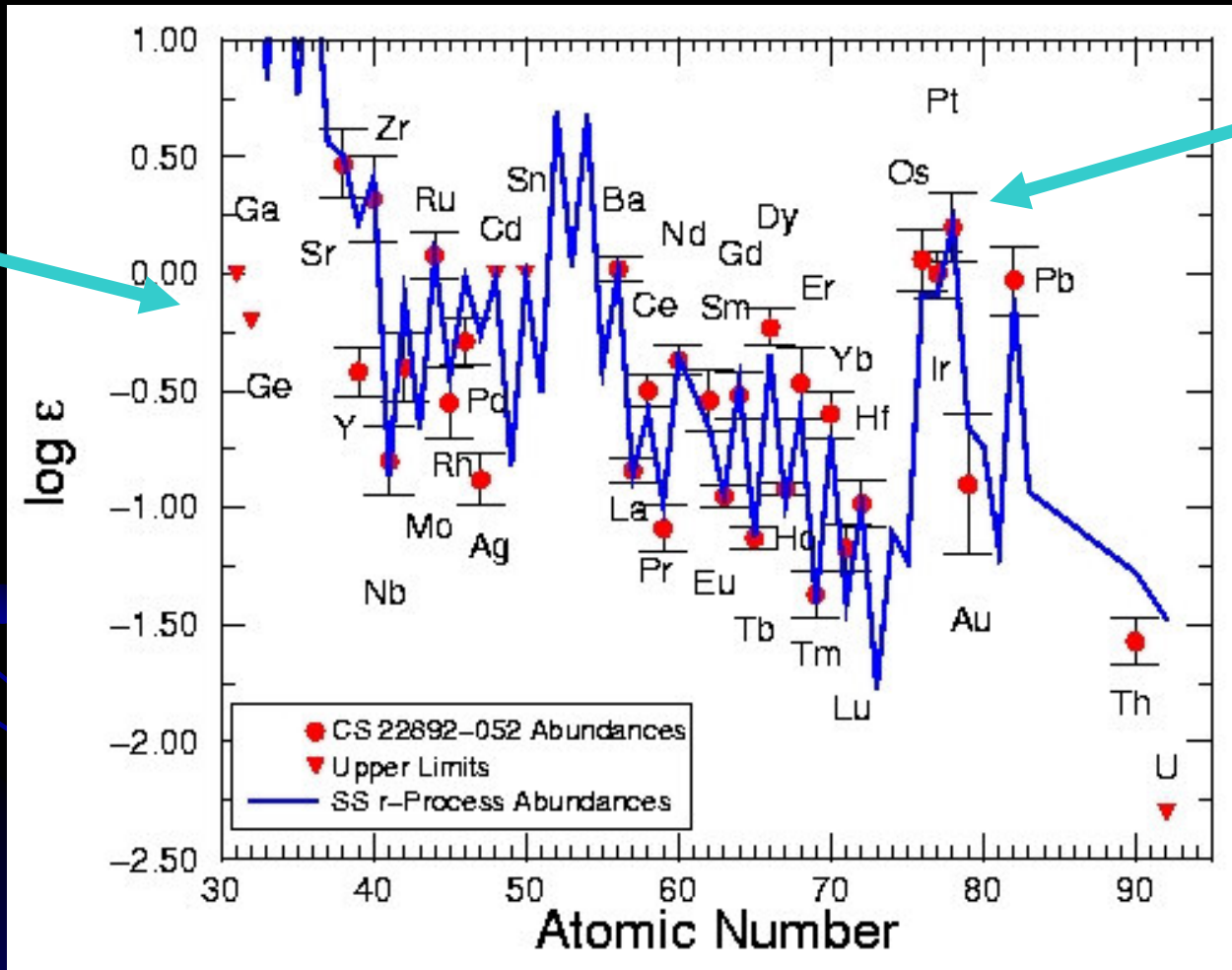
Hf done (Lawler et al. 2007)

