Previous Visit in 2001

110 Years of the r-process!

TORQUING THE ELEMENTAL ABUNDANCES FROM SR-YB IN METAL-POOR STARS

J. J. Cowan (OU), C. Sneden (UT), I. U. Roederer (OCIW), J. E. Lawler (UW), R. Boyd (LLNL)

Heavy Elements Nucleosynthesis and the LEPP - October 10, 2011

Abundances: Some results, Some questions and Some Clues

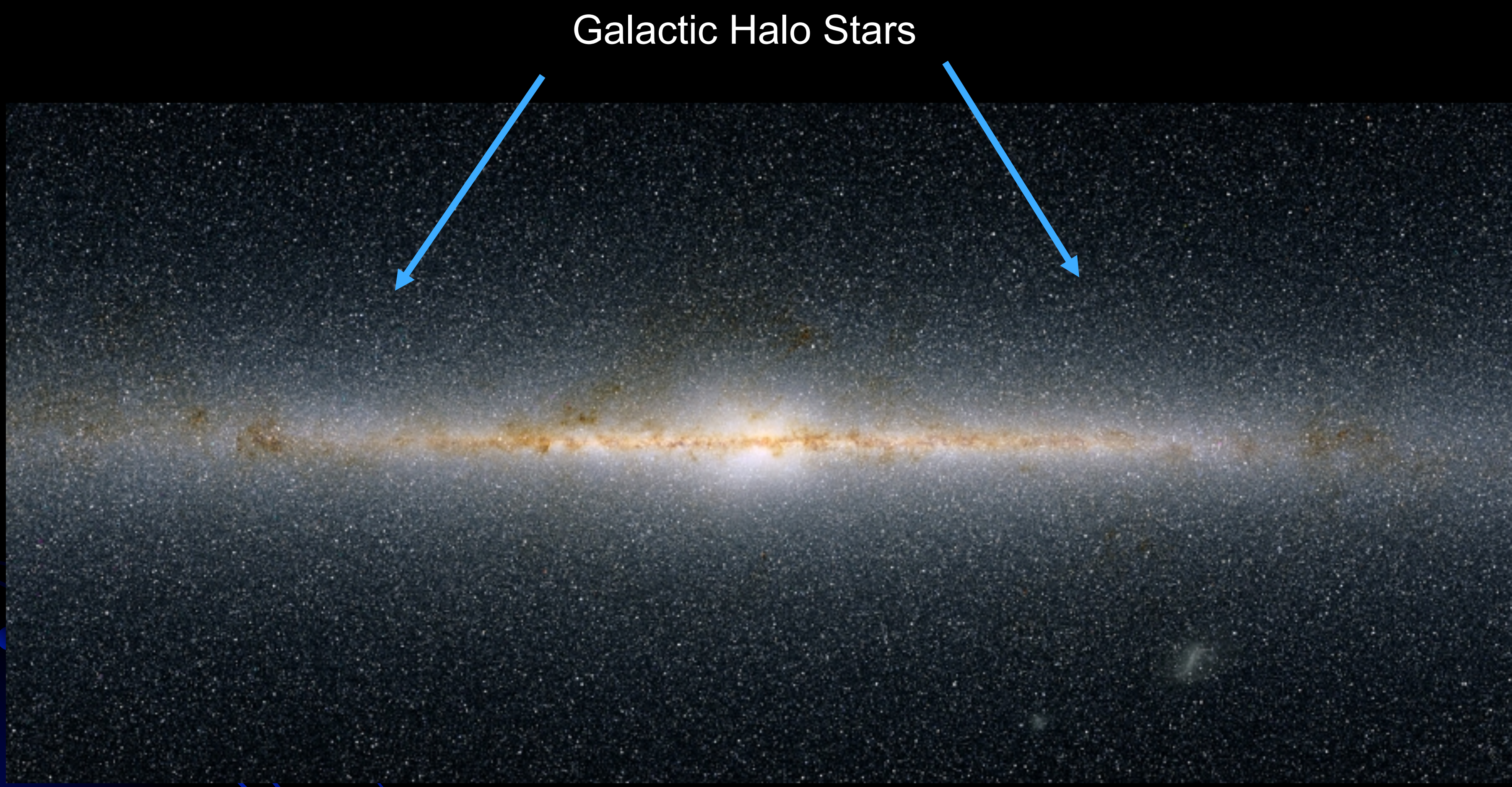
- New abundances (HST & Keck) of n-capture elements in low-metallicity Galactic halo stars :

1. New experimental atomic data providing much more precise abundances, particularly for rare earth elements
2. r-rich stars consistency at the upper end, but differences between r-poor stars
3. What do Ge abundances tell us?
4. What about Sr-Zr? What about Z=40-50 elements?
5. New results for Yb: ``the ugly duckling'' element

→ How does the LEPP fit into all of this?

Periodic Table

2MASS View of the Milky Way



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

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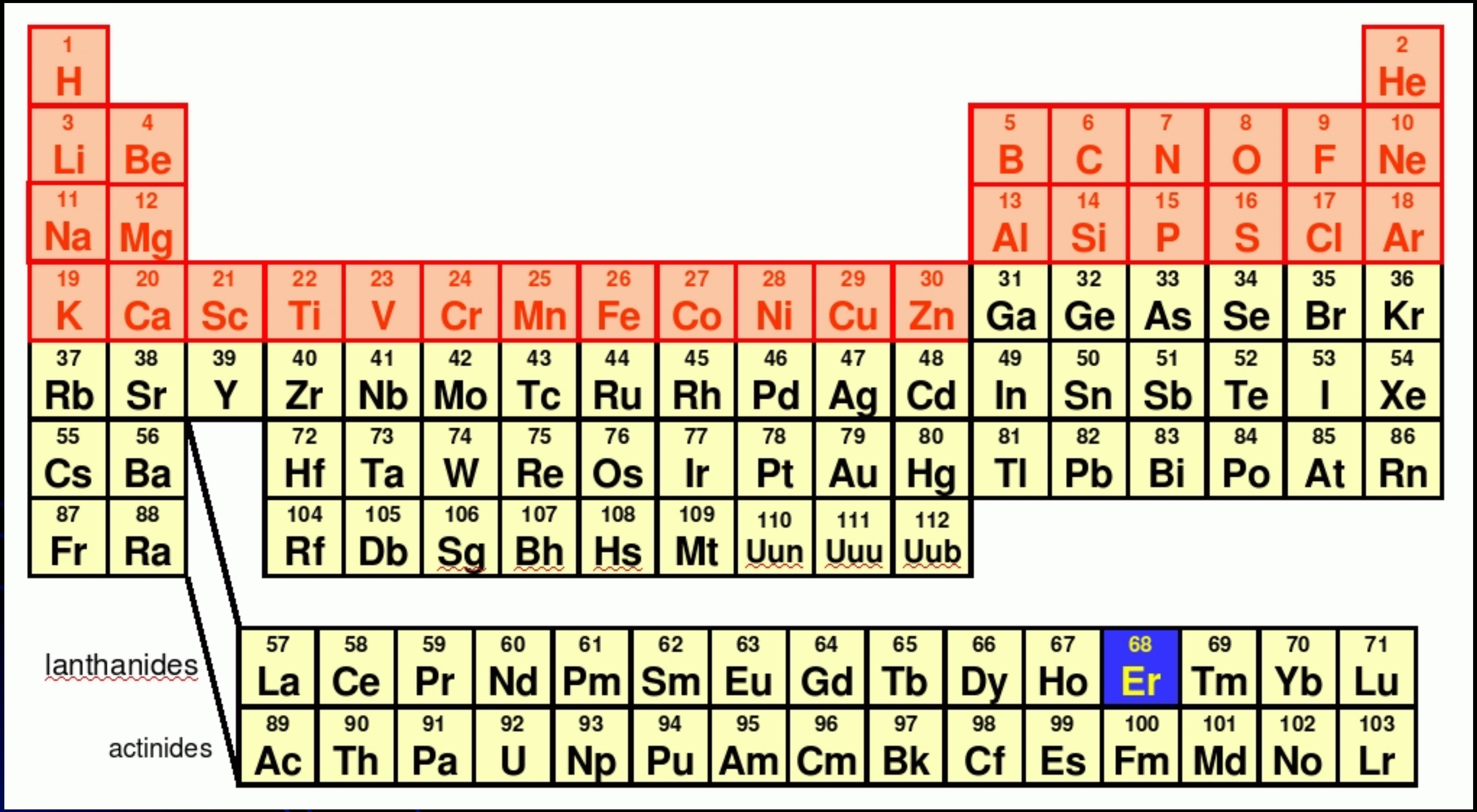
New Atomic Data to Improve Elemental Abundance Values



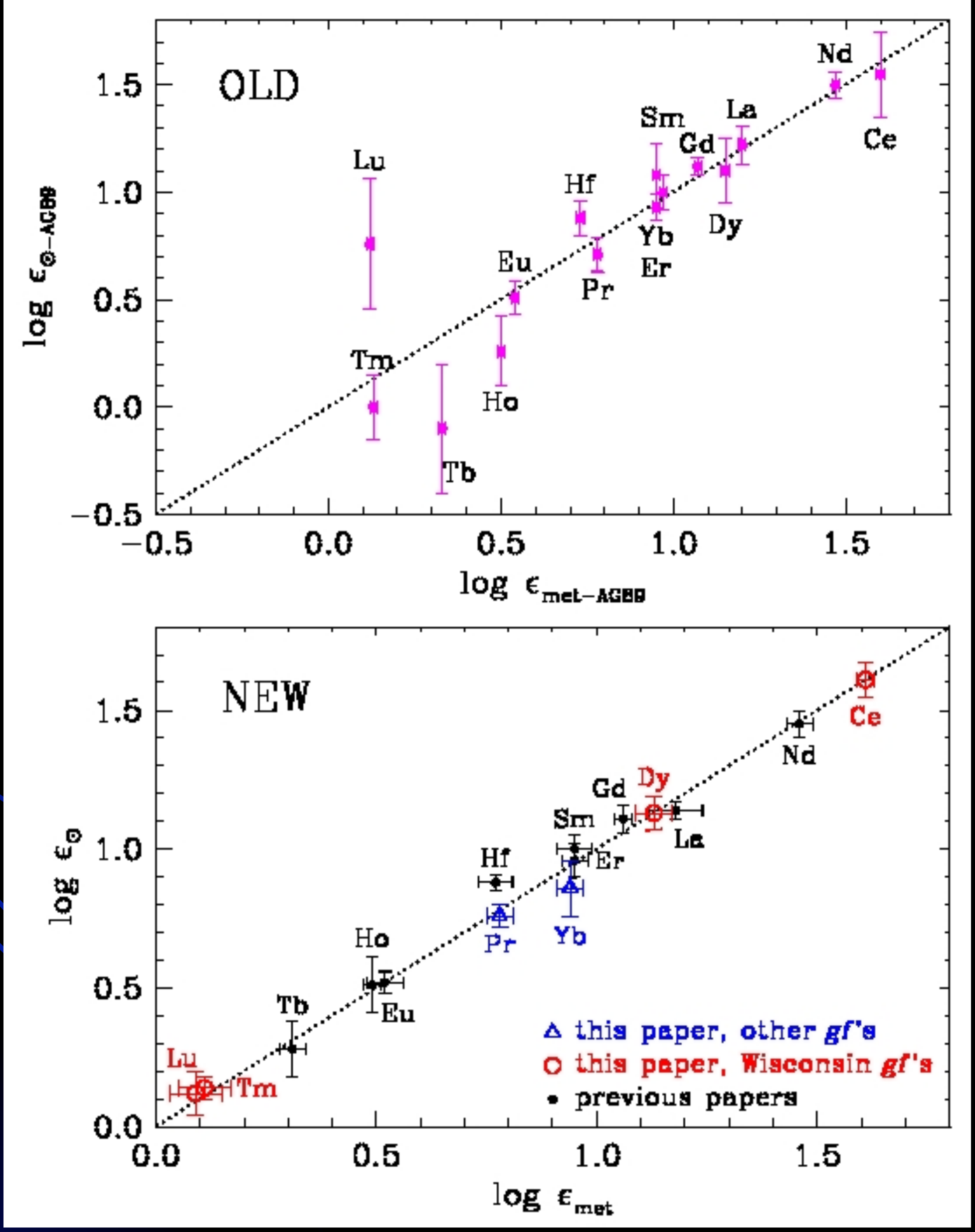
Concentrating on the Rare-Earth Elements

transition probabilities from Lawler's Wisconsin group

Focus On Rare Earth Elements

Comparisons of SS meteoritic & photospheric values of the REE

Working our way through the periodic Table!

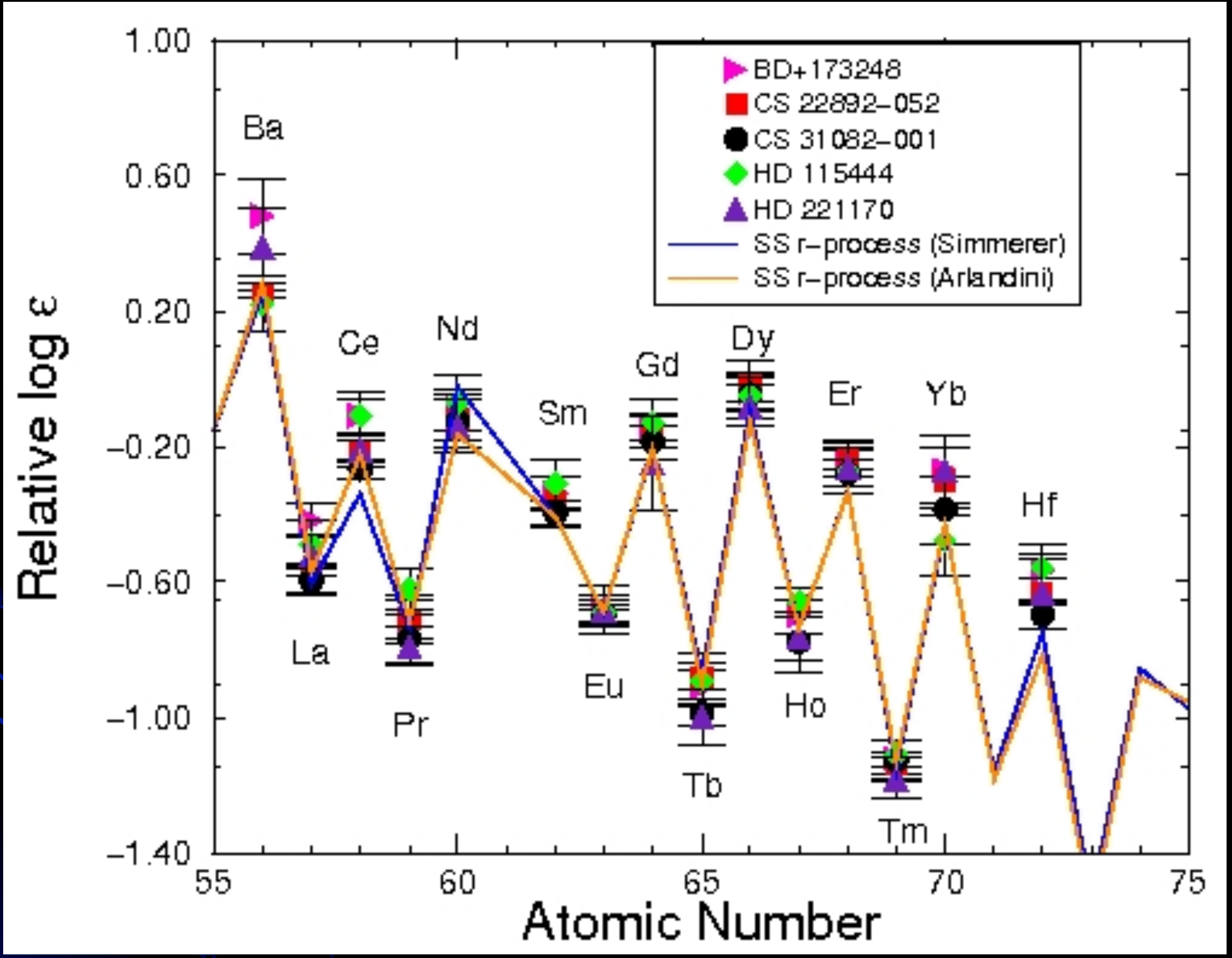


New experimental atomic physics data:

- 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)
- Er done (Lawler et al. 2008)
- Ce, Pr done (Lawler et al. 2009, Sneden et al. 2009)

