STELLAR ABUNDANCE OBSERVATIONS AND THE R-PROCESS

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JINA r-process workshop at Notre Dame

TOP 11 GREATEST UNANSWERED QUESTIONS OF PHYSICS[1]

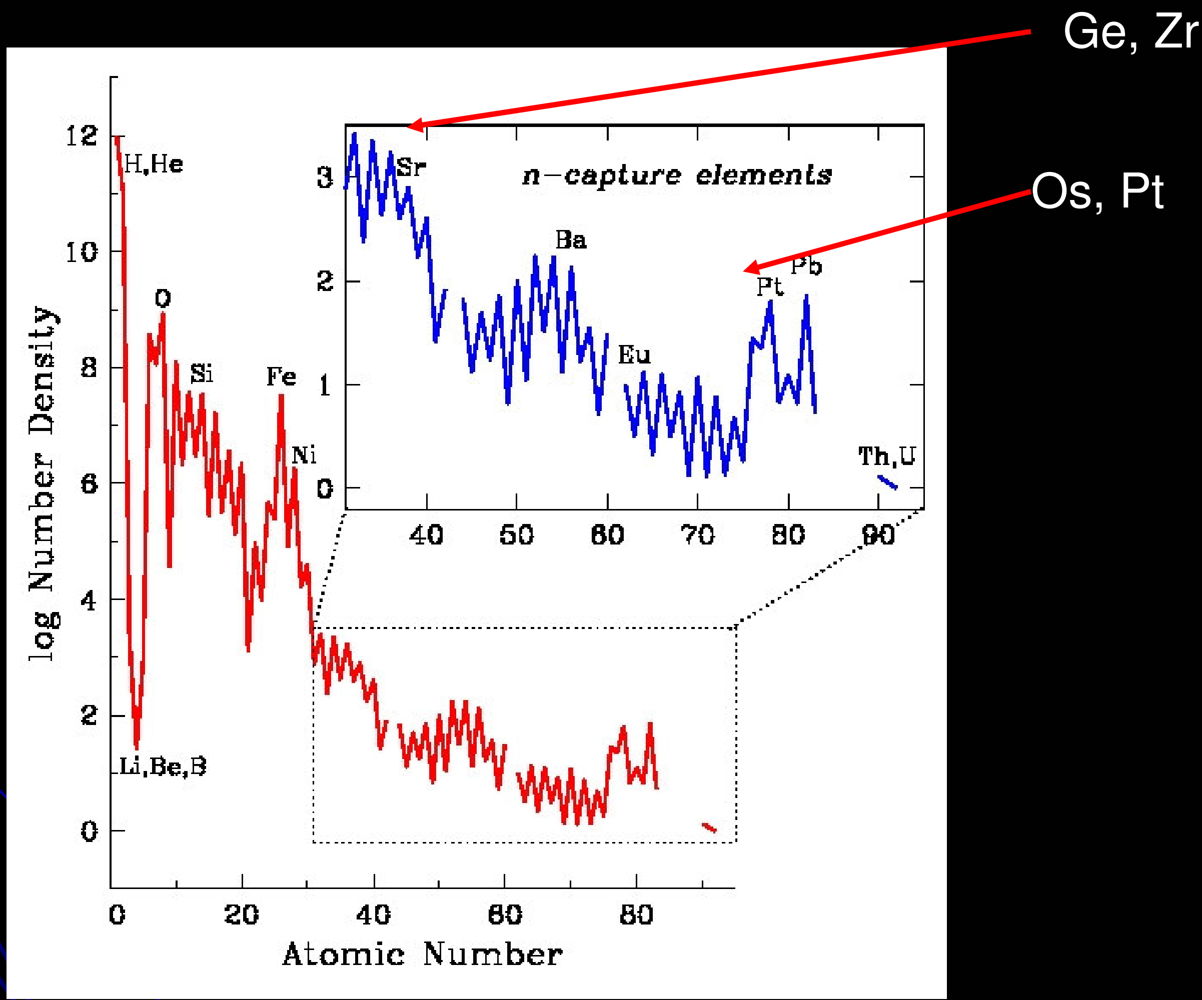
1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. New light and matter theory needed at ultra-high energies?
7. New states of matter at ultrahigh temperatures and densities?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

[1] Discover Magazine, February 2002.