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

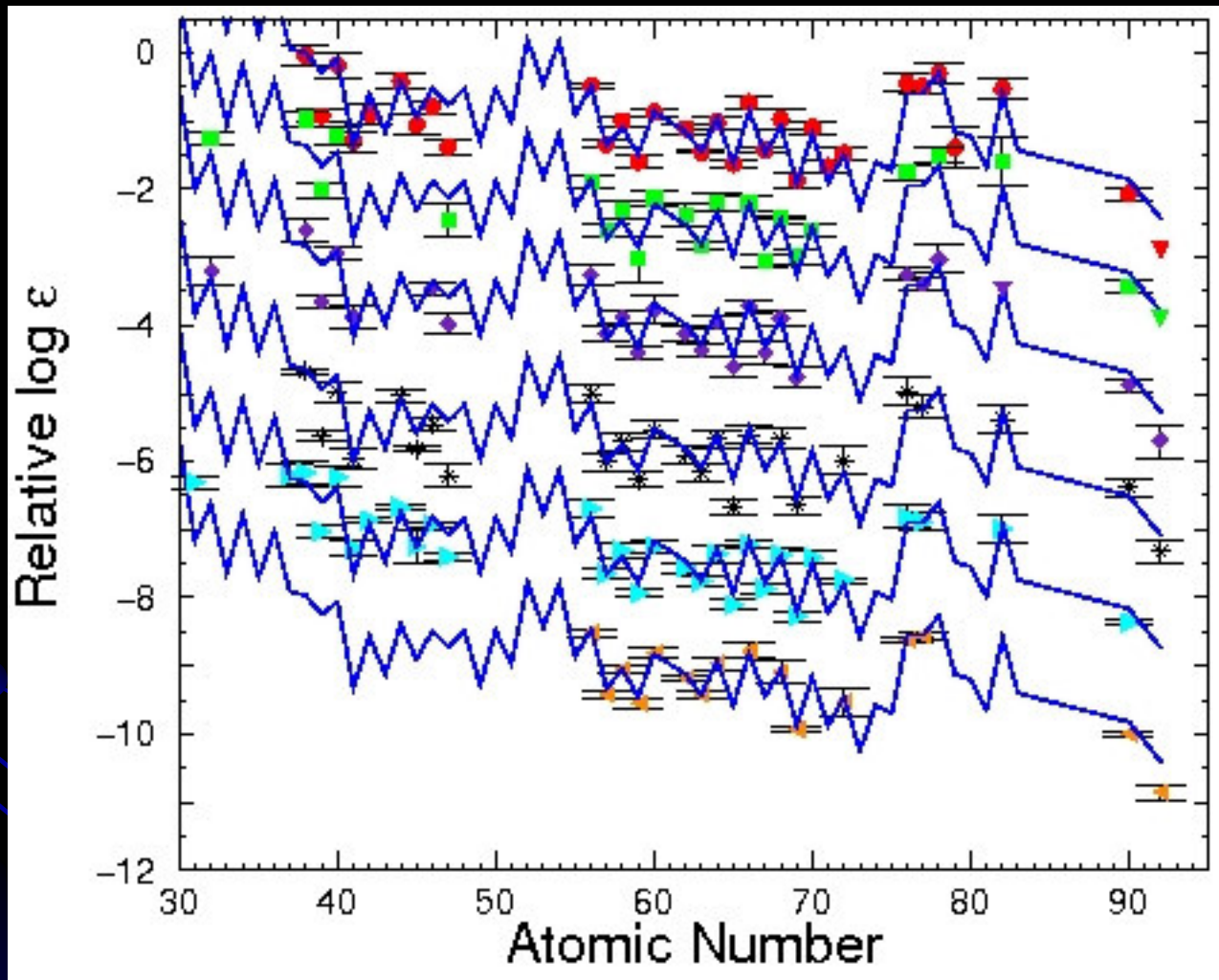


Platinum  
(64 HST Orbits)

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

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

# Observational Summary of Total Abundances



CS 22892-052

HD 115444

BD +17 3248

CS 31082-001

HD 221170

HE 1523-0901

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 ?

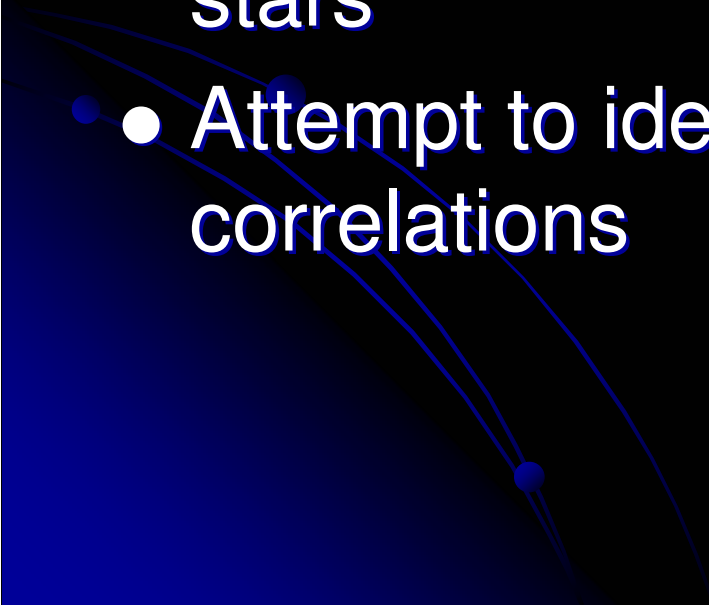
- Only recently any detections of elements,  $Z = 40-50$ 
  - Best previous evidence CS 22892-052
- Heavier element ( $Z \geq 56$ ) abundances seem to follow SS r-process curve, not so for the lighter elements
  - Now seeing (?) similar pattern for light n-capture elements in several other r-process rich stars

What about new observations of HD 221170?