Rare Earth Abundances in Five r-Rich Stars

Comparisons of new REE abundances with SS r-only predictions



Very little scatter

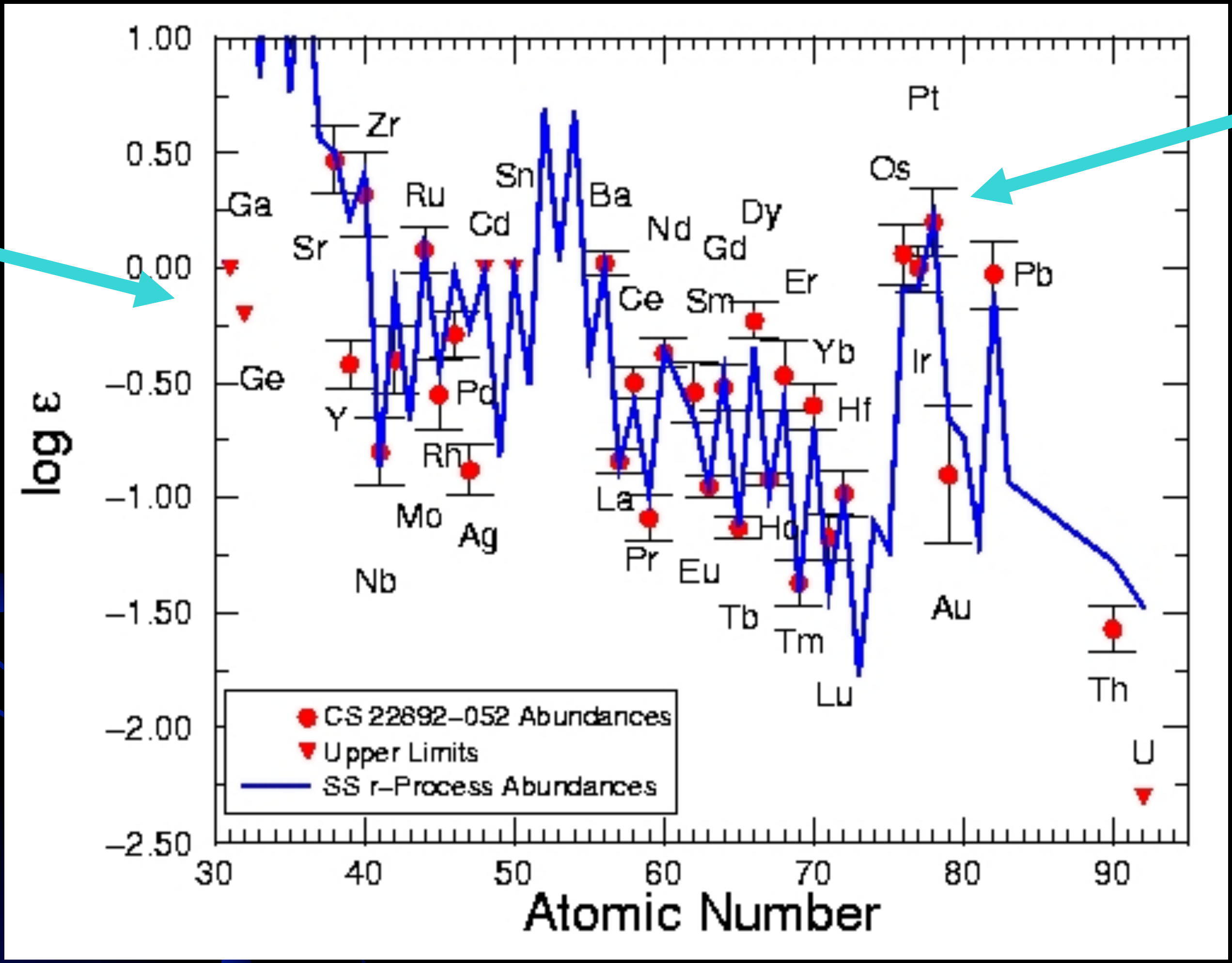
All normalized to Eu

Sneden et al. (2009): culmination of years of effort

CS 22892-052 Abundances

(with new atomic and stellar data)

31 N-Capture Elements Detected ➡ The Old King



Germanium

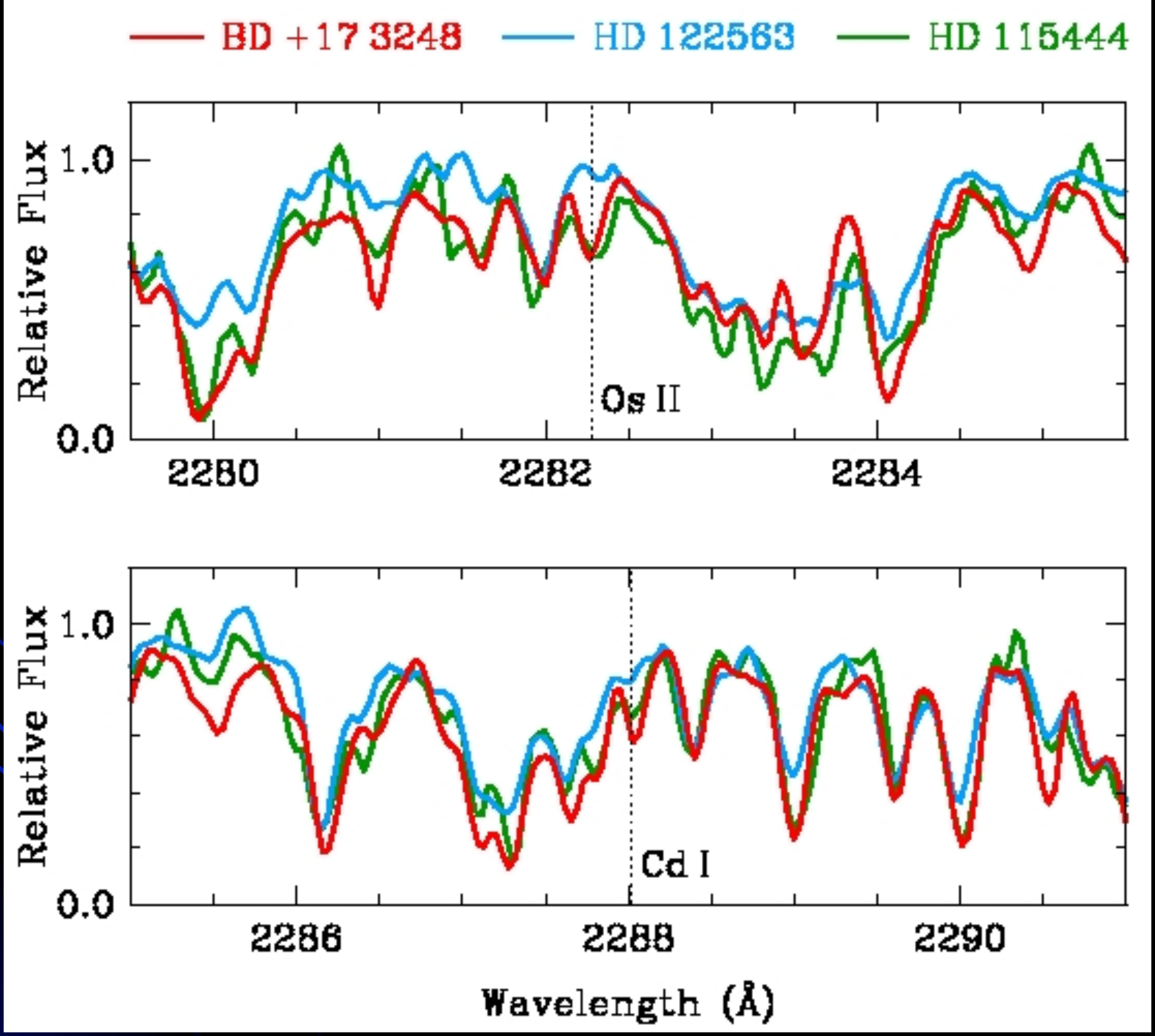
Platinum

(64 HST Orbits)

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

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

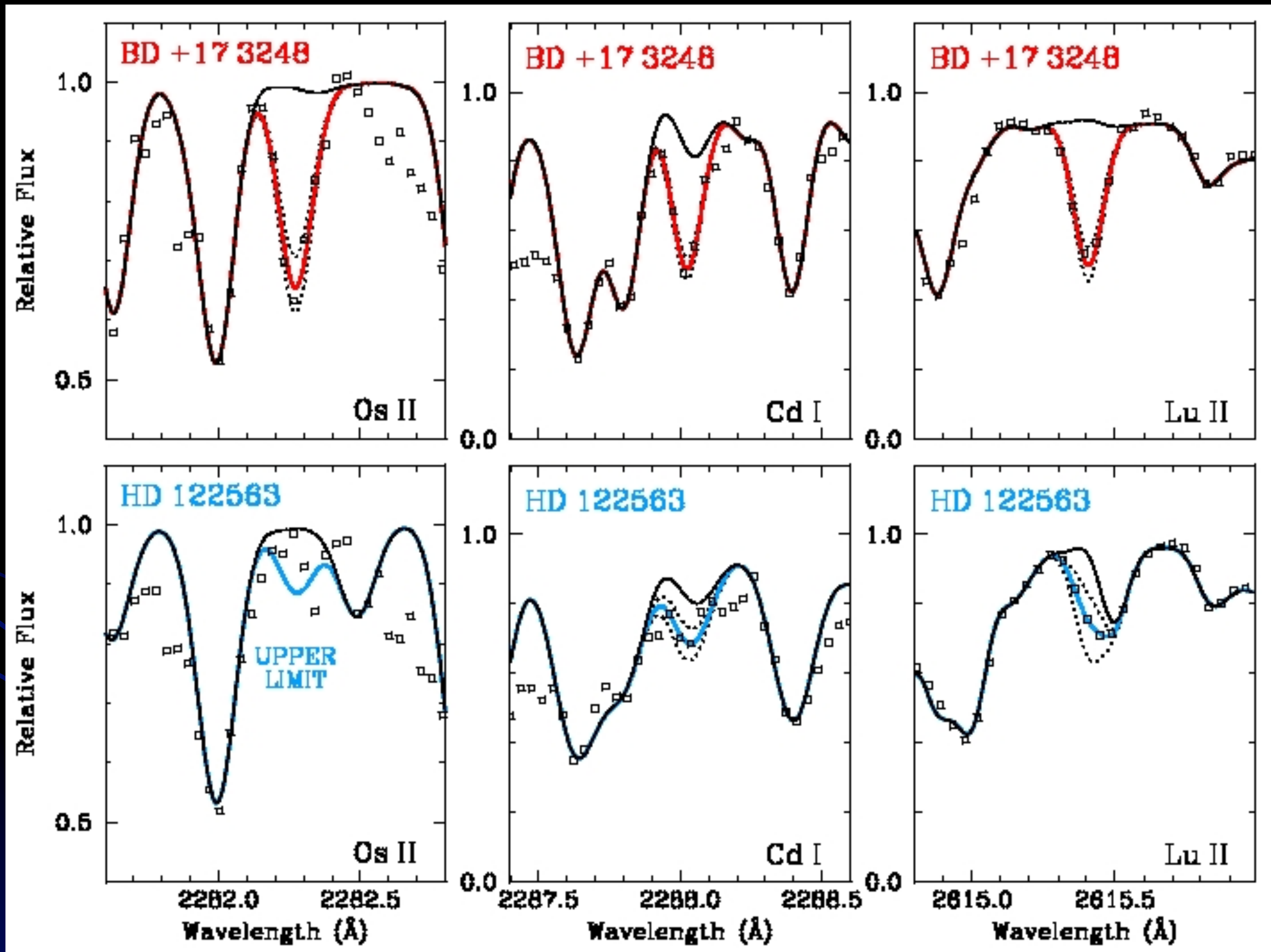
New Abundance Detections in BD +17 3248



UV: HST STIS

Roederer et al. (2010a)

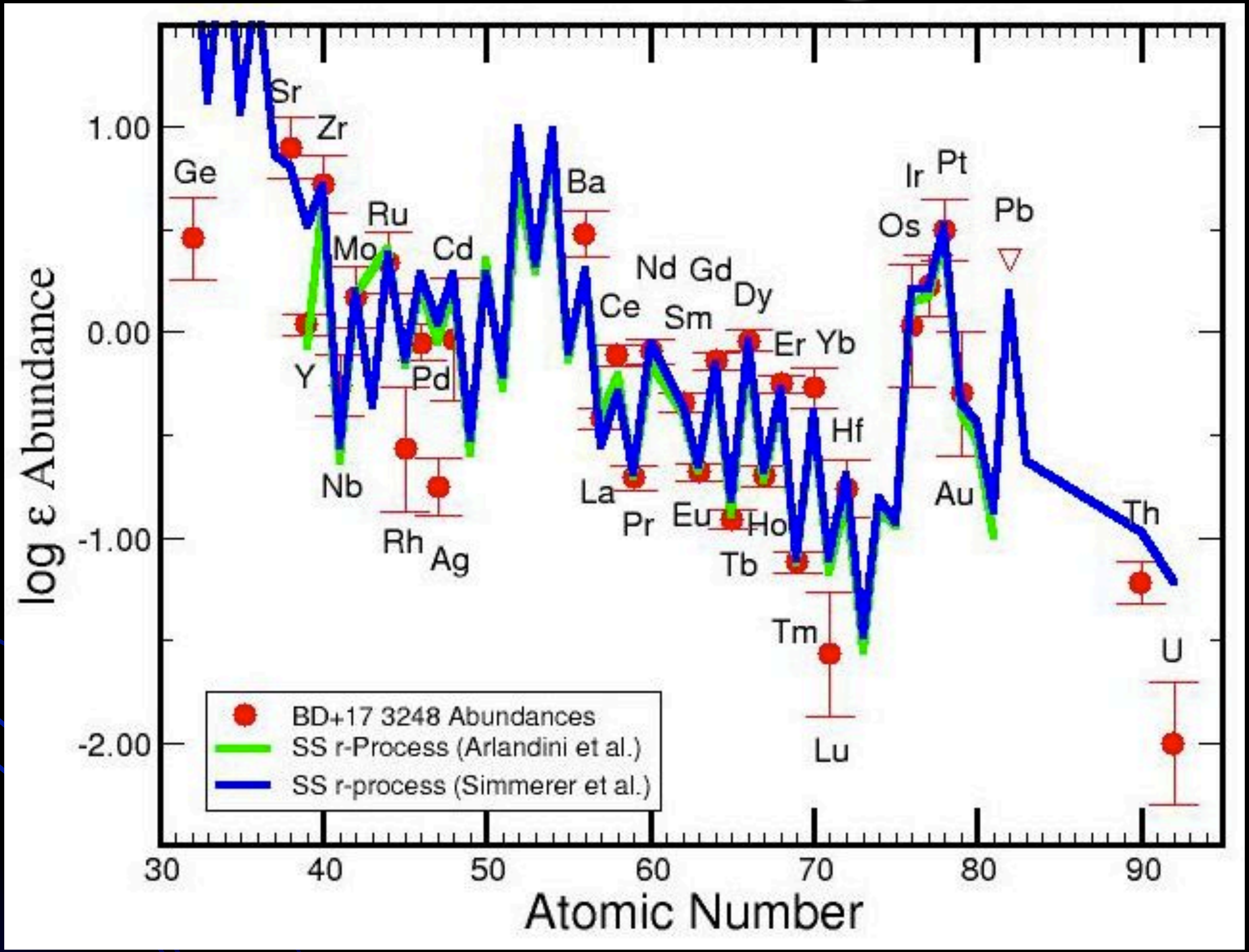
New Abundance Detections of Cd I, Lu II and Os II in BD +17 3248



Roederer et al. (2010a)

First detections of these n-cap species in metal-poor stars

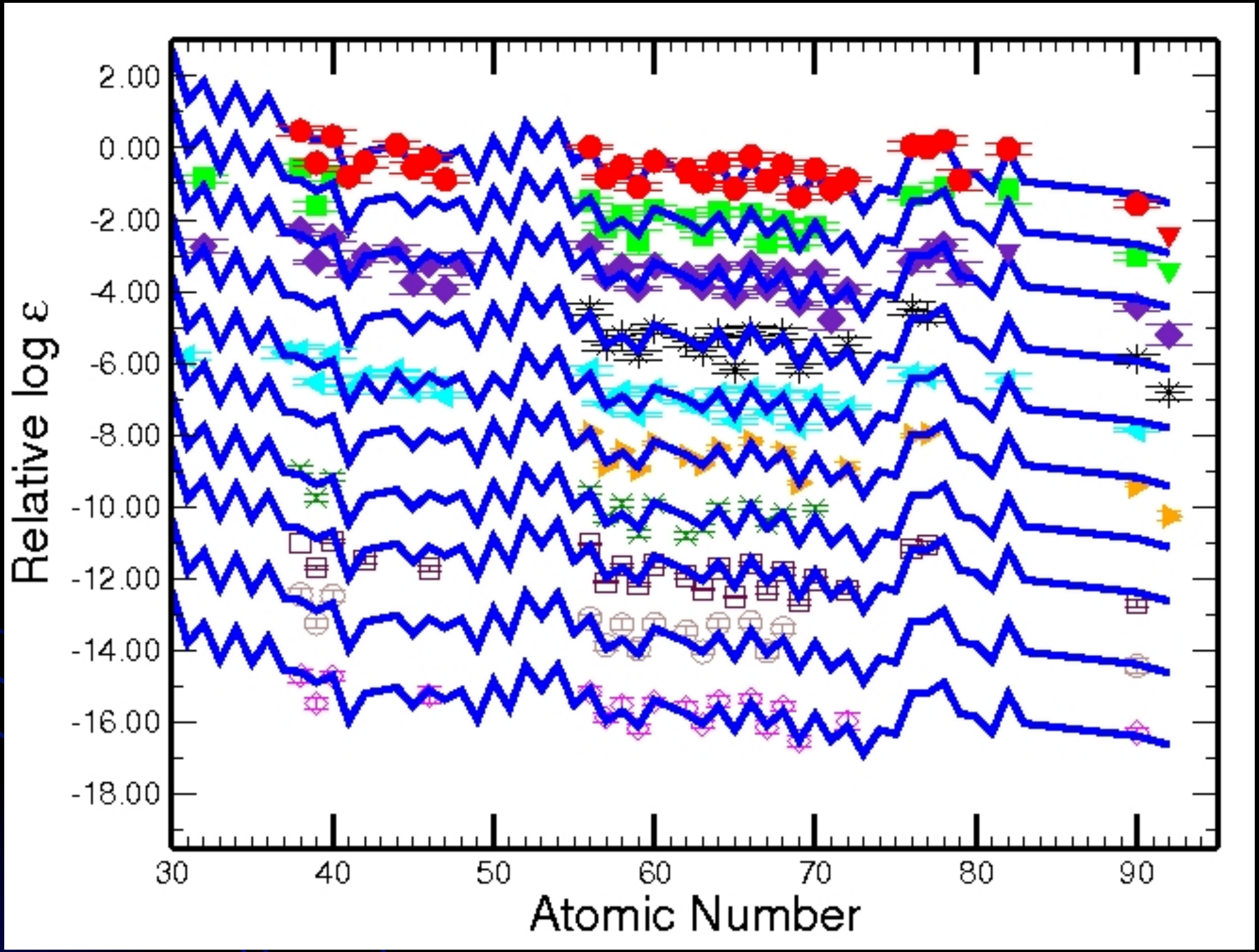
Abundances in BD+17 3248: Meet the New King!