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

Solar System Abundances



Sneden & JC (2003)

Most Likely Site(s) for the r-Process

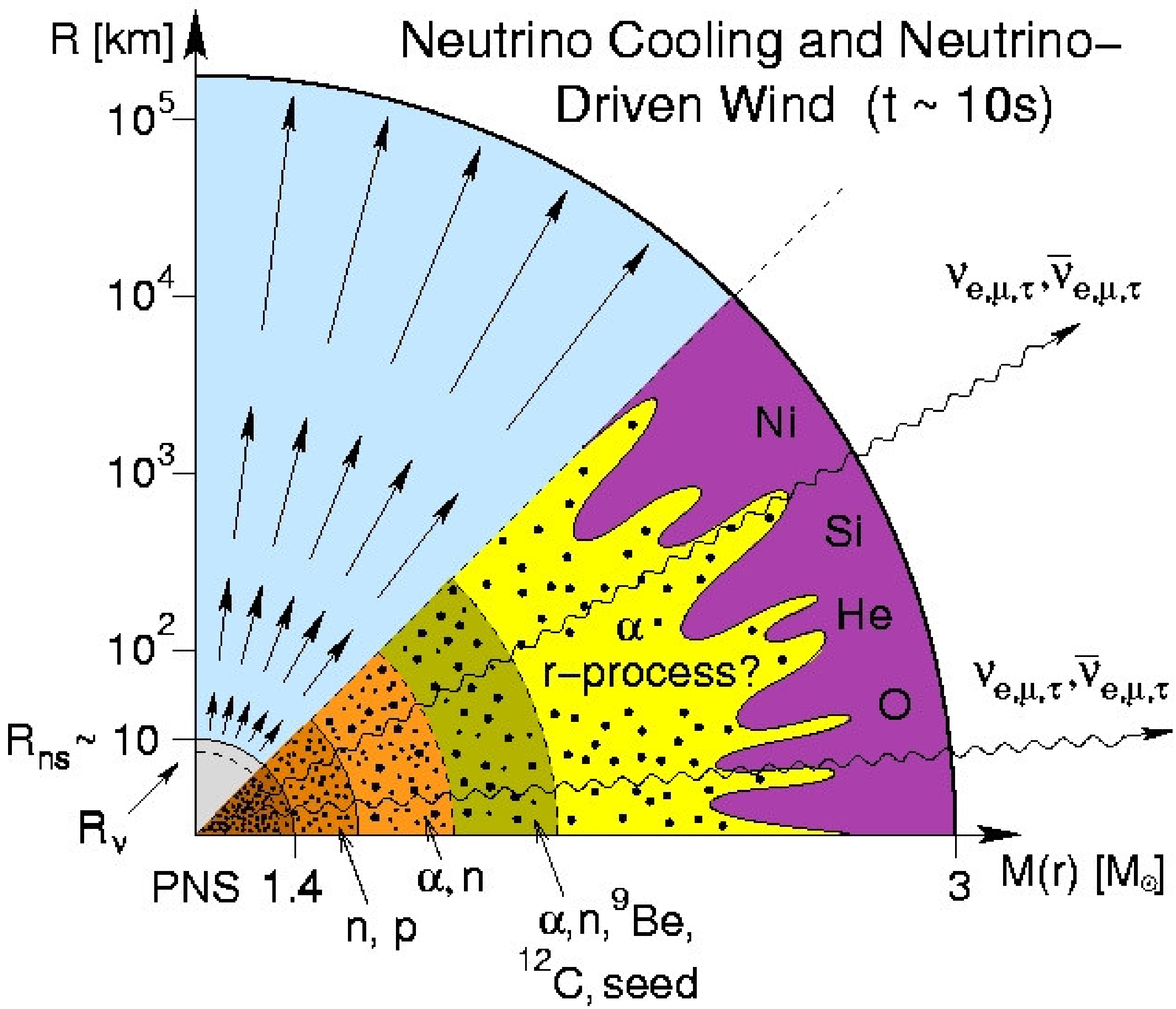
- Supernovae: The Prime Suspects

  → Regions just outside neutronized core: (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)