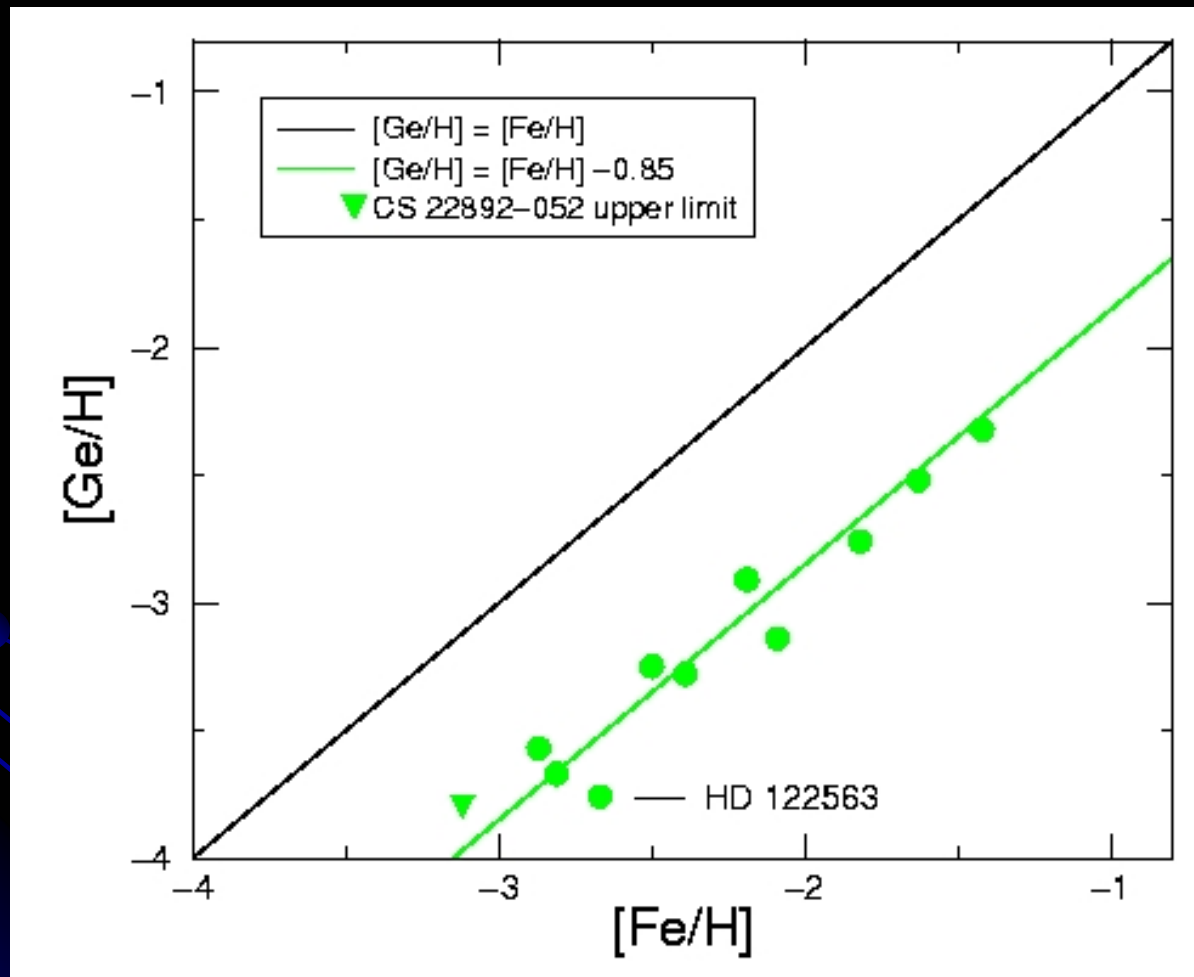
- Two separate sites based upon SS meteoritic data (Wasserburg, Busso & Gallino): strong and weak r-process (two types of SNe or SNe and NS mergers) or
- One site (different epochs or regions)

[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  $\propto$  Fe

Challenge to theorists.  
vp process?

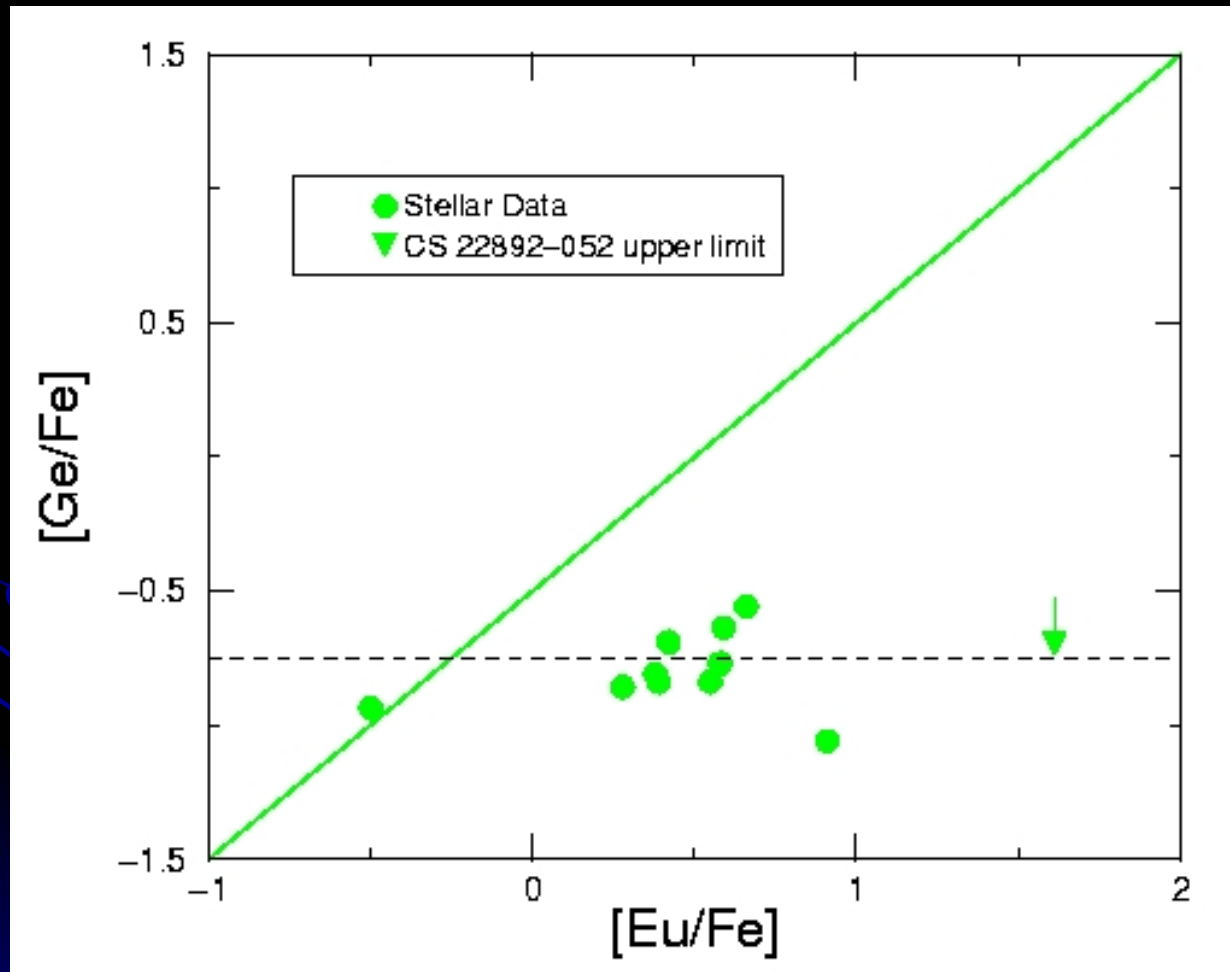
What happens at higher [Fe/H] with the s-process?