➔ note Ge: for halo stars not from n-cap

32 n-capture elements detected in BD +17 3248 ➡ Most in any metal-poor halo star to date!

Consistency for r-Rich Stars

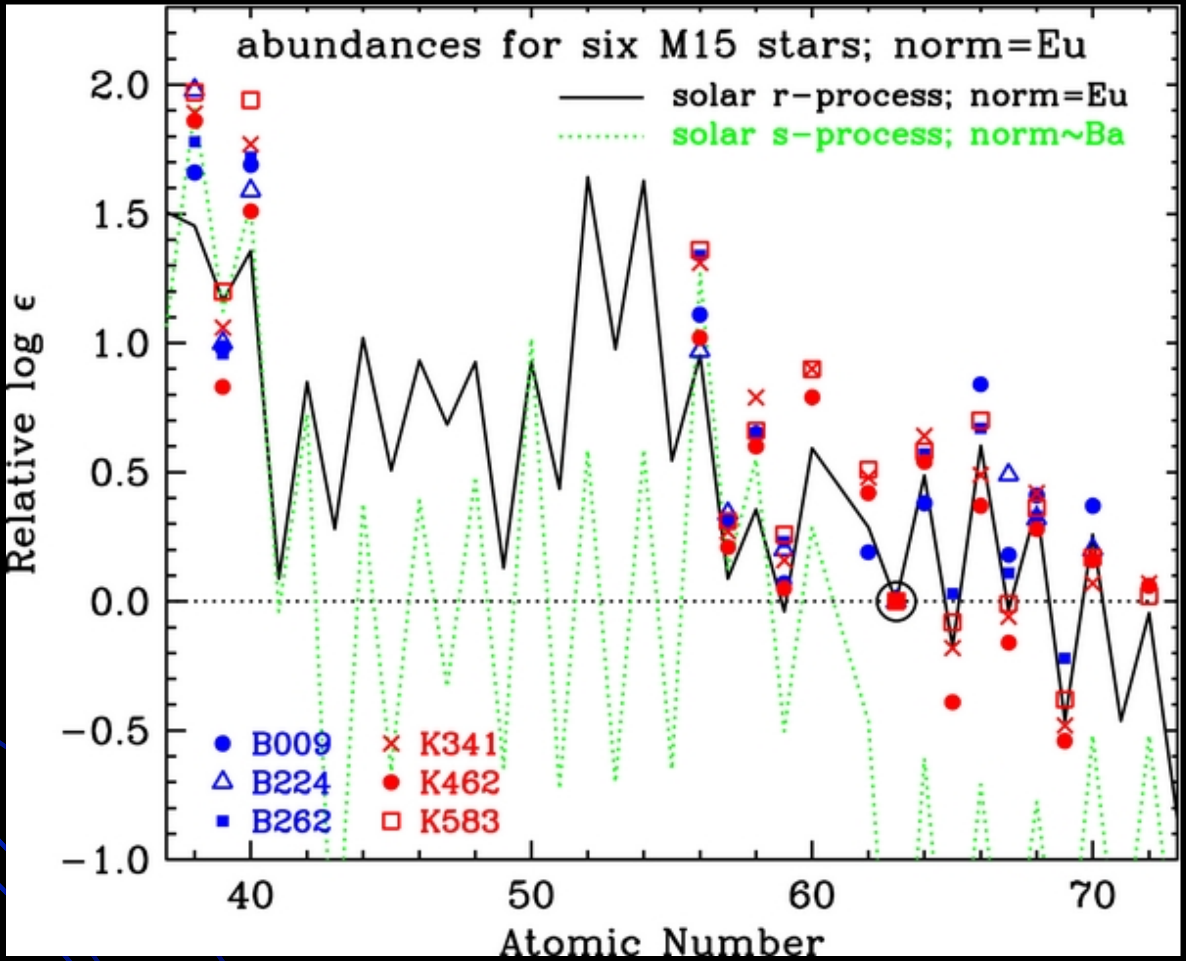


CS 22892-052
HD 115444
BD +17 3248
CS 31082-001
HD 221170
HE 1523-0901
CS 22953-03
HE 2327-5642
CS 2941-069
HE 1219-0312

10 r-process rich stars

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

Abundances in a Globular Cluster

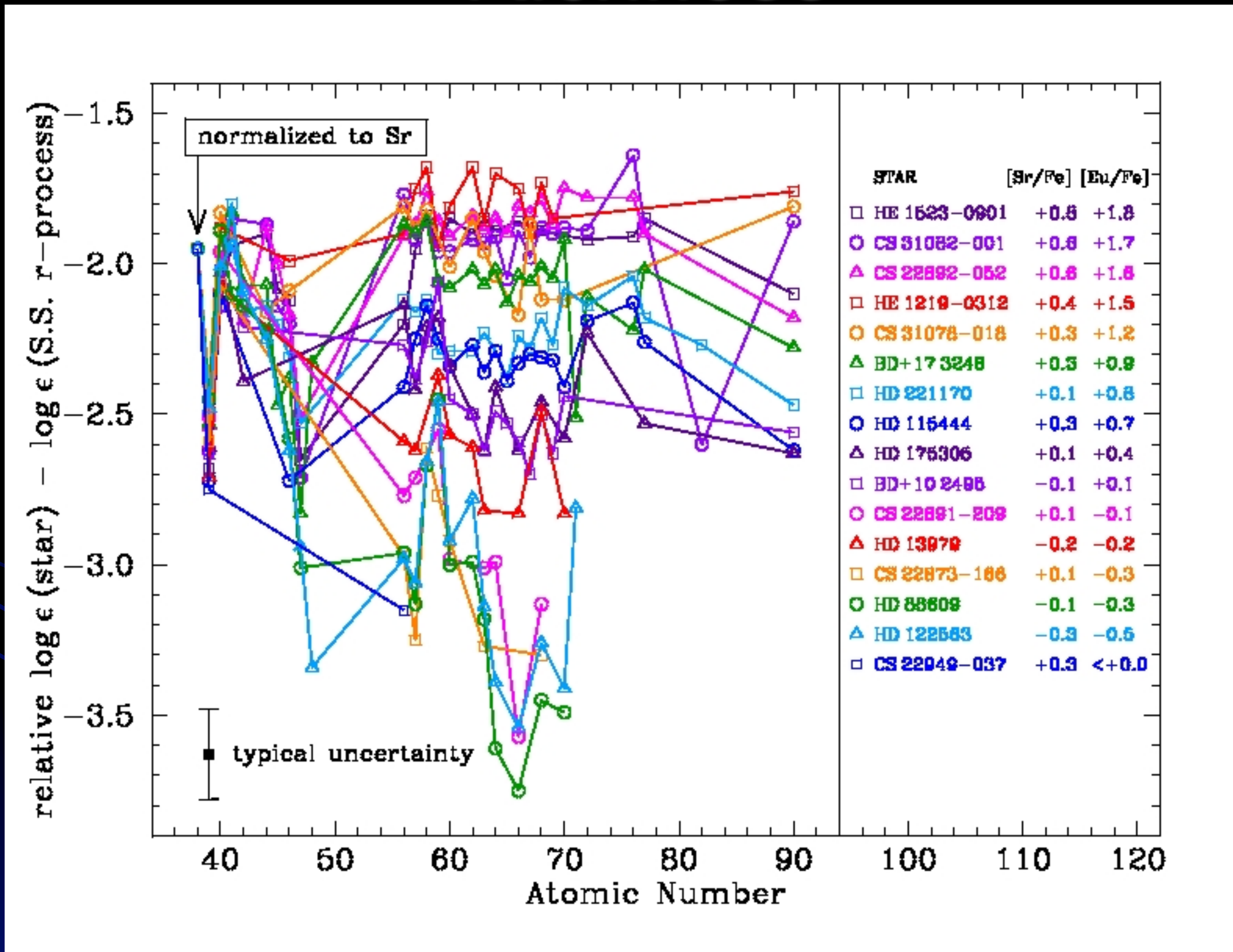


Sobeck et al. (2011)

RGB and RHB stars

Upper end SS r-process. Sr-Zr not fit.

Looking at a Range of r-Process Richness

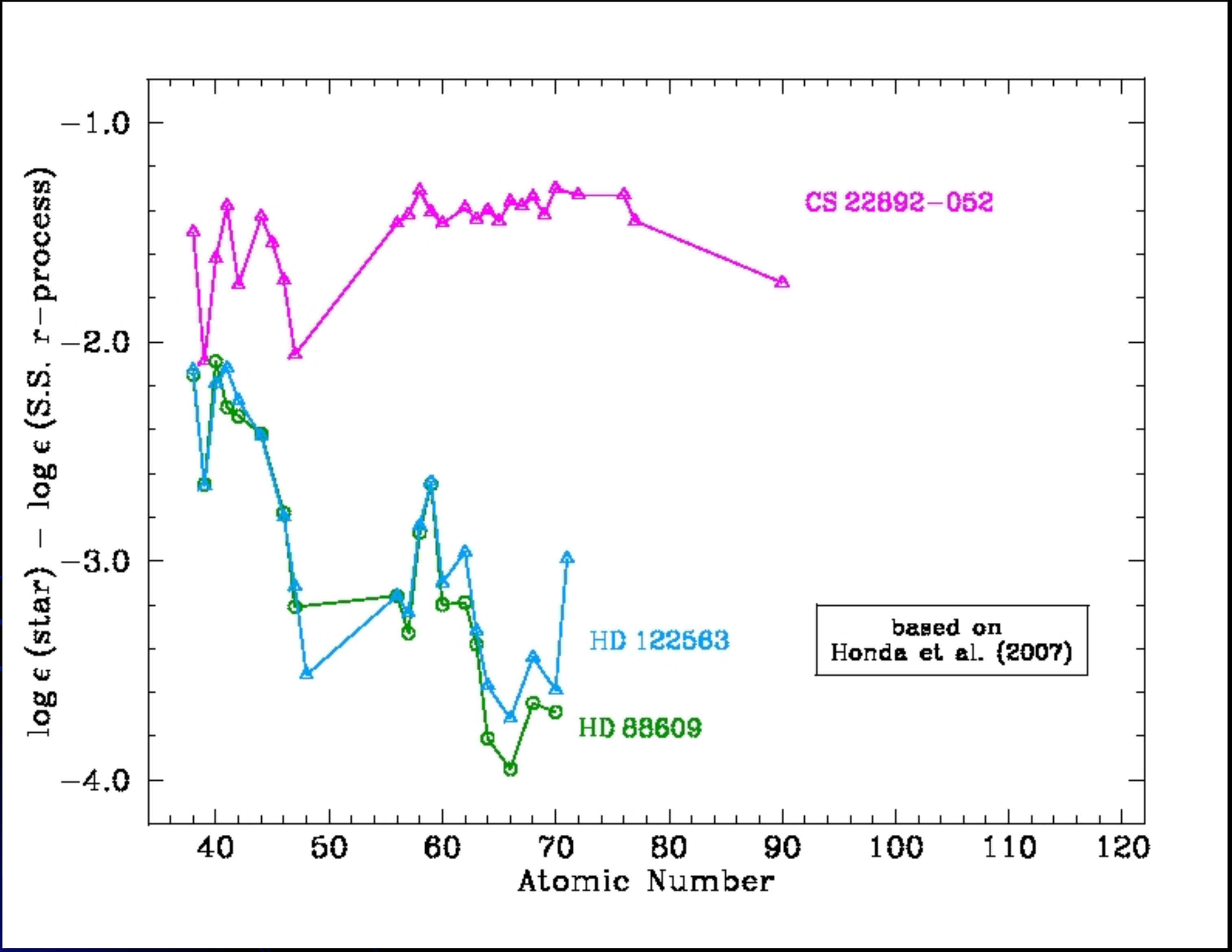


Eu/Fe

(r-process richness)

The ubiqiuity of the r-process (Roederer et al. 2010b)

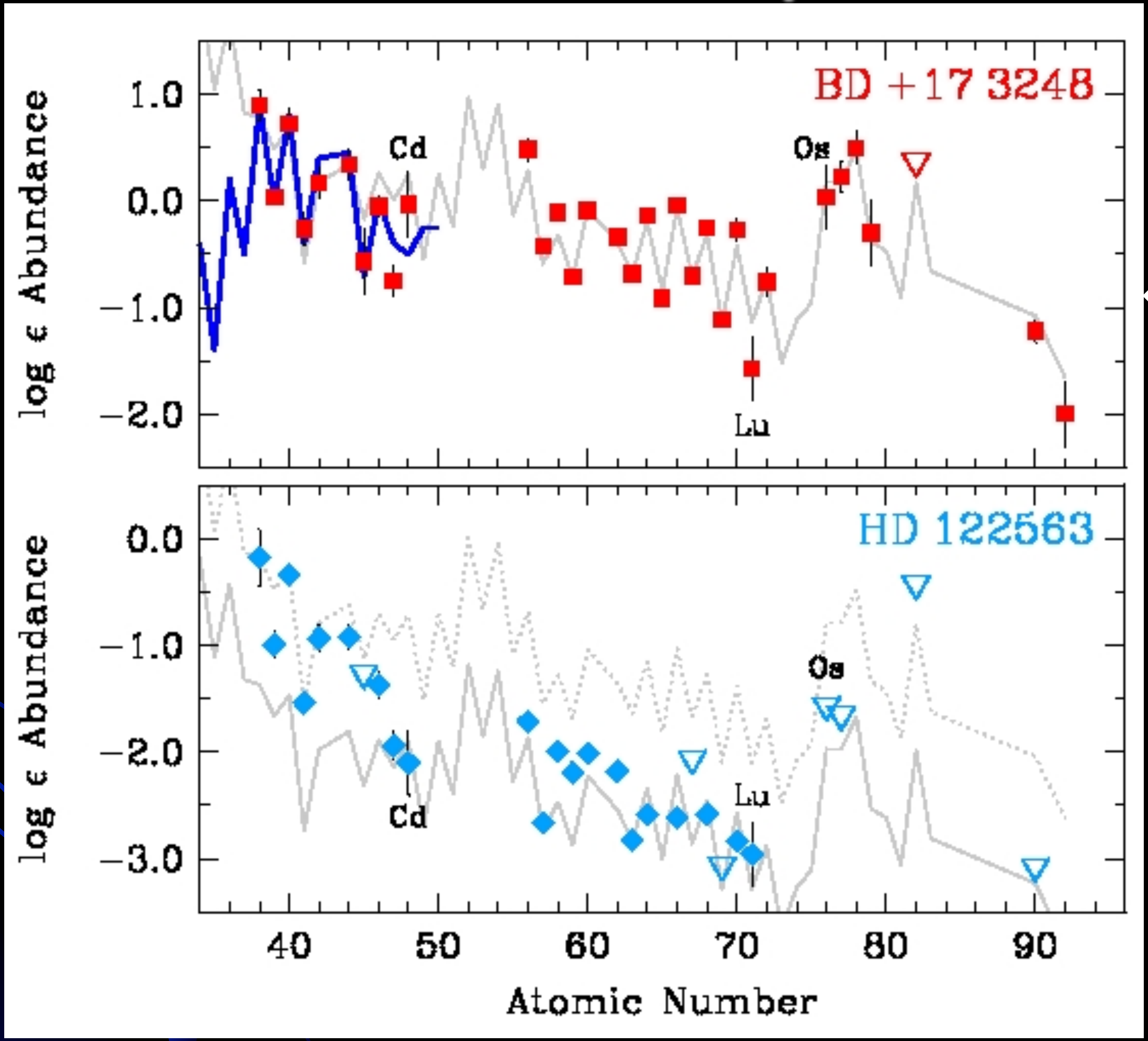
r-Process Rich vs. r-Process Poor



Abundance Comparisons

HEW

SS r-process (Sr,Eu)