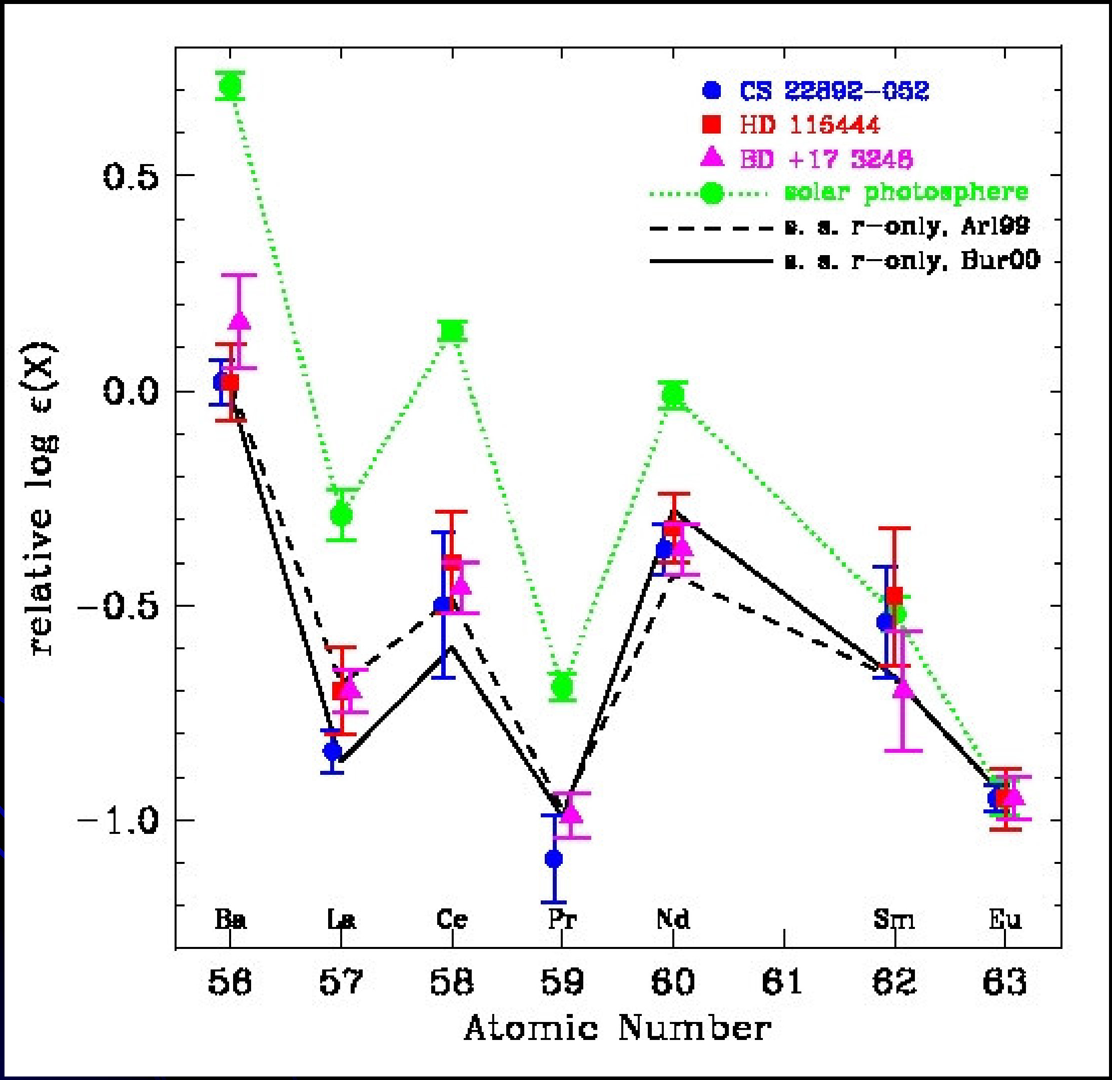
- NS & NS-BH mergers (Rosswog et al. 1999; Freiburghaus et al. 1999)



Neutrino Cooling and Neutrino–Driven Wind (t ~ 10s)
R [km]
10^5
10^4
10^3
10^2
R_ns ~ 10
R_ν
PNS 1.4
n, p
α, n
α, n, 9Be, 12C, seed
α
r–process?
Ni
Si
He
O
ν e,μ,τ, ν̄ e,μ,τ
ν e,μ,τ, ν̄ e,μ,τ
3
M(r) [M☉]