JC et al. (2005)

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

# 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?

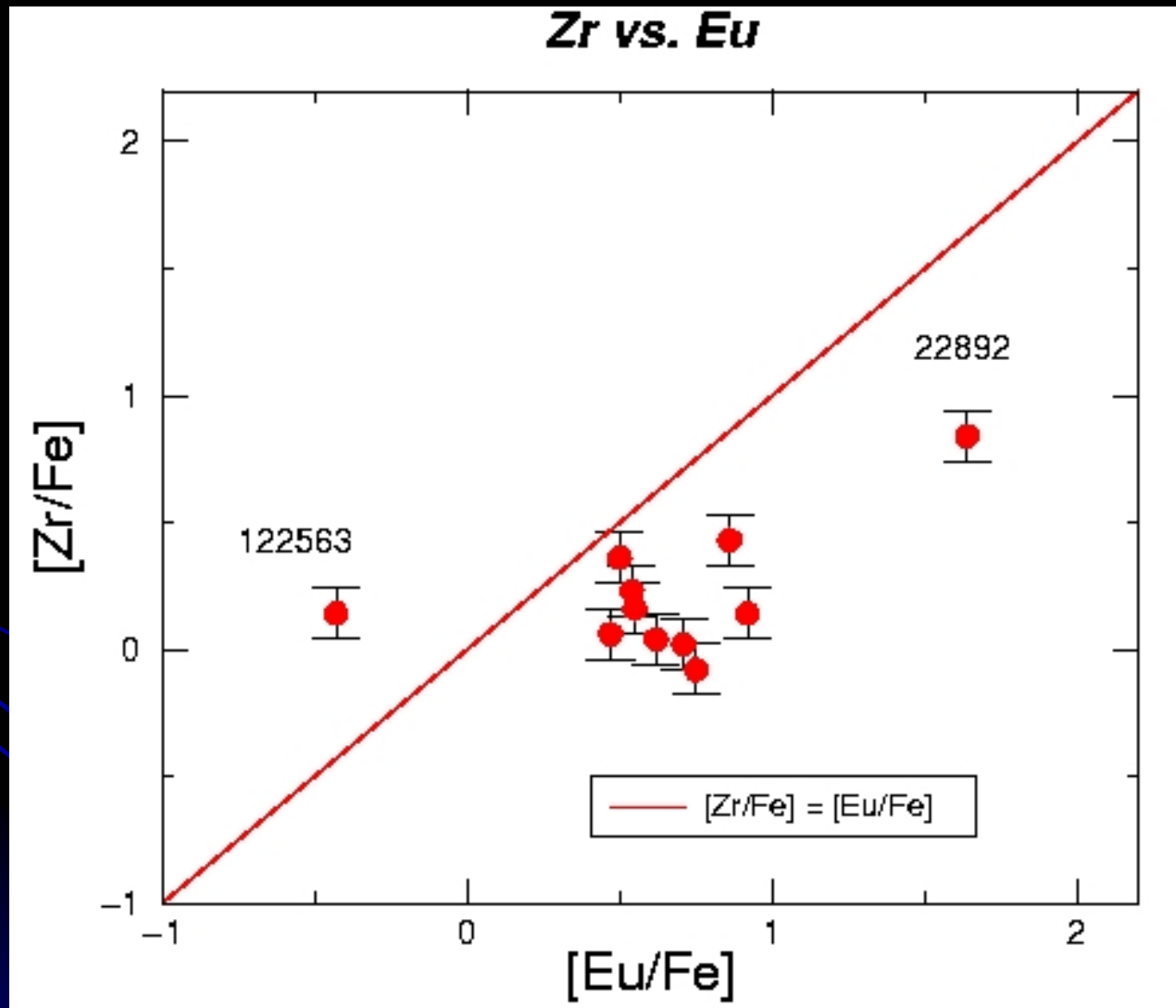


Ge  $\propto$  Eu

JC et al. (2005)