r-process rich

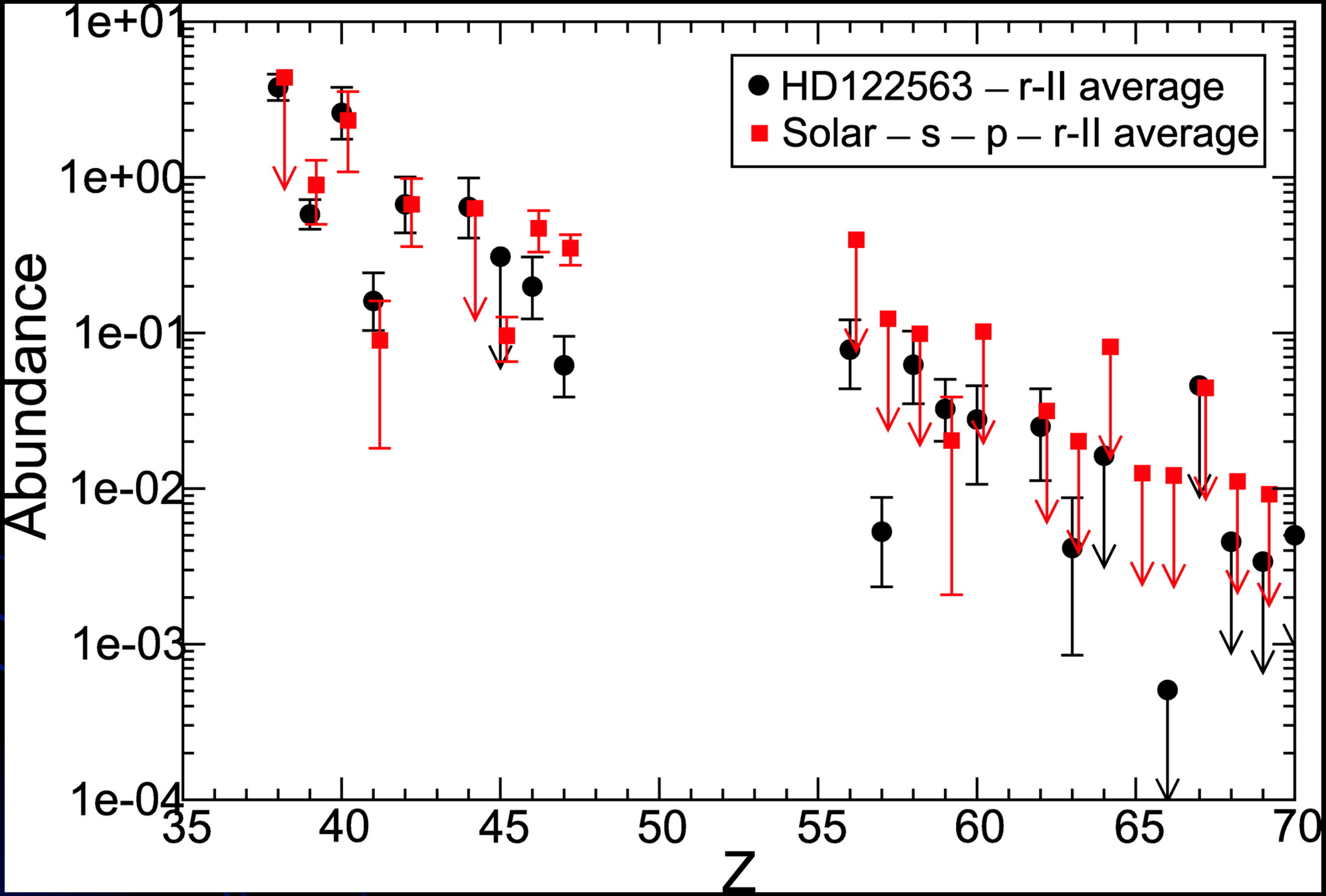
SS r-process

r-process poor

Note general fall off:
weak r-process or LEPP (Montes et al. 2007)

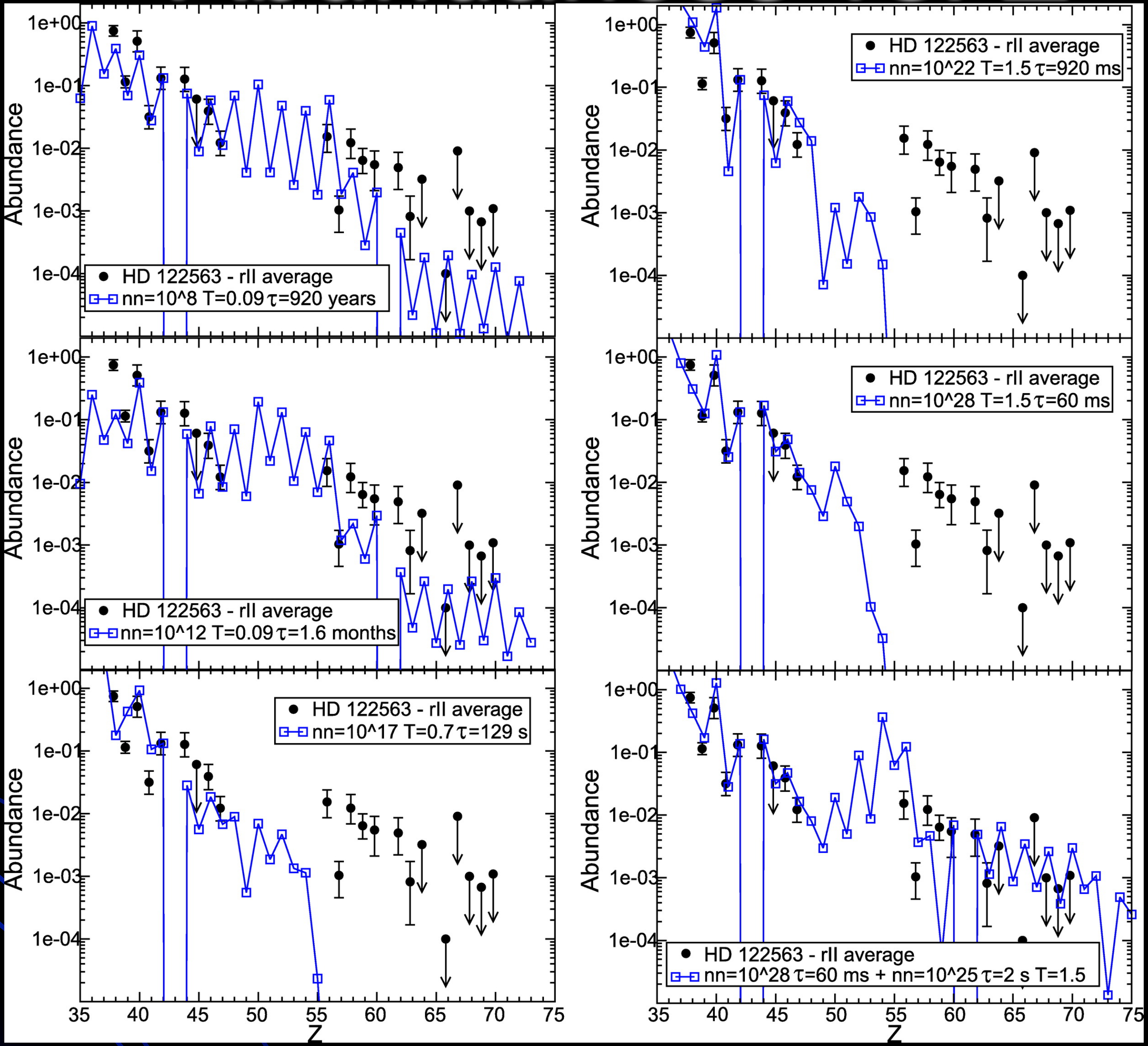
Roederer et al. (2010a)

Abundance Pattern Created by the LEPP from Montes et al.



Solar LEPP and stellar LEPP

Abundances vs. Z



Montes et al. (2007)

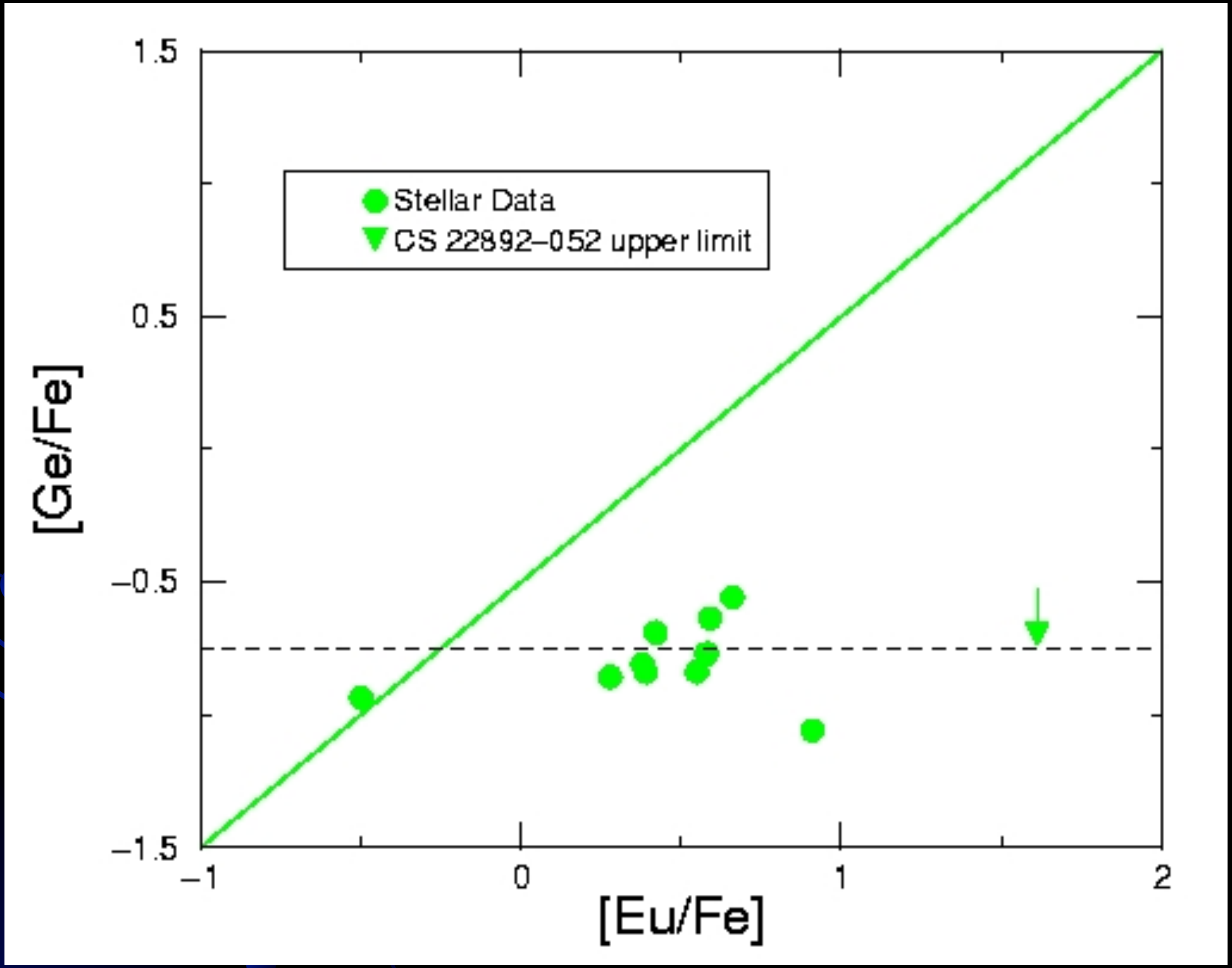
Normalized to Mo and compare with the stellar LEPP pattern

Focus on Observations of Ranges of Lighter N-Capture Elements

- Elements just past the iron peak: Ge
- Sr, Y and Zr
- Z=40-50 including Ag and Cd
- New abundance determinations for selected elements from Sr to Yb (preliminary work)

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?

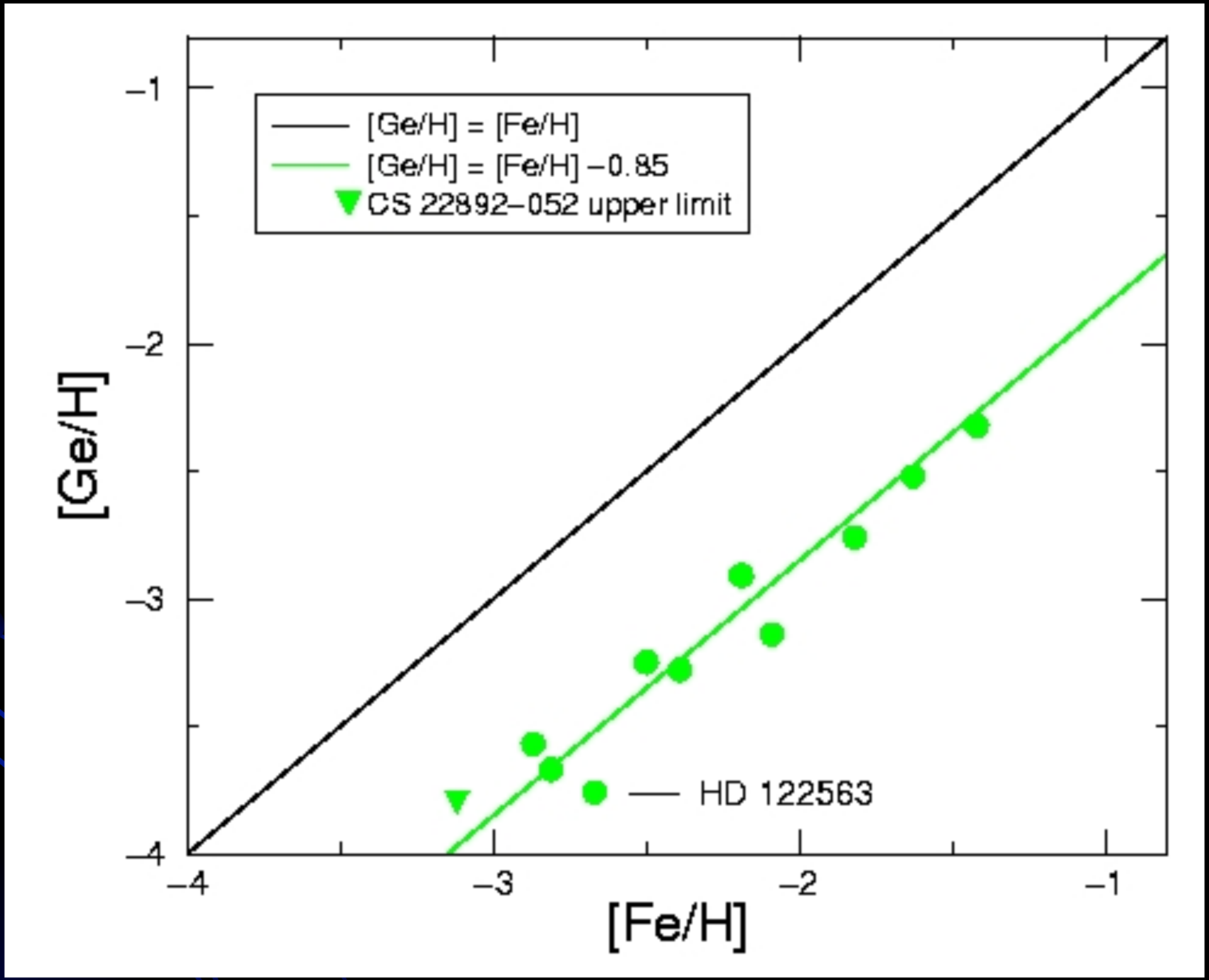


Ge $\not\propto$ Eu

JC et al. (2005)