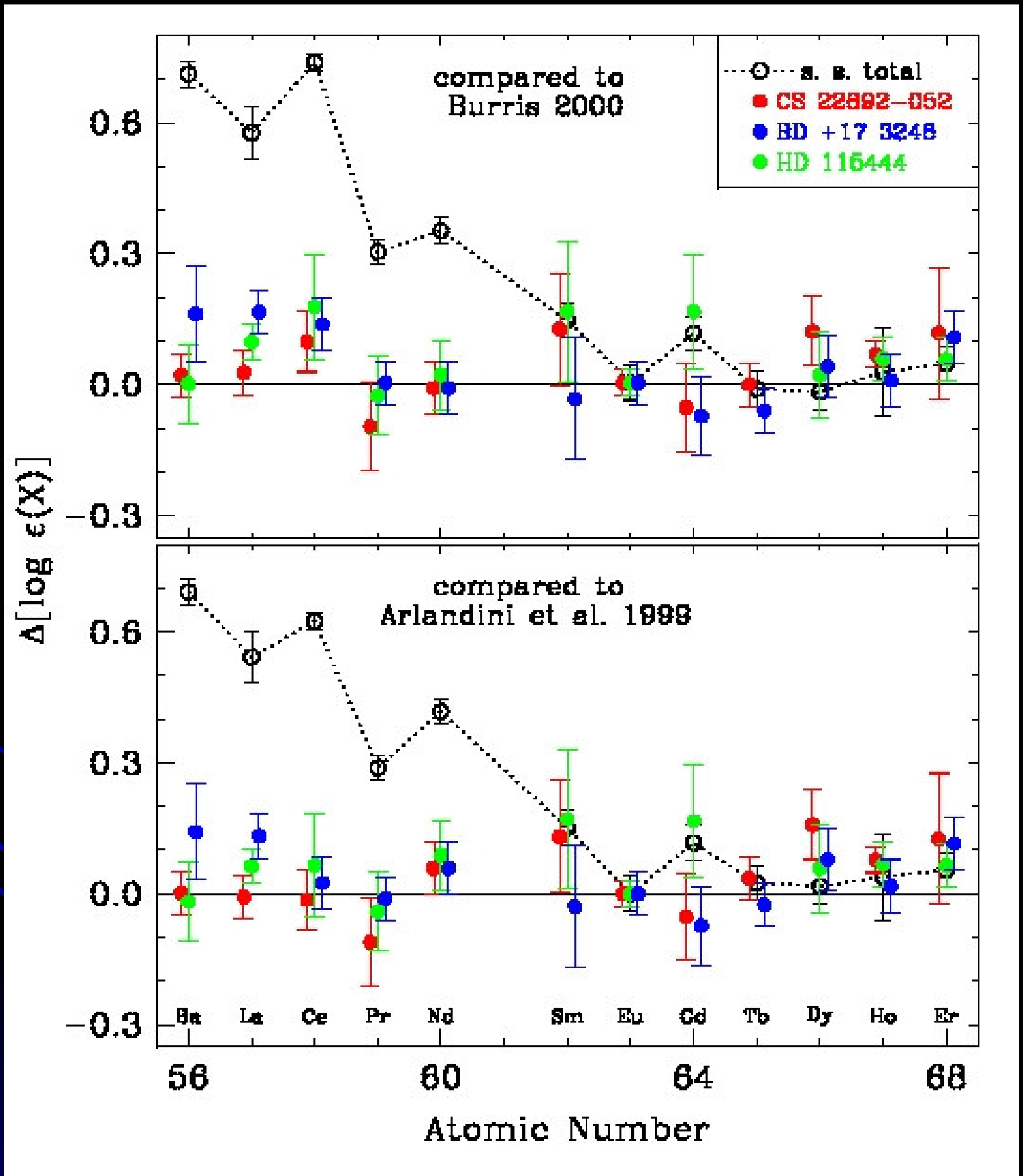
Abundances in Metal-Poor Halo Stars Focus On Individual Elements: Nd

Decreased scatter with new observations & atomic data. Consistent with SS r-only abundances. Much below total SS abundances.



New experimental atomic physics data.
Den Hartog et al. (2003).