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

# Zr and Eu Abundances in Halo Stars



Zr  $\neq$  Eu

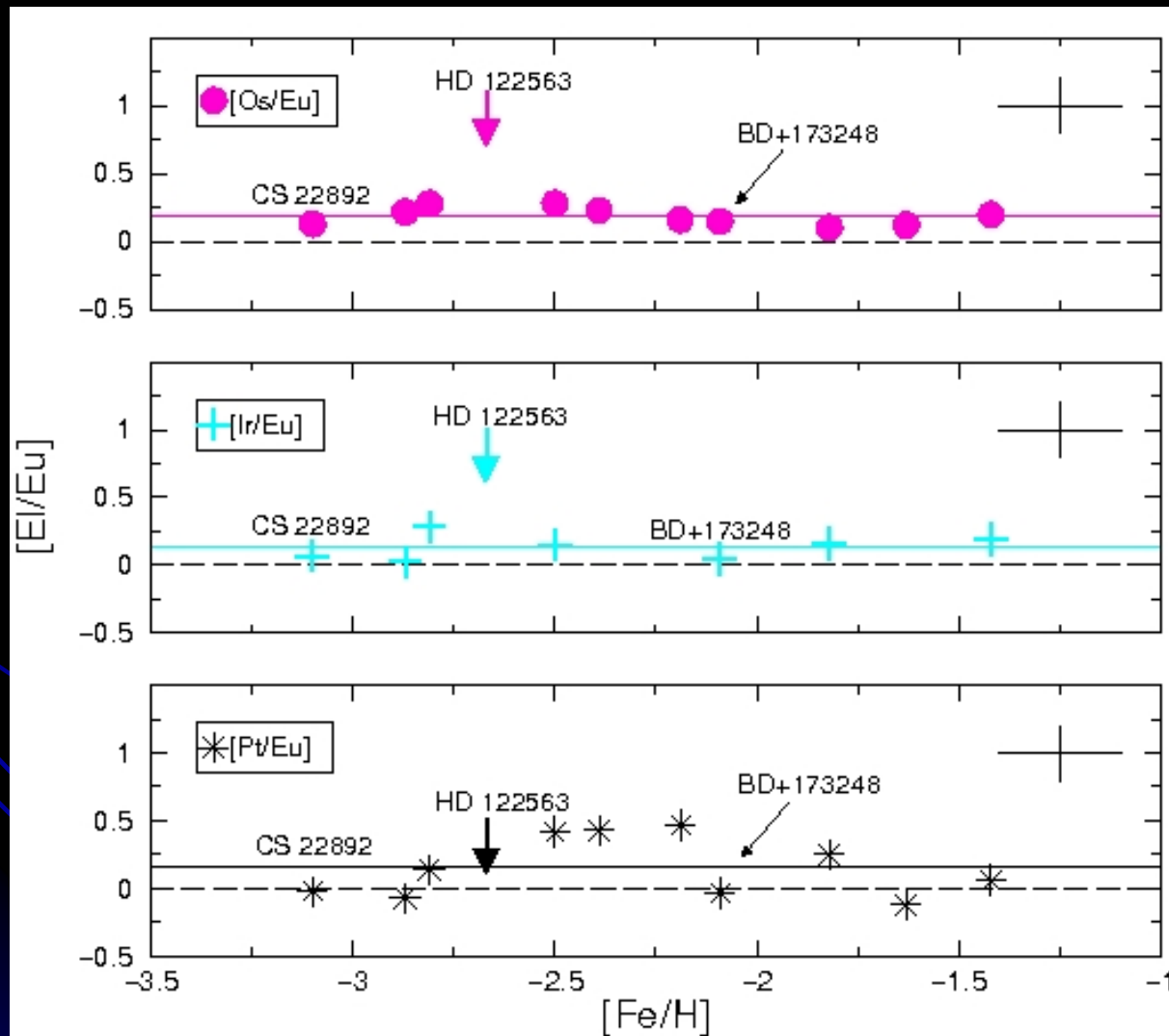
Both n-cap  
elements  
but not  
from same  
source?

LEPP?  
SN models?



# n-Capture Element Correlations: 3<sup>rd</sup> r-Process Peak

3<sup>rd</sup> r-process  
peak elements  
correlate with  
Eu.