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

Ge Abundances in Halo Stars



Ge ∝ Fe

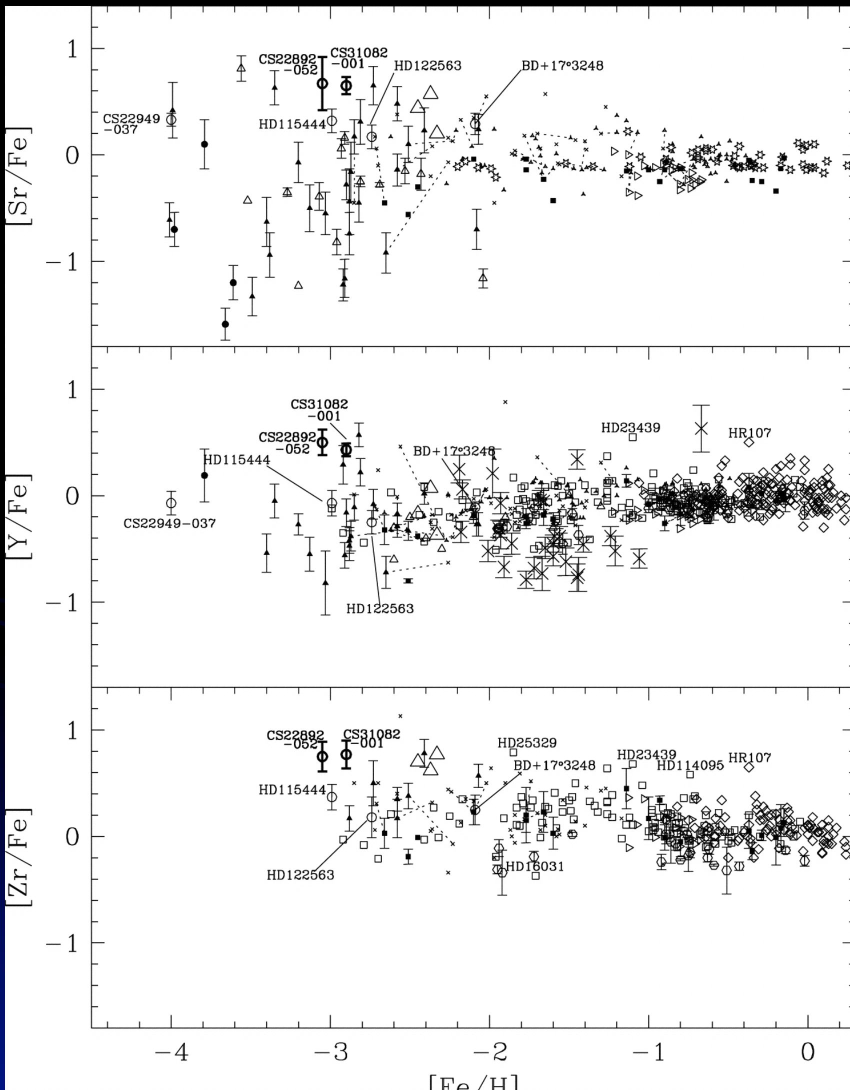
Challenge to theorists.
vp-process (Frolich et al.)

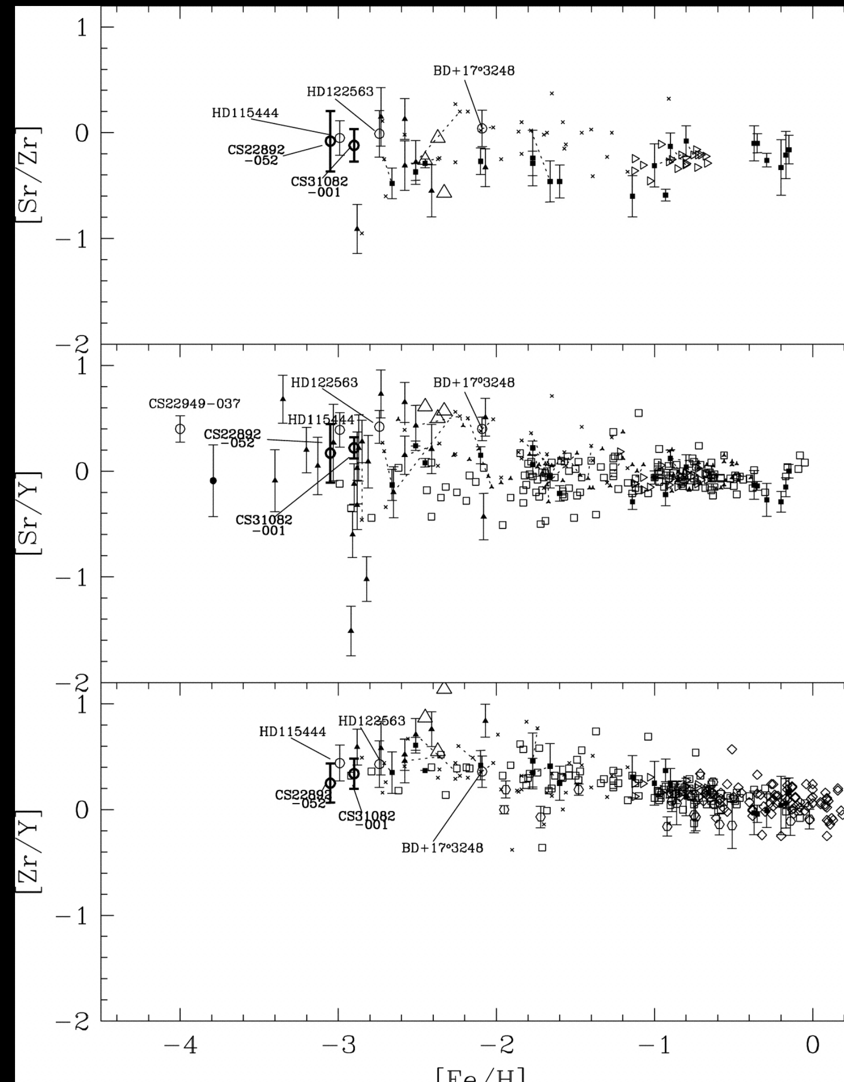
What happens at higher [Fe/H] with the s-process?

JC et al. (2005)

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

Metallicity Effects on Sr-Zr



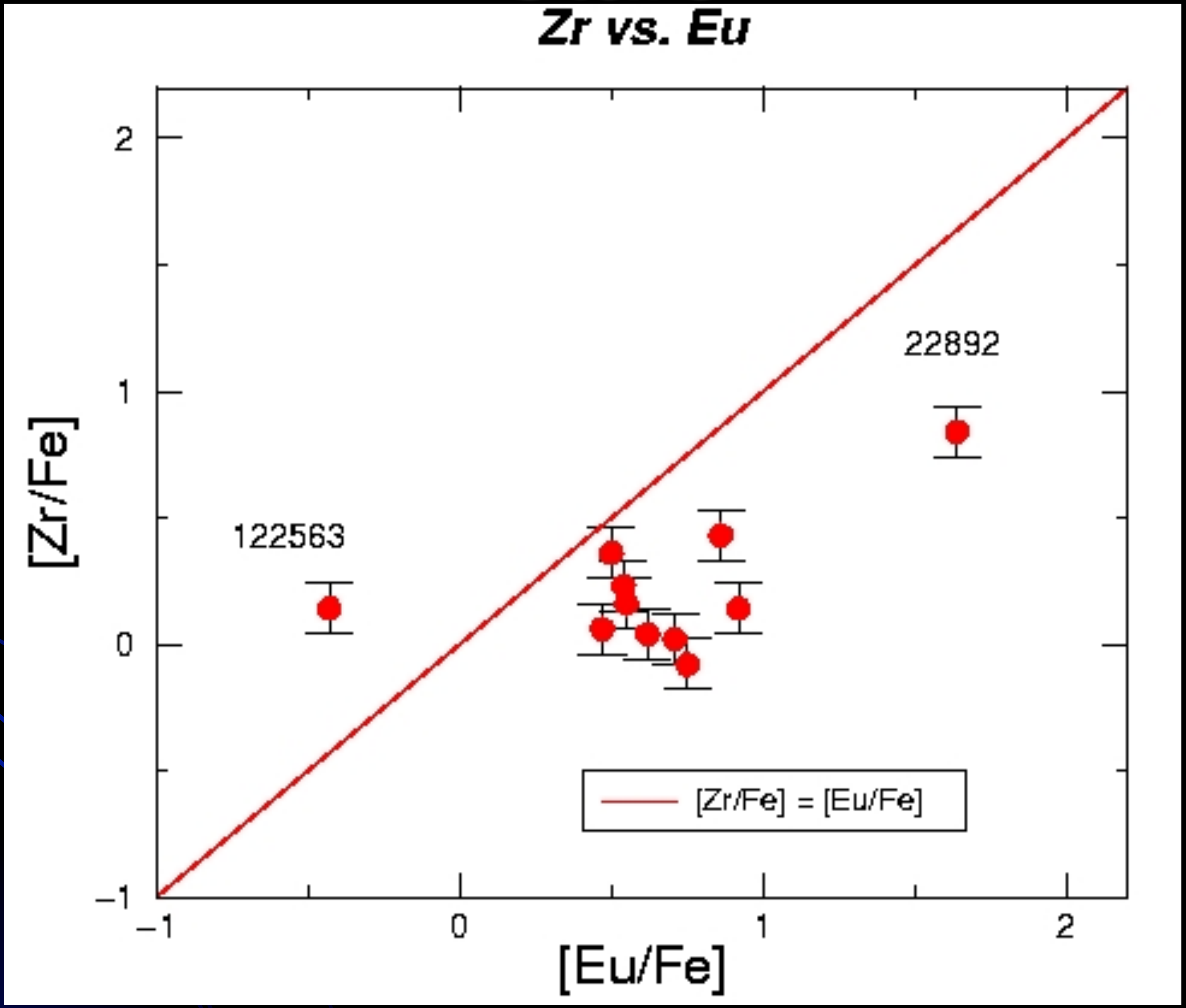


Travaglio et al. (2004)

The Famous LEPP Invention

- Making use of the very *r*-process rich and very metal-poor stars like CS 22892-052 and CS 31082-001, we find hints and discuss the possibility of a *primary process* in low-metallicity massive stars, different from the "classical *s*-process" and from the "classical *r*-process" that we tentatively define LEPP (lighter element primary process). (Travaglio et al. 2004)

Zr (HST) and Eu Abundances in Halo Stars



Zr $\not\propto$ Eu

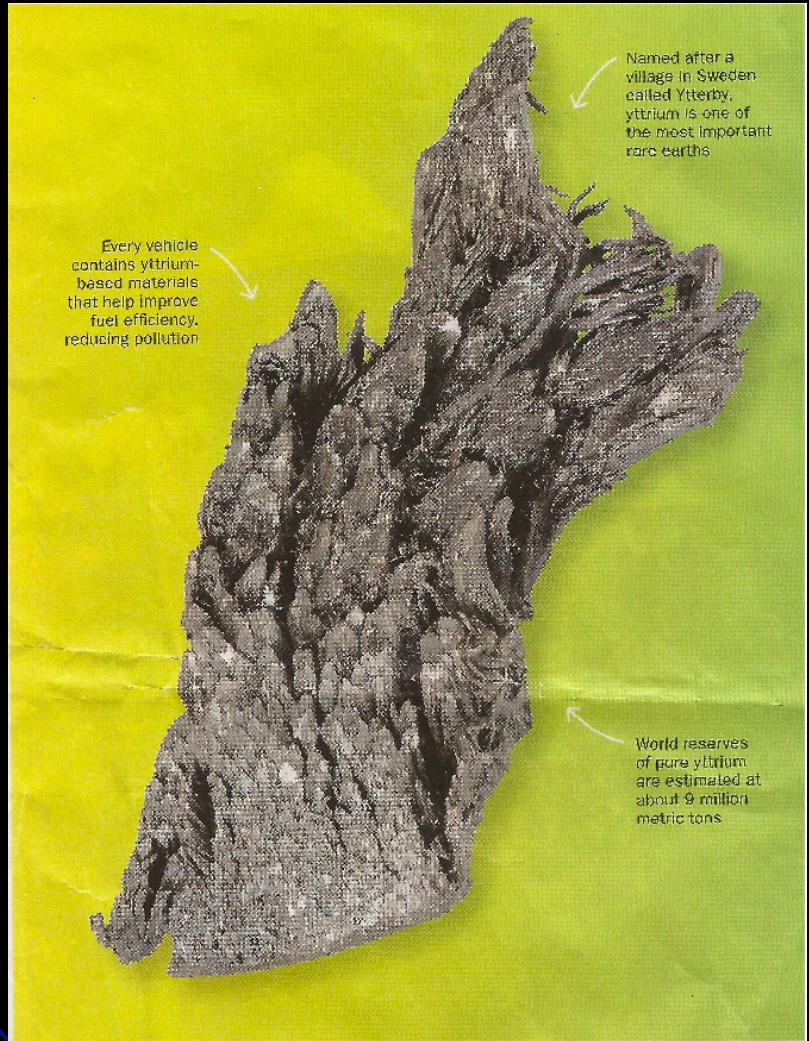
Both n-cap elements but not from same source?

LEPP?
SN models?

JC et al. (2005)

Trend first noticed by Travaglio et al. (2004)

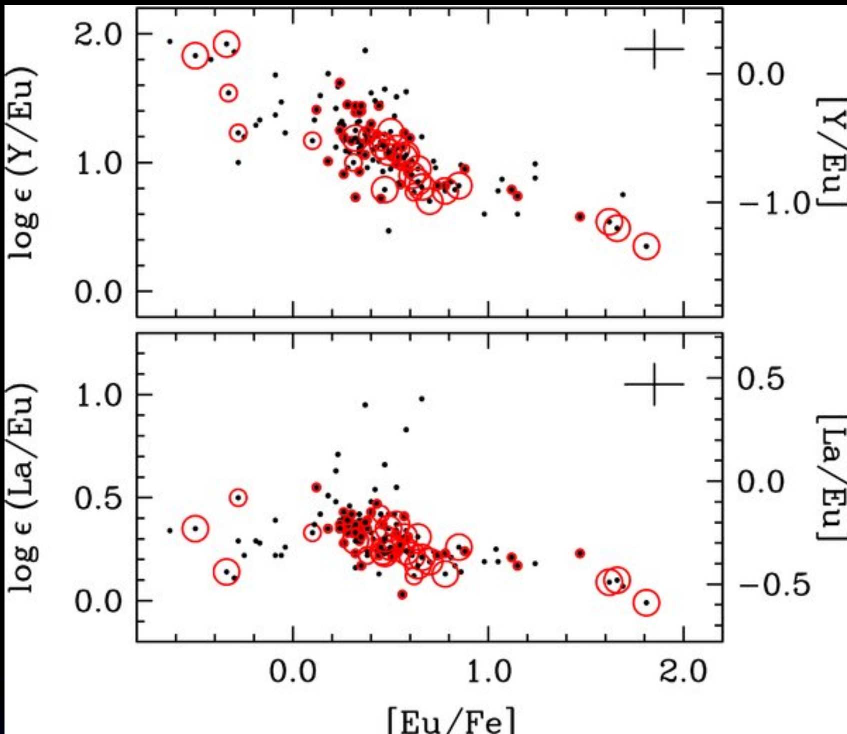
Y Rare on Earth!