Focus On Individual Elements: Ho



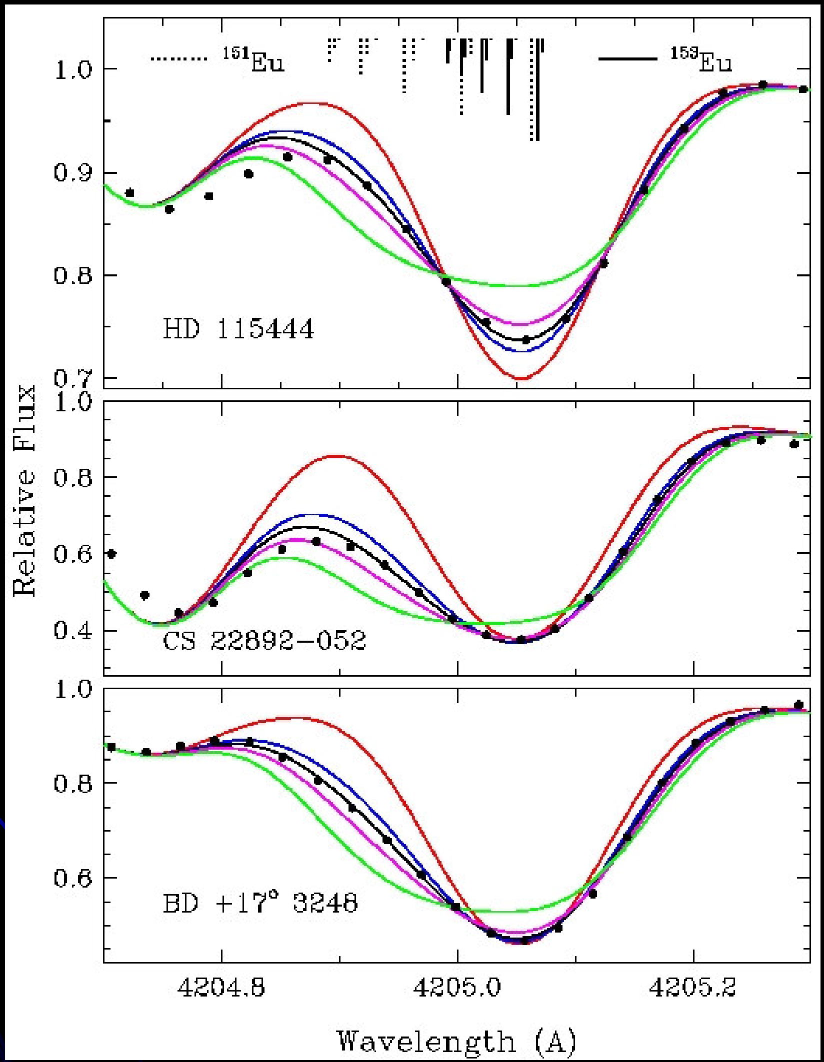
New experimental atomic physics data. Lawler et al. (2004).

Pt (Den Hartog et al 2005)
Sm (in progress)

Working our way through the Periodic Table!

Eu Isotopic Abundances in 3 Metal-Poor Halo Stars

151Eu:
- 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.

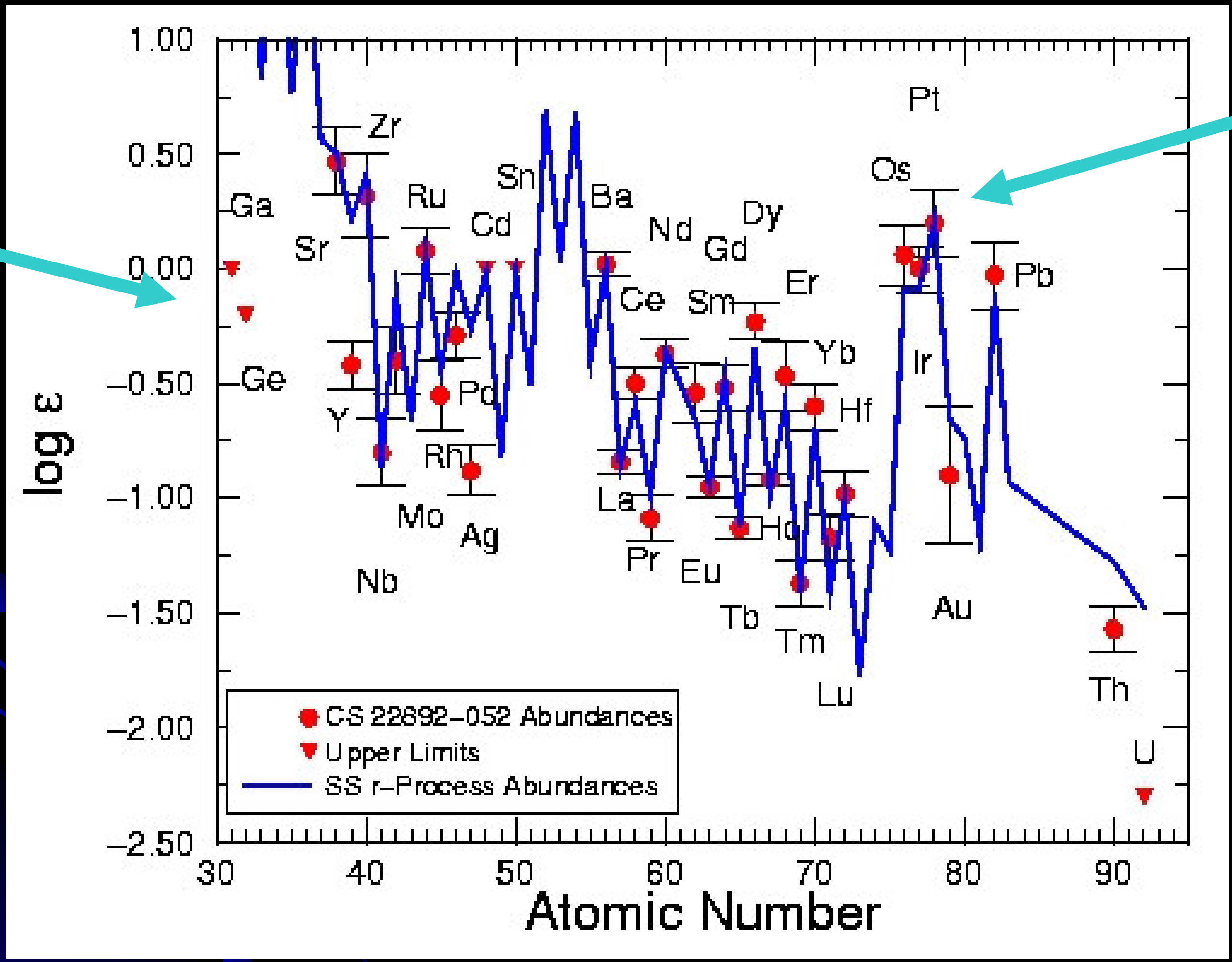
Sneden et al. (2002)