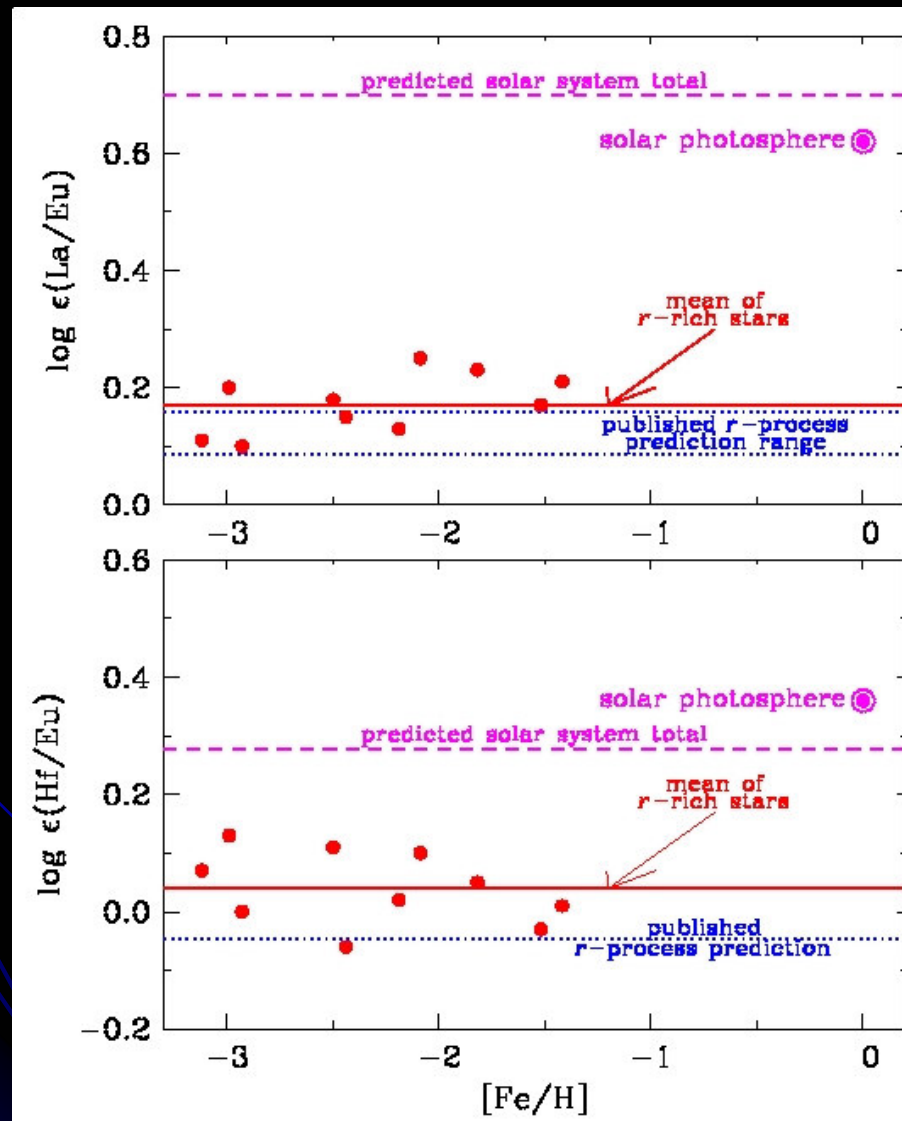


+  
= typical  
error

←← 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.

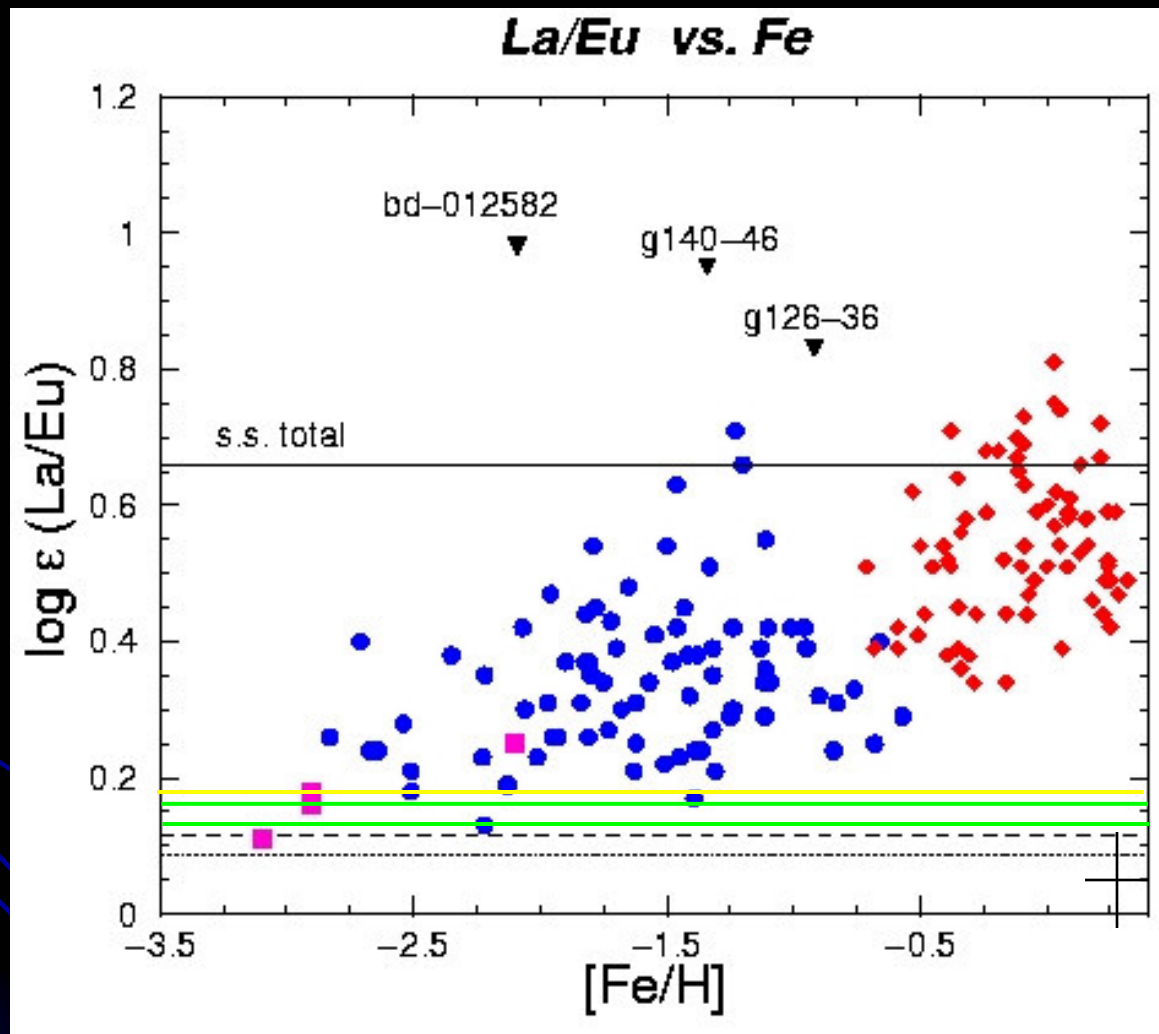


Observed ratios of La/Eu and Hf/Eu larger than previous estimates of SS r-only values