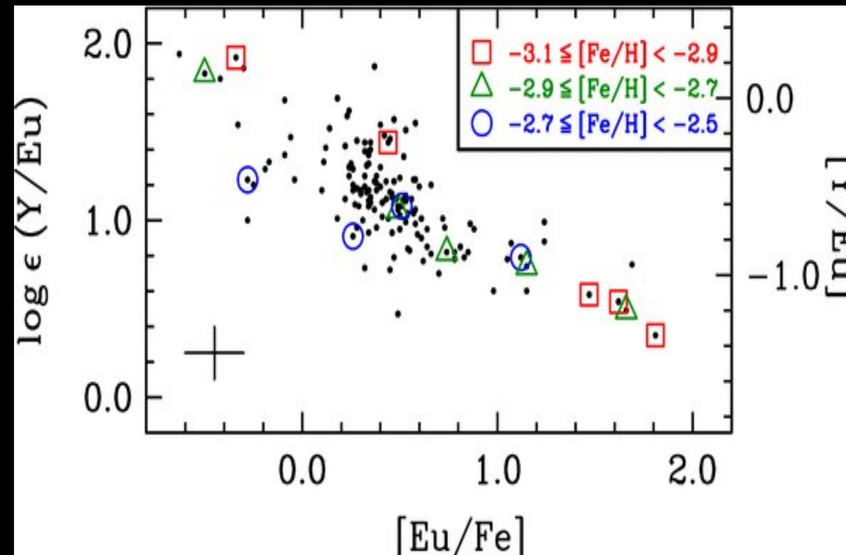


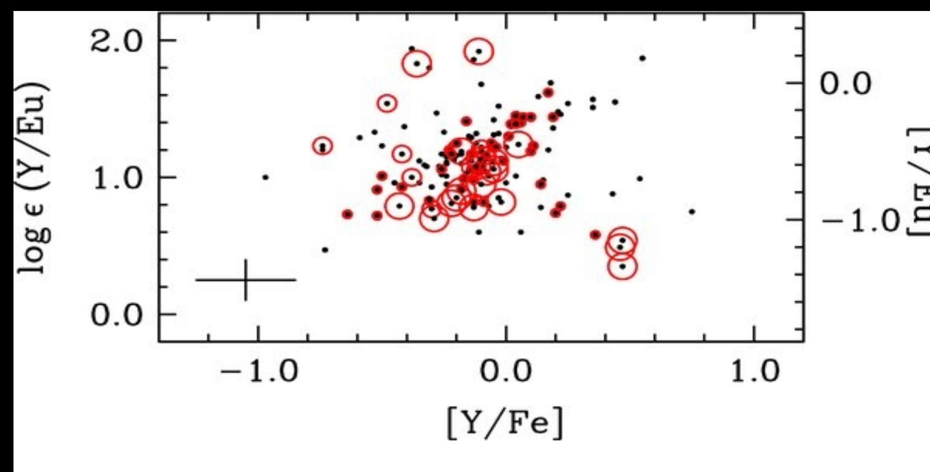
Got Yttrium? Probably not. Rare earths are key to tech, but China controls the supply. A U.S. mine is trying to change that

BY BRYAN WALSH

Y vs. Eu







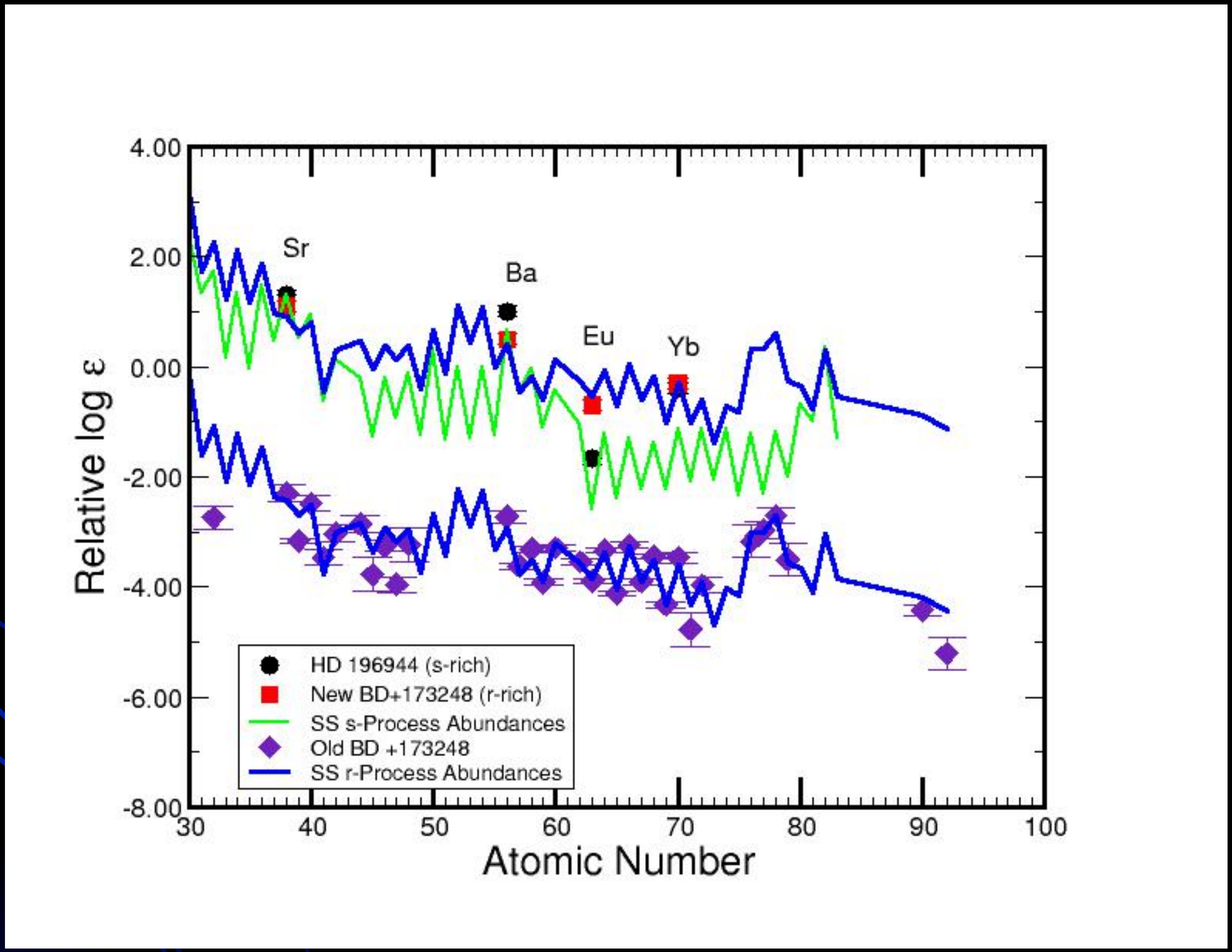
Note anticorrelation of [Y/Eu] vs. [Eu/Fe] – see also Montes et al.

Roederer et al. (2010b)

[Eu/Fe] & [Y/Eu] independent of [Fe/H] (Montes et al. 2007)

[Y/Eu] & [Y/Fe] not related, except for r-rich

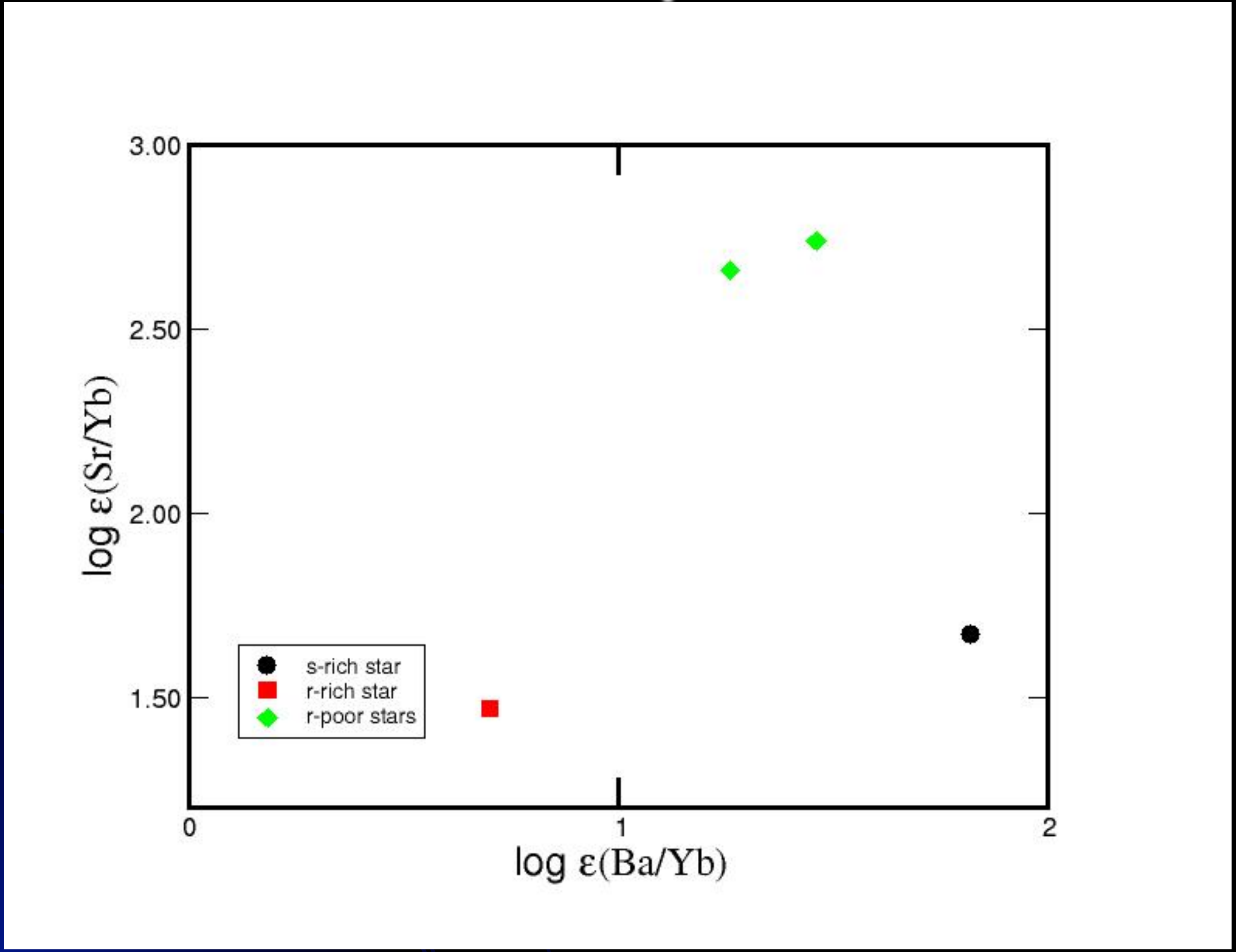
New Abundances for Elements: Sr-Yb



Only one Spectral Line near 3695 A So hard!

New abundances from Sr-Yb (Sneden et al. 2012)

How to Discriminate s-rich, r-rich and r-poor Stars?



Ba/Eu gives r/s dominance s=2.7, r=1.1-1.2

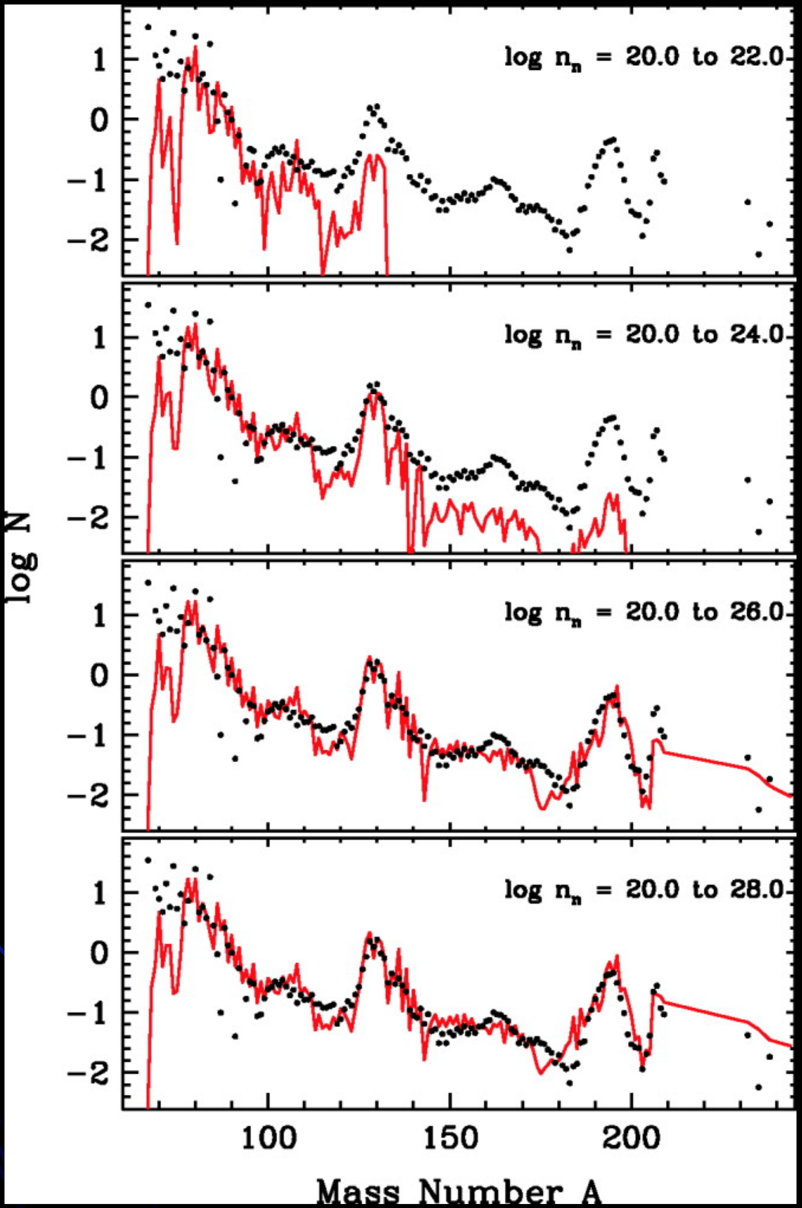
Ba/Yb shows r completeness (note lower nos.)

Sr/Yb shows r completeness BUT

New abundances from Sr-Yb (Sneden et al. 2012)

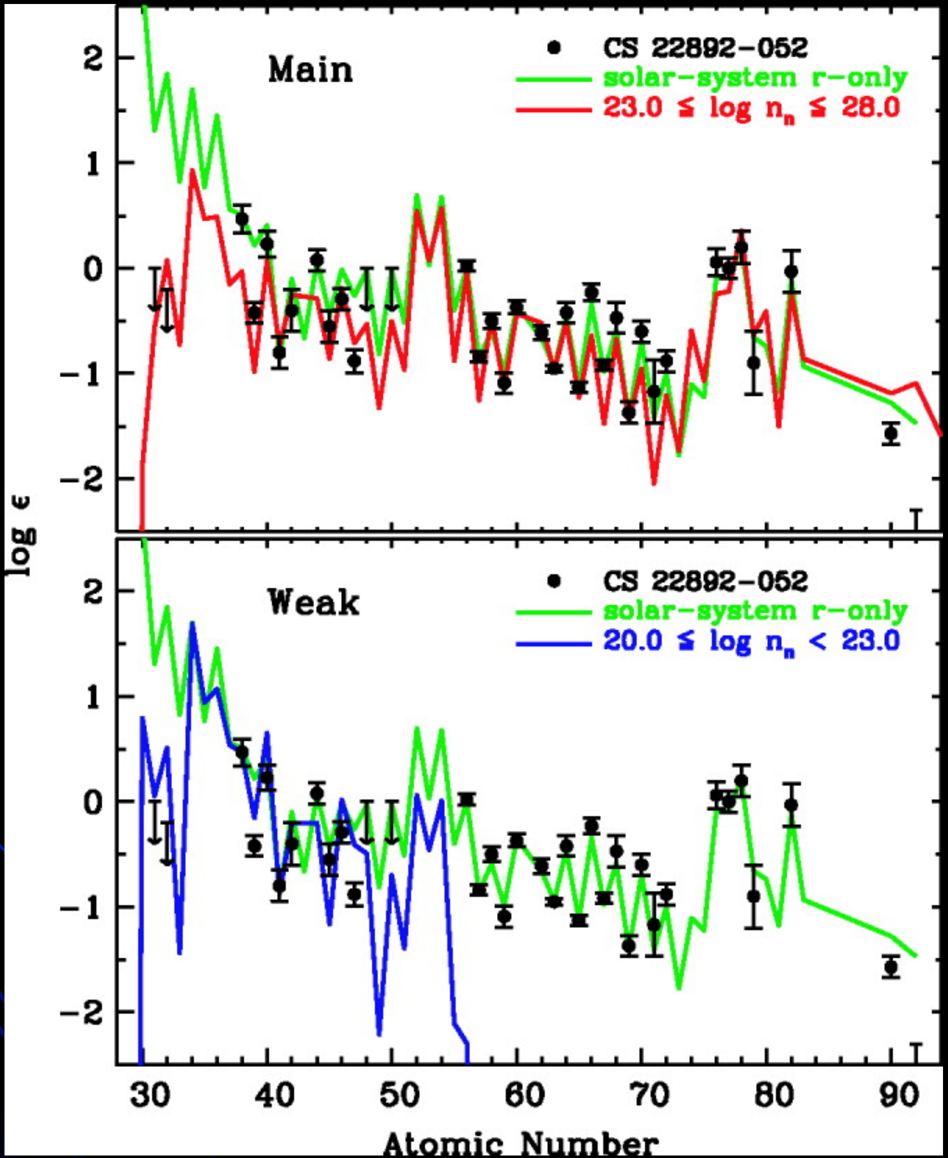
``Weak'' r-Process Model

Classical w-p approximation



Kratz et al. (2007)