CS 22892-052 Abundances

Cowan et al. (2005)

Germanium

Ba from r-
(not s-)
process
early
in Galaxy.



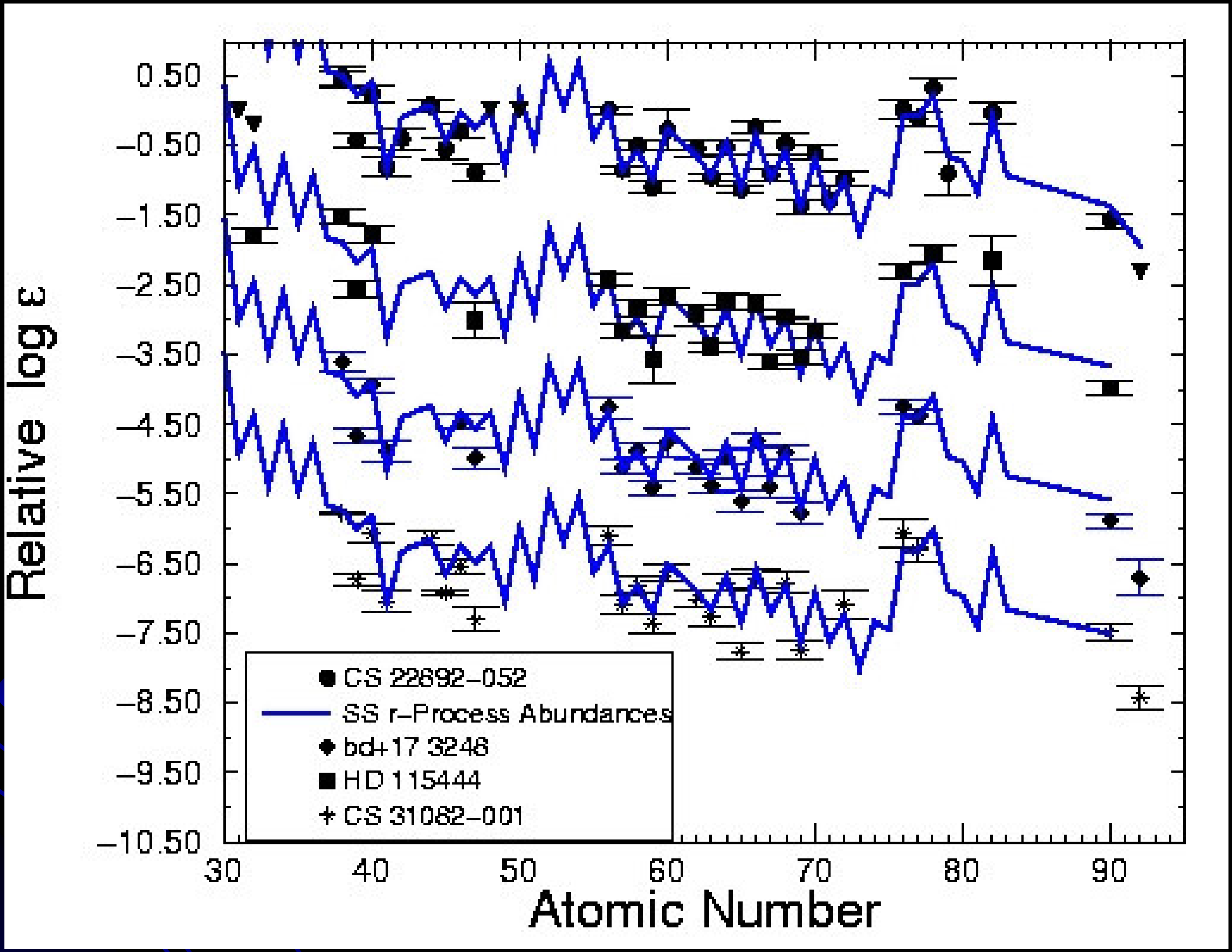
Platinum

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

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

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

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 ?

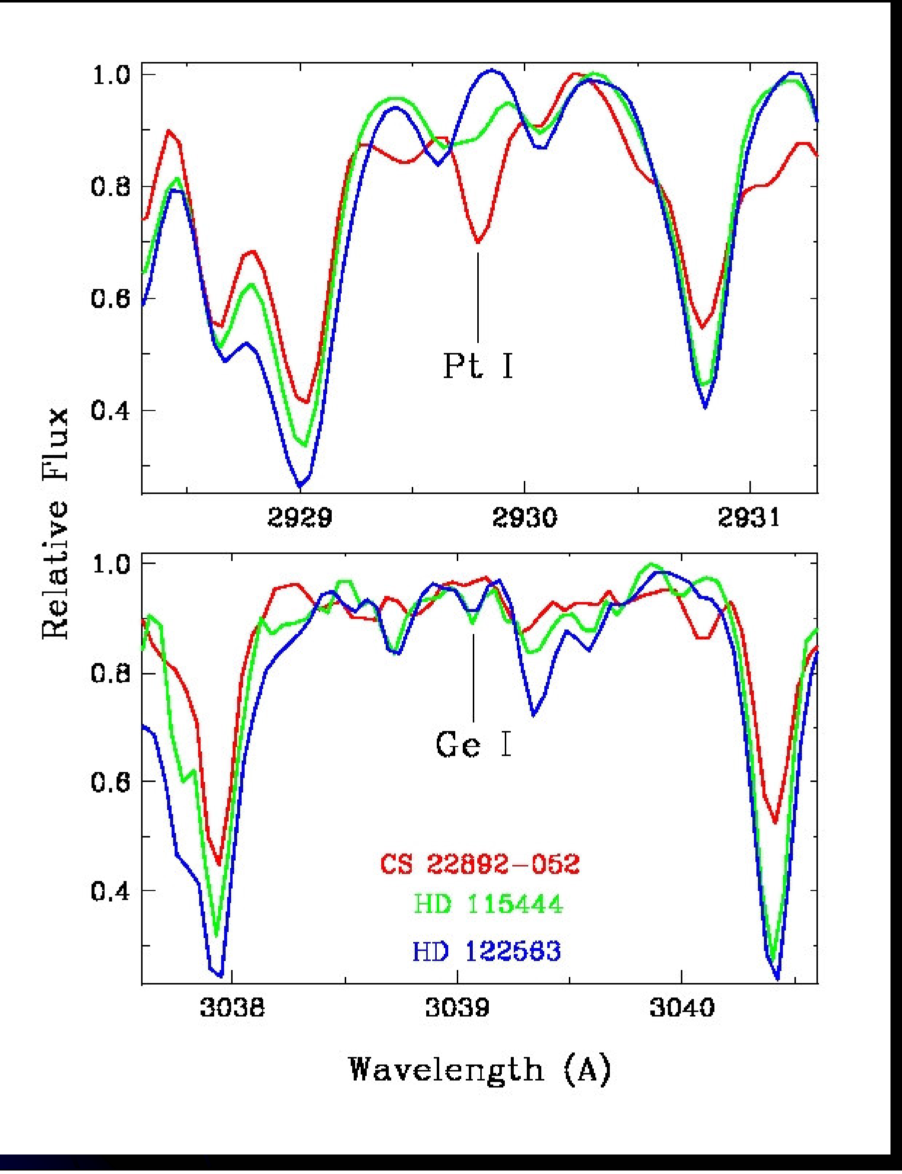
- Only recently any detections of elements, Z = 40-50
  → Best evidence CS 22892-052
- Heavier element (Z ≥ 56) abundances seem to follow SS r-process curve, not so for the lighter elements
  → Same pattern appears in several other r-process rich stars
- Two separate sites (Wasserburg, Busso & Gallino): strong and weak r-process (2 types of SNe or SNe and NS mergers) or
- One site (different epochs or regions)