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

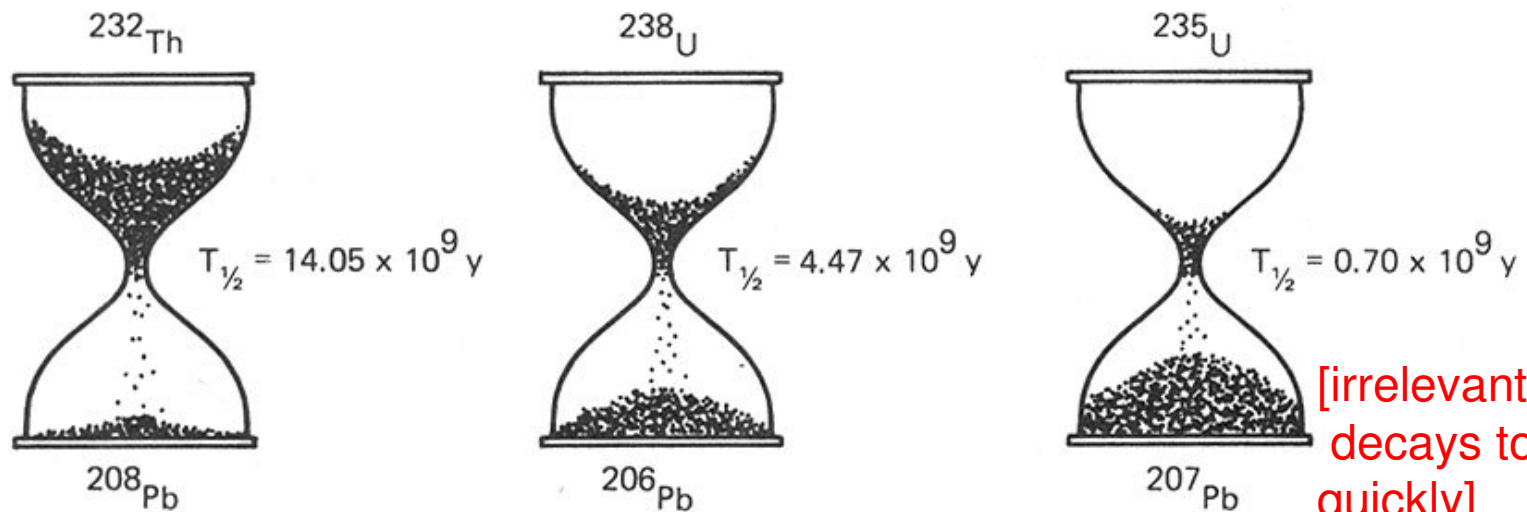
O'Brien et al.  
(2003)

Burris et al.  
(2000)

■ r-process enhanced, ● halo stars, ◆ disk stars

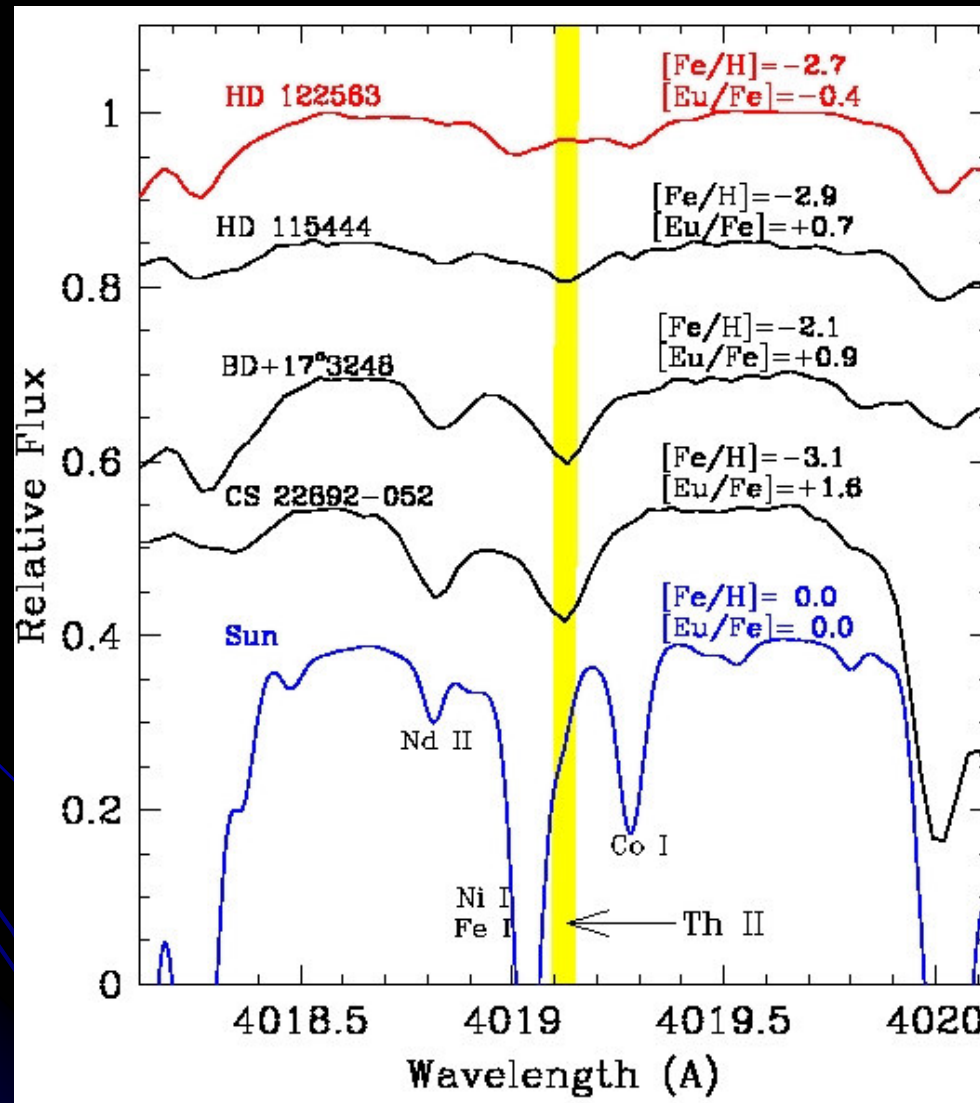
# Cosmochronometers

## THE RADIOACTIVE AEON GLASSES



Rolfs & Rodney (1988)