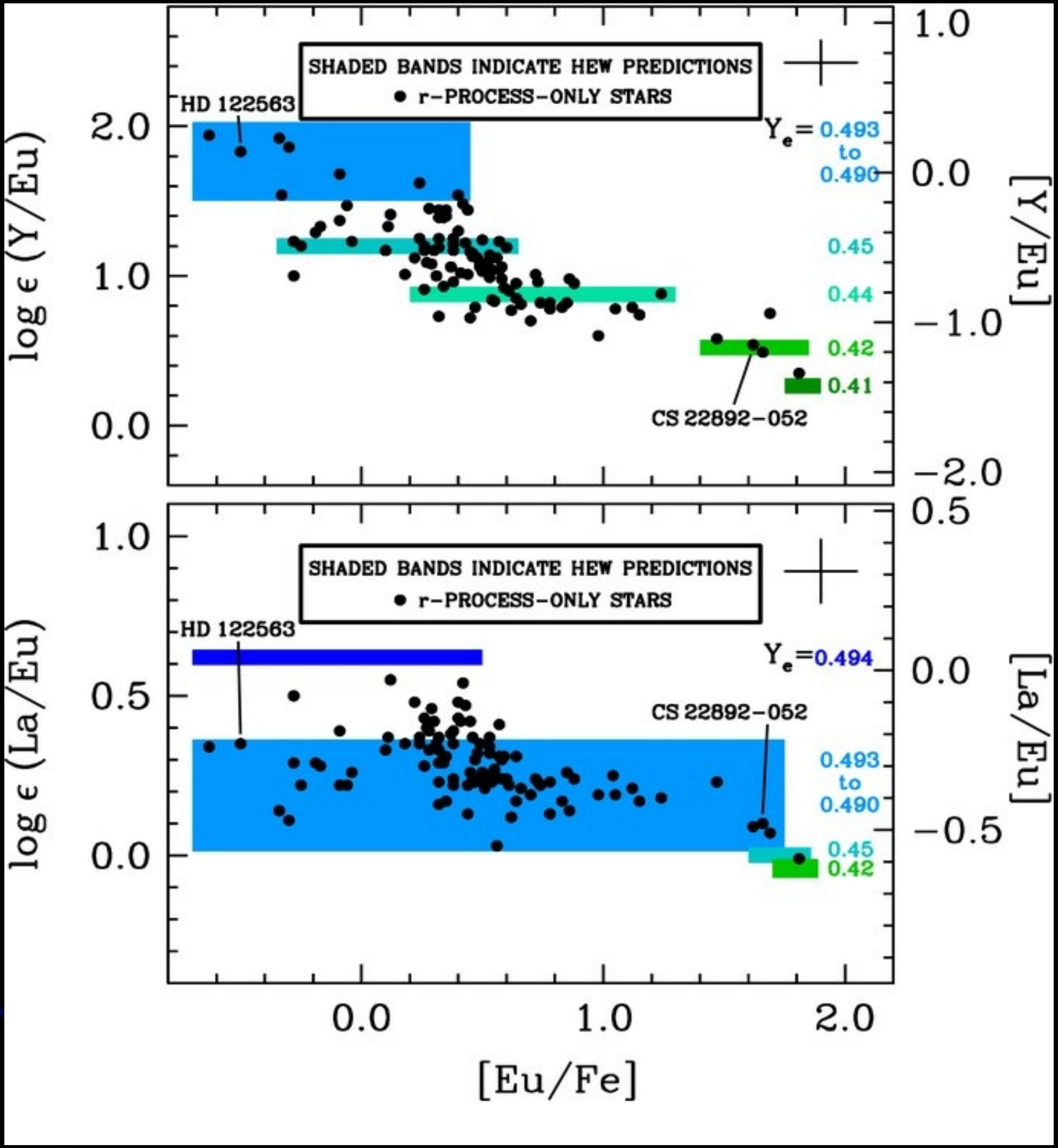
W-P Models for CS 22892-052



Kratz et al. (2007)

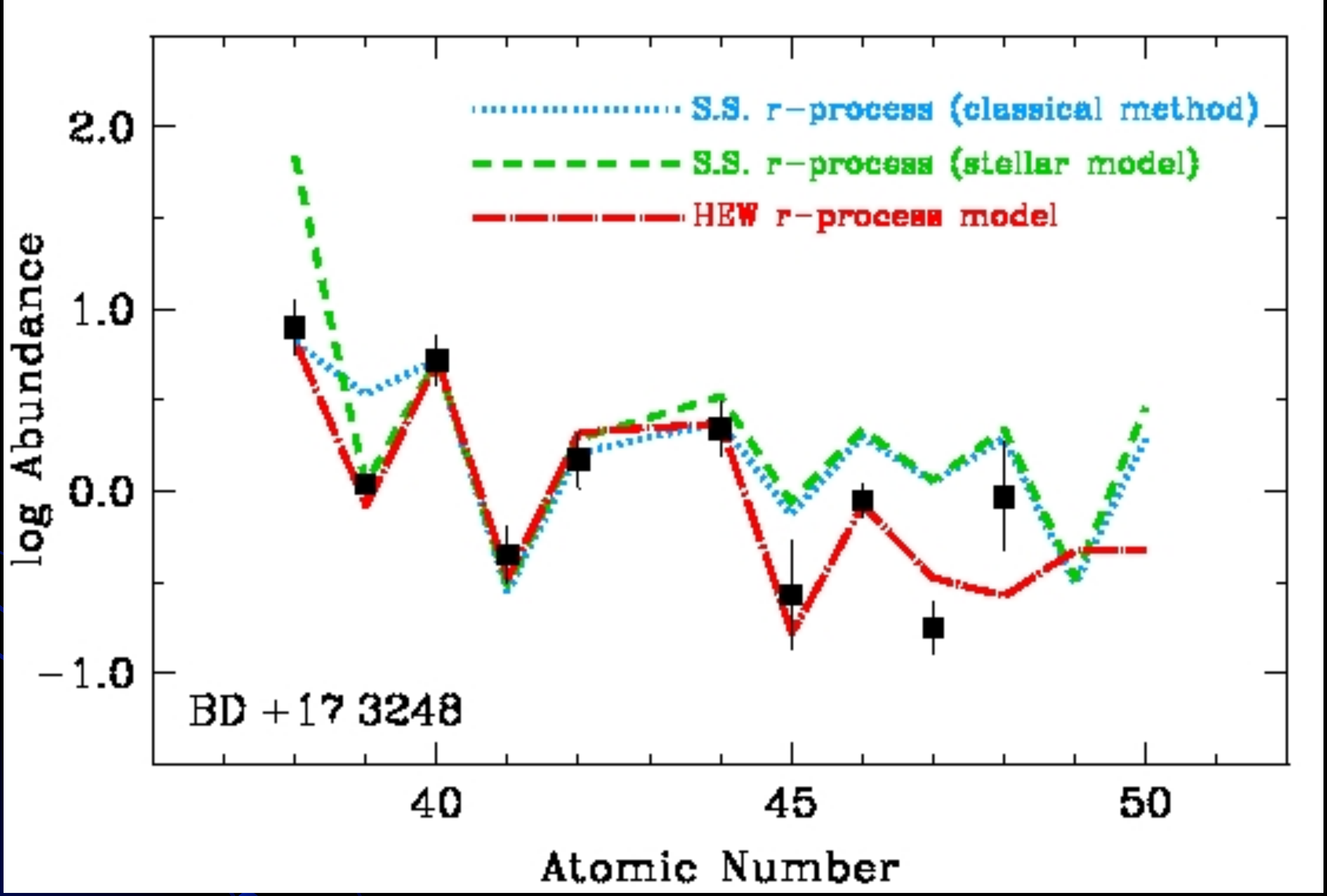
HEW Models

CP or a-rich freezeout
+ beta-delayed ns
⟶ low entropy components
for Sr-Zr ⟶ LEPP?



Roederer et al. (2010b)

Origin of the Lighter n-Capture Elements: Work in Progress



Note Ag, Cd

JC et al. (2011)

Lighter n-Cap Element Origin?

- Incomplete (``weak'') r-process, classical wp approximation, lower n-number densities
- More sophisticated: alpha-rich (charged particle with beta-delayed neutron recapture) freeze-out/ HEW (Kratz and Farouqi et al.) makes many of the elements from Sr-Pd but not Ag and Cd
- What about LEPP (Travaglio et al. and Montes et al.)? Weak s-process at low [Fe/H] for Sr-Zr?
- For some elements like Ge (and others?) nu-p process (Frohlich et al.)
- Maybe multiple processes?

What is needed now?

- More observations of n-capture elements in the very metal-poor stars

→ more abundance determinations in r-process poor stars

- More observations of lighter n-capture elements, including Ag, Ge, etc. in metal-poor halo stars
- More theoretical models for light n-capture synthesis

→ better (experimental & theoretical) nuclear data, better SN models

With Collaborators at:

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

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

Summary

- Three new n-capture species (Cd I, Lu II and Os II) detected in r-process rich star BD+17 3248 with HST
- Combined with other observations from Keck: new abundances for Mo I, Ru I, Rh I - brings to 32 n-capture element detections

→ most in any metal-poor star so far

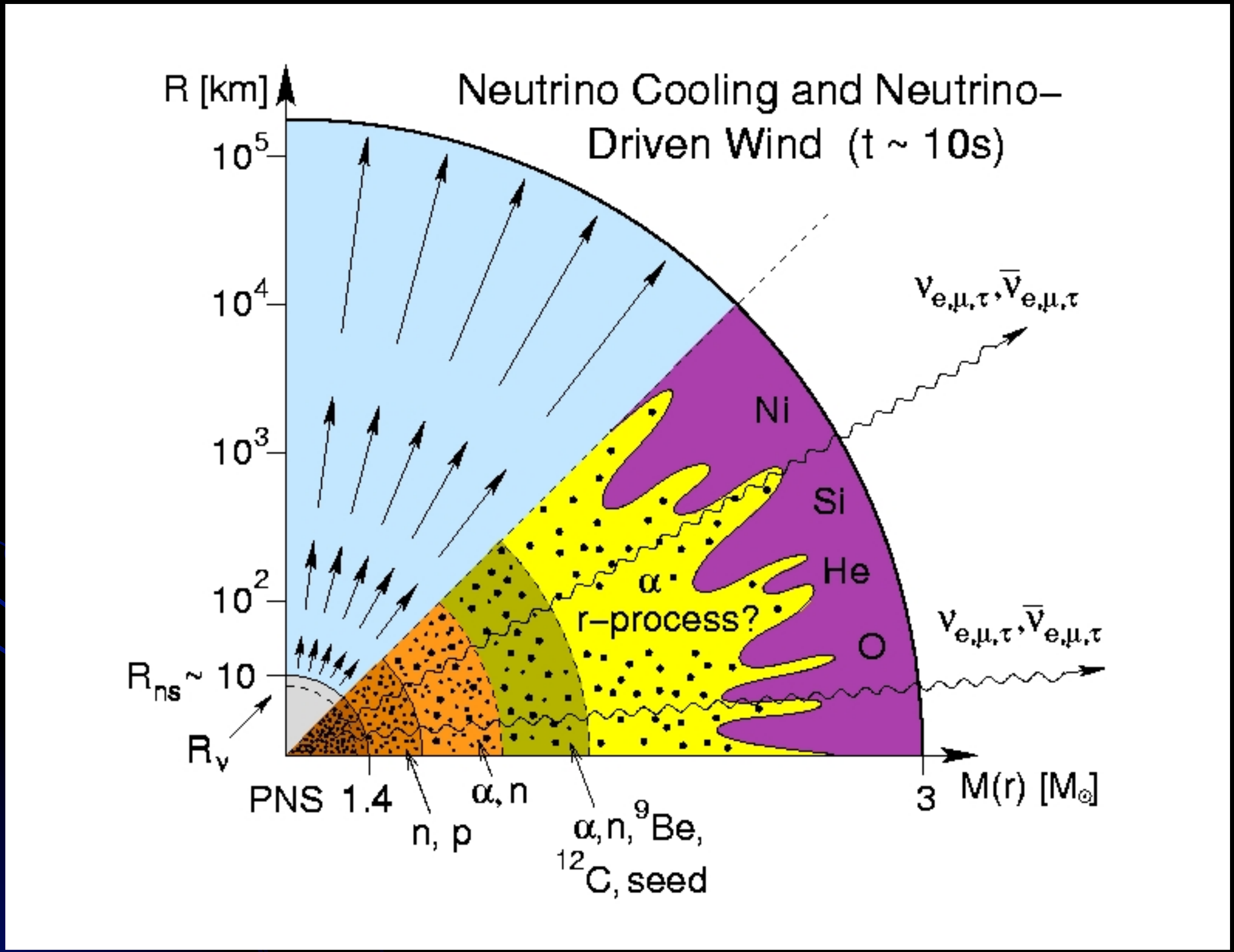
- Lighter n-capture element abundances do not fit the scaled SS r-process curve

→ places constraints on sources and/or sites for these elements

- r-process is ubiquitous in the early Galaxy – not necessarily same pattern as CS 22892-052

HAPPY 80TH BIRTHDAY GEORGE

Rapid Neutron Capture in Type II SNe ?



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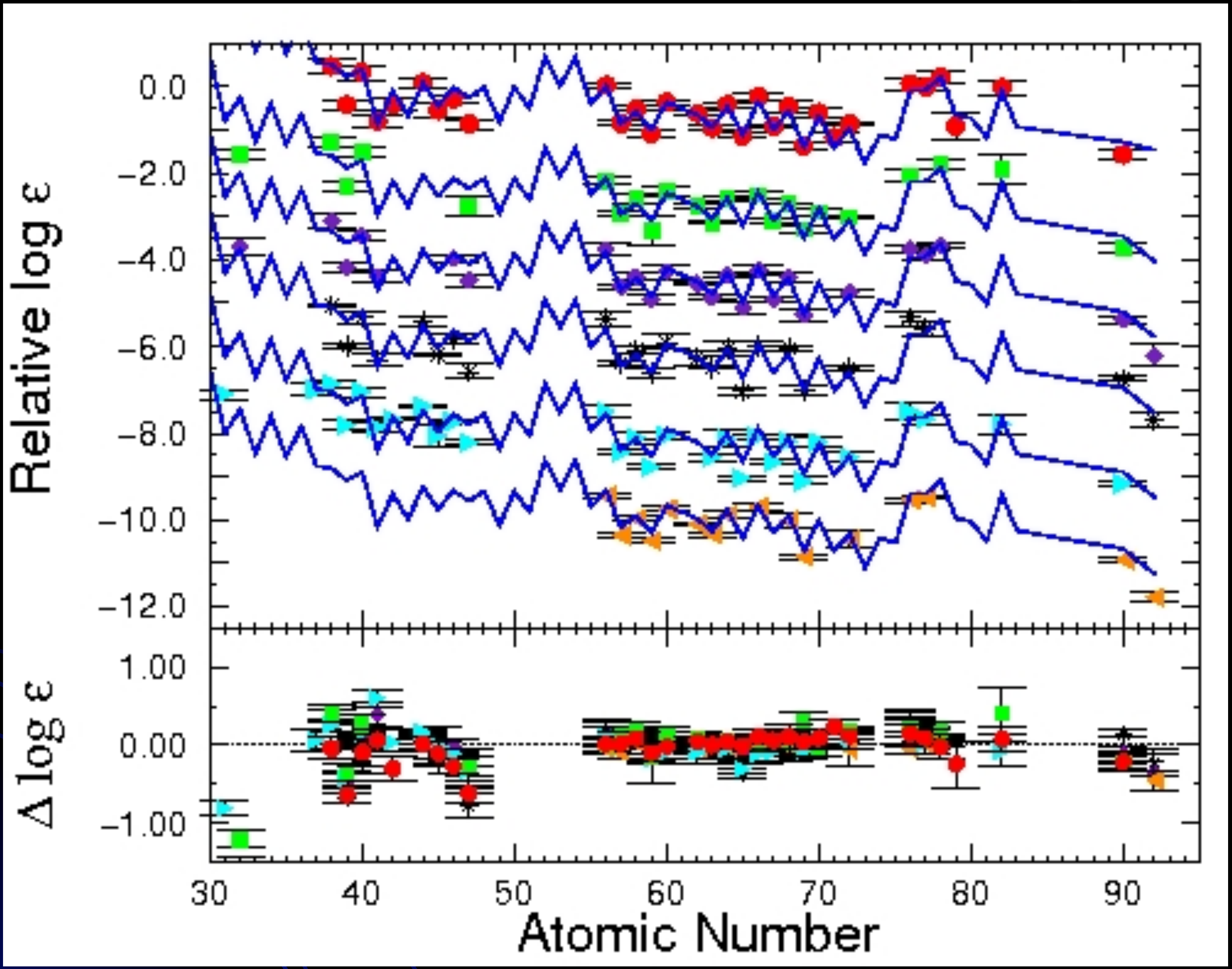
Elemental Abundance Comparisons



Sneden, JC & Gallino (2008)