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

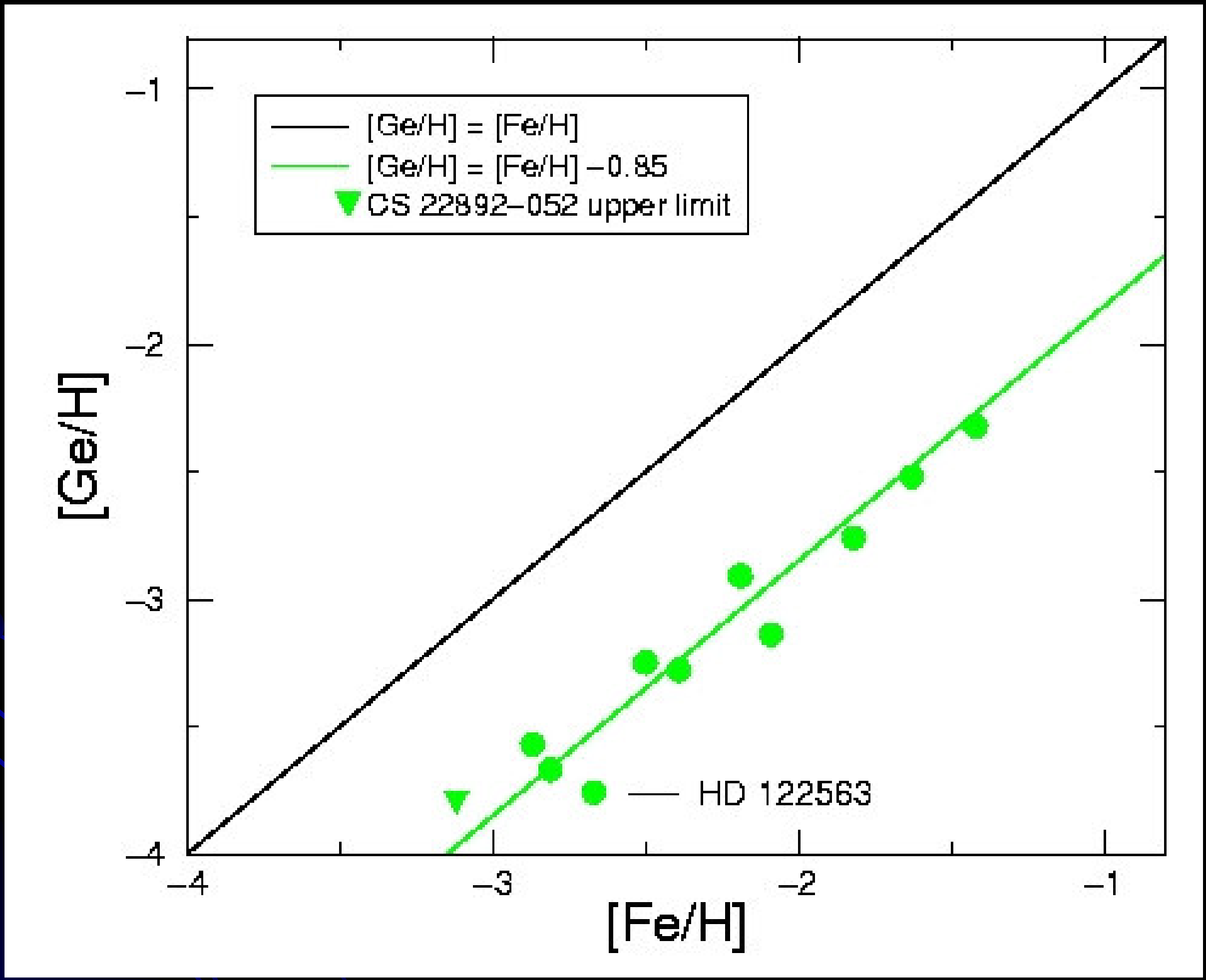
NUV HST STIS Spectra

Heavy n-capture elements do not scale with iron.



Ge scales with Fe.

Ge Abundances in Halo Stars



Ge ∝ Fe