# Th Detections in Four Halo Stars and the Sun



Note the strength of the Th lines independent of metallicity

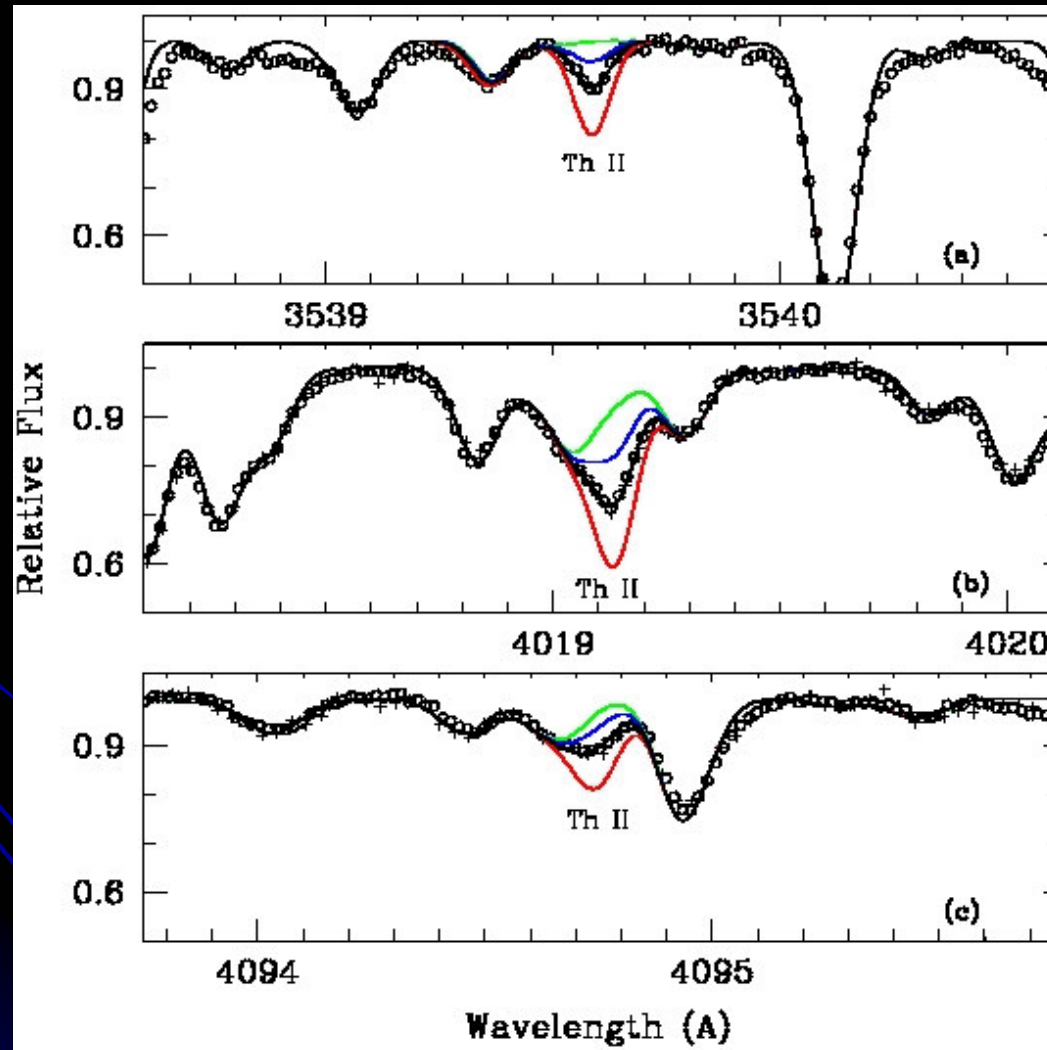
More Chronometers?

No

Yes



# Observed and Synthetic Spectra of Th Lines in HD 221170



Keck ○  
McDonald +

Ivans et al. (2006)

[Other studies](#)

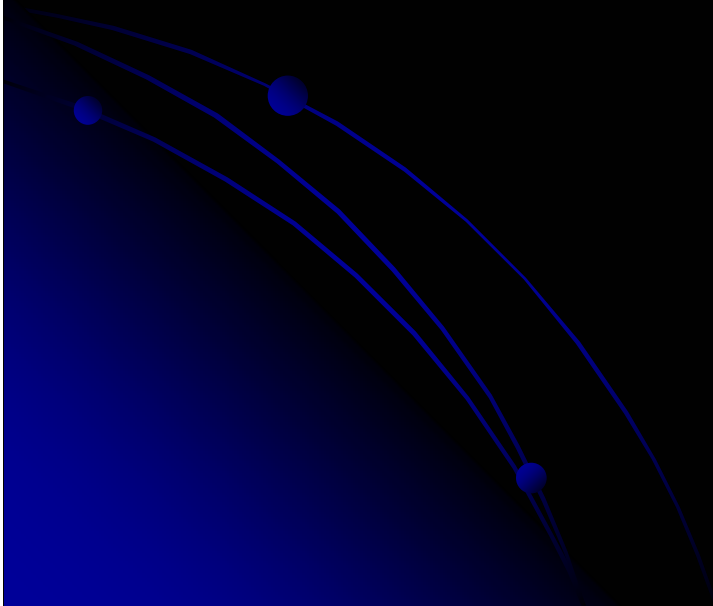
# Some Concluding Thoughts on: Nucleosynthesis Early in the Galaxy

- 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  $[\text{Fe}/\text{H}]$ : how?
- Detections of radioactive elements (Th & U) allow age estimates for oldest stars: putting limits on the age of the Galaxy & Universe

**HAPPY BIRTHDAY FRANZ!**



# 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

With generous support from:  
the National Science Foundation  
& the Space Telescope Science Institute.