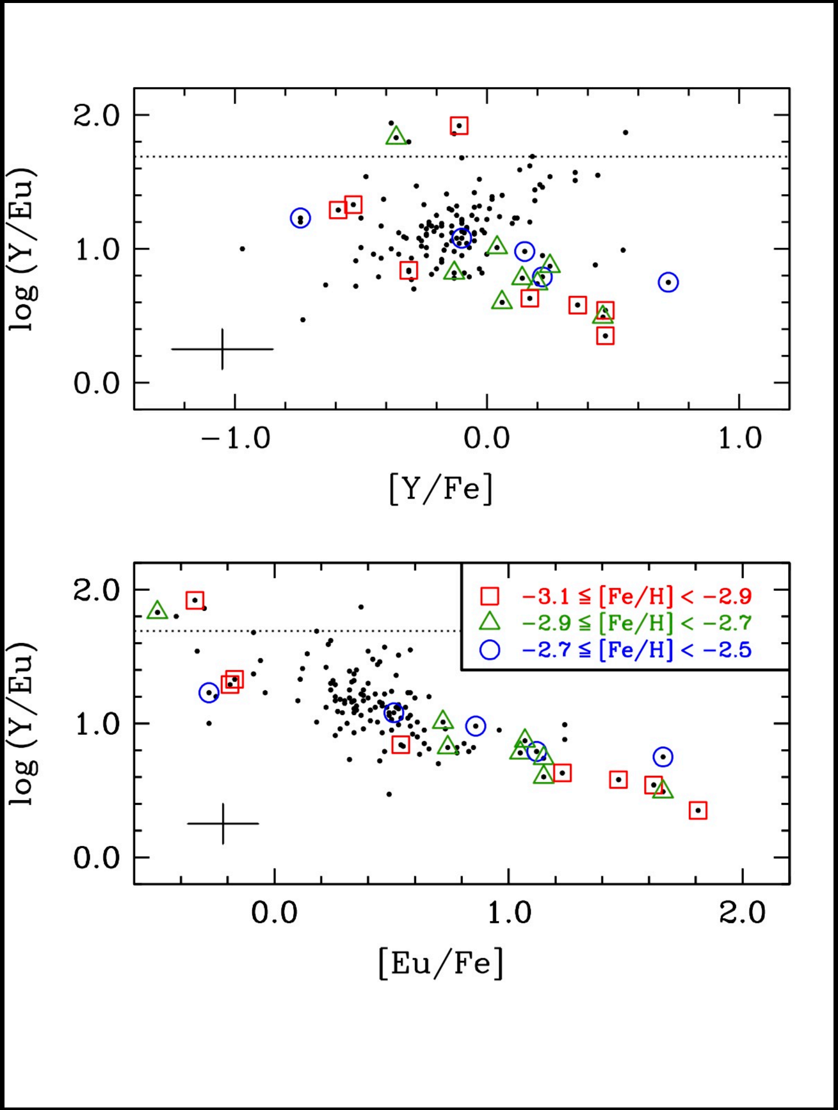
6 r-process rich stars

Cadmium: Good in Stars, Bad in People!

- Heavy Metal: It is not as pervasive as lead. But a study is underway to establish safe levels of cadmium.
- McDonald's recently recalled 12 million Shrek-themed glasses because of concern about the level of cadmium contained in the enamel.

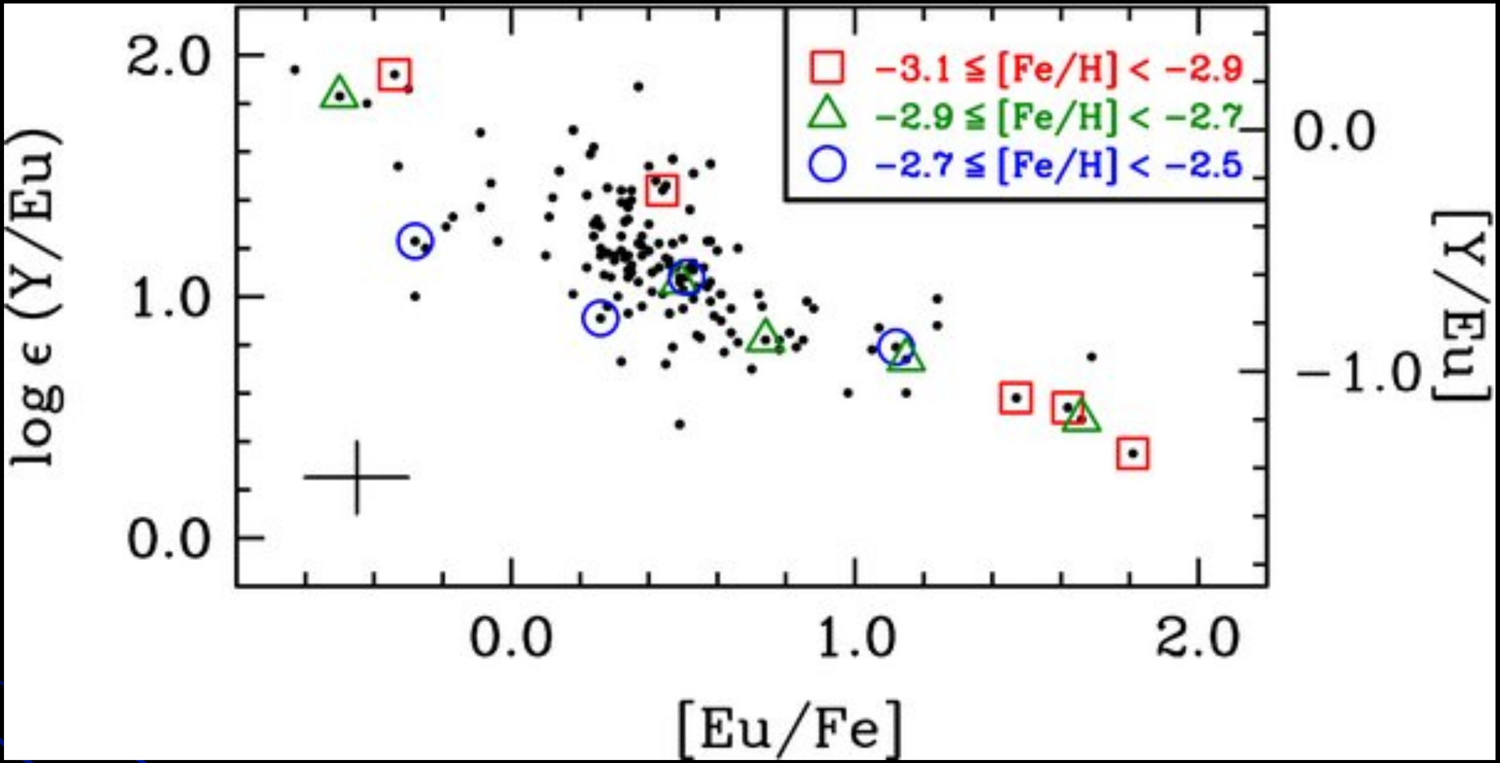
Time Magazine – July 12, 2010

Y vs. Eu



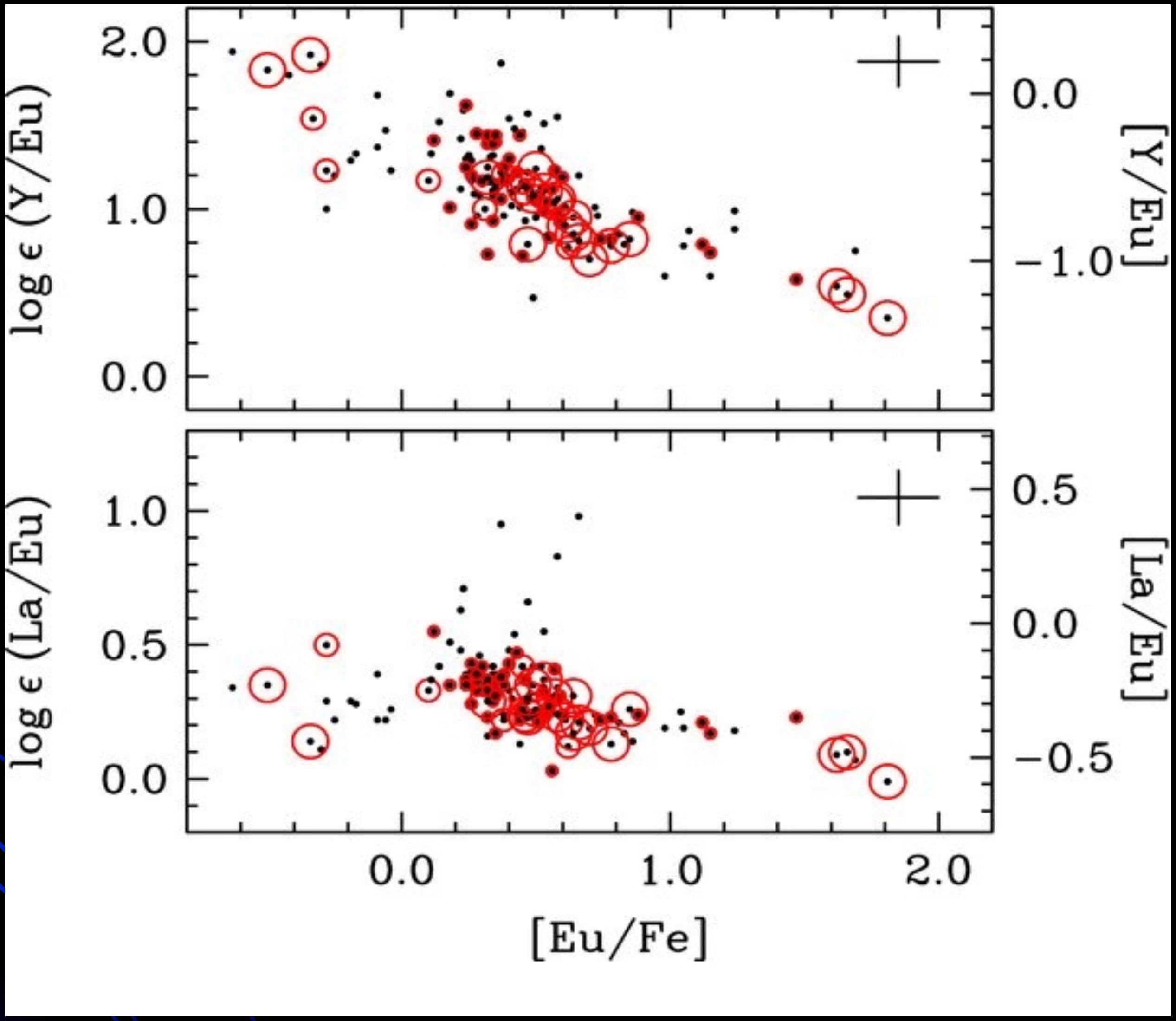
Roederer et al. (2010b)

Y vs. Eu

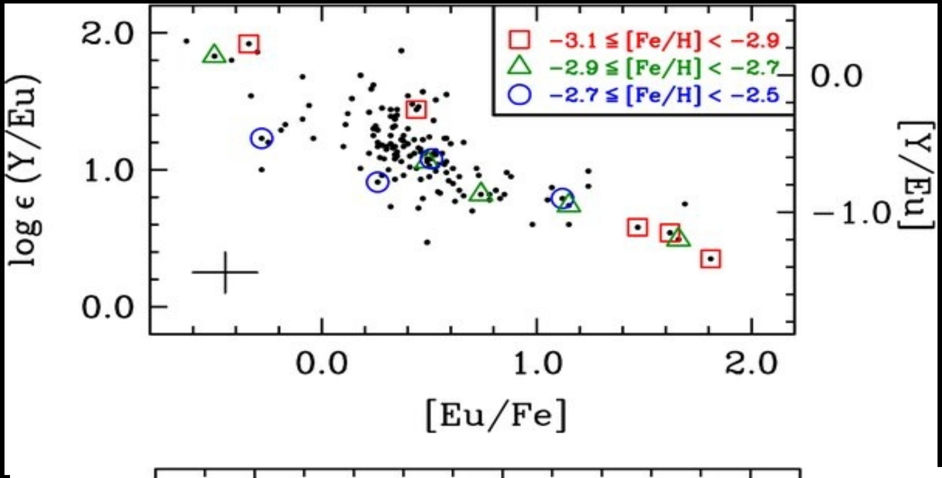


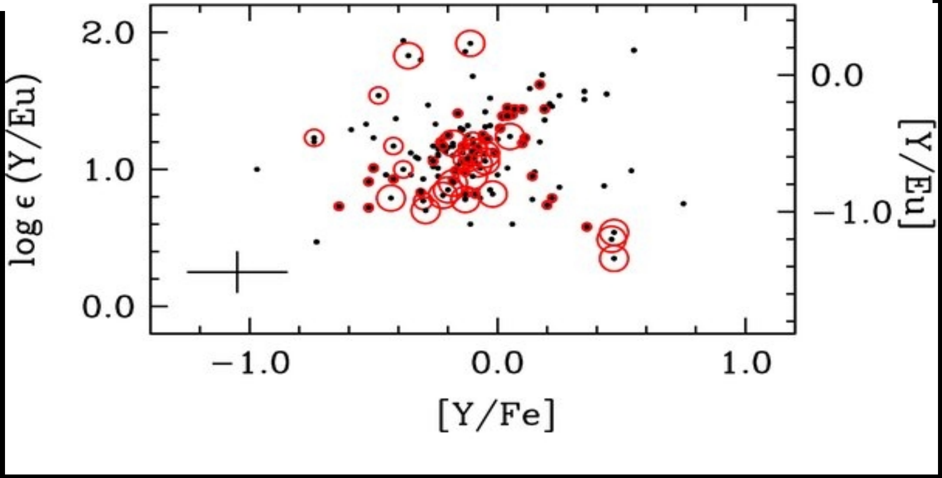
[Y/Eu] not correlated with [Y/Fe]

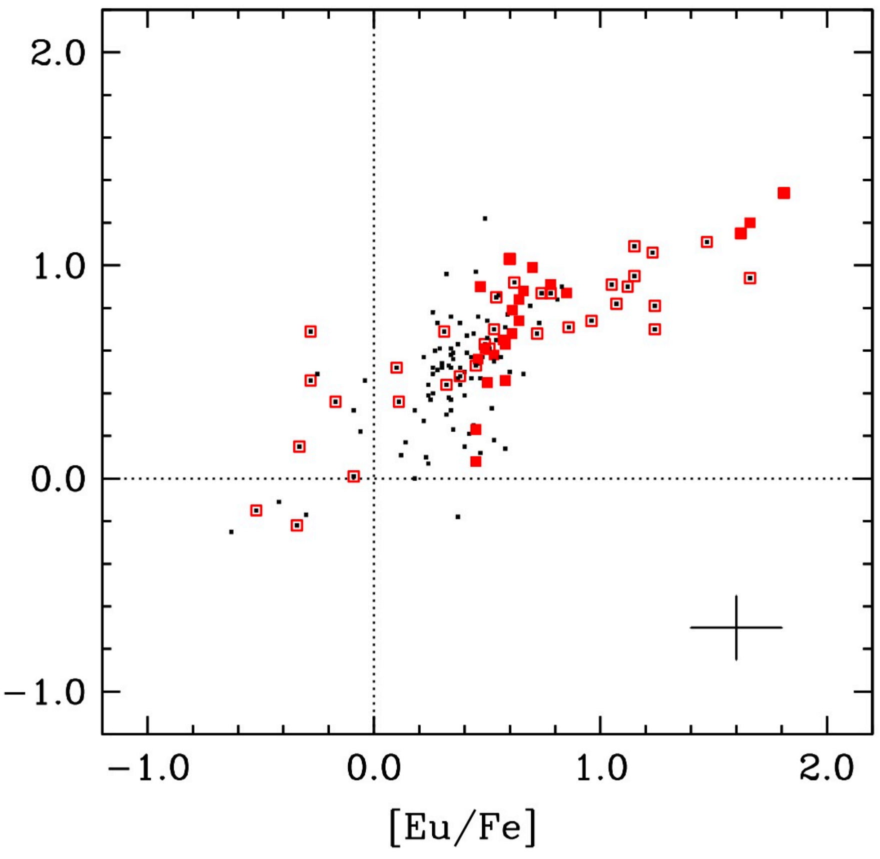
Roederer et al. (2010b)



log ε (Y/Eu)
[Y/Eu]
log ε (La/Eu)
[La/Eu]
[Eu/Fe]
2.0
1.0
0.0
−1.0
0.5
−0.5


−3.1 ≦ [Fe/H] < −2.9
−2.9 ≦ [Fe/H] < −2.7
−2.7 ≦ [Fe/H] < −2.5
log ϵ (Y/Eu)
[Y/Eu]
[Eu/Fe]
0.0
1.0
2.0
−1.0


log ϵ (Y/Eu)
[Y/Eu]
[Y/Fe]
−1.0
0.0
1.0
2.0



2.0
1.0
0.0
−1.0
[Eu/Y]
−1.0
0.0
1.0
2.0
[Eu/Fe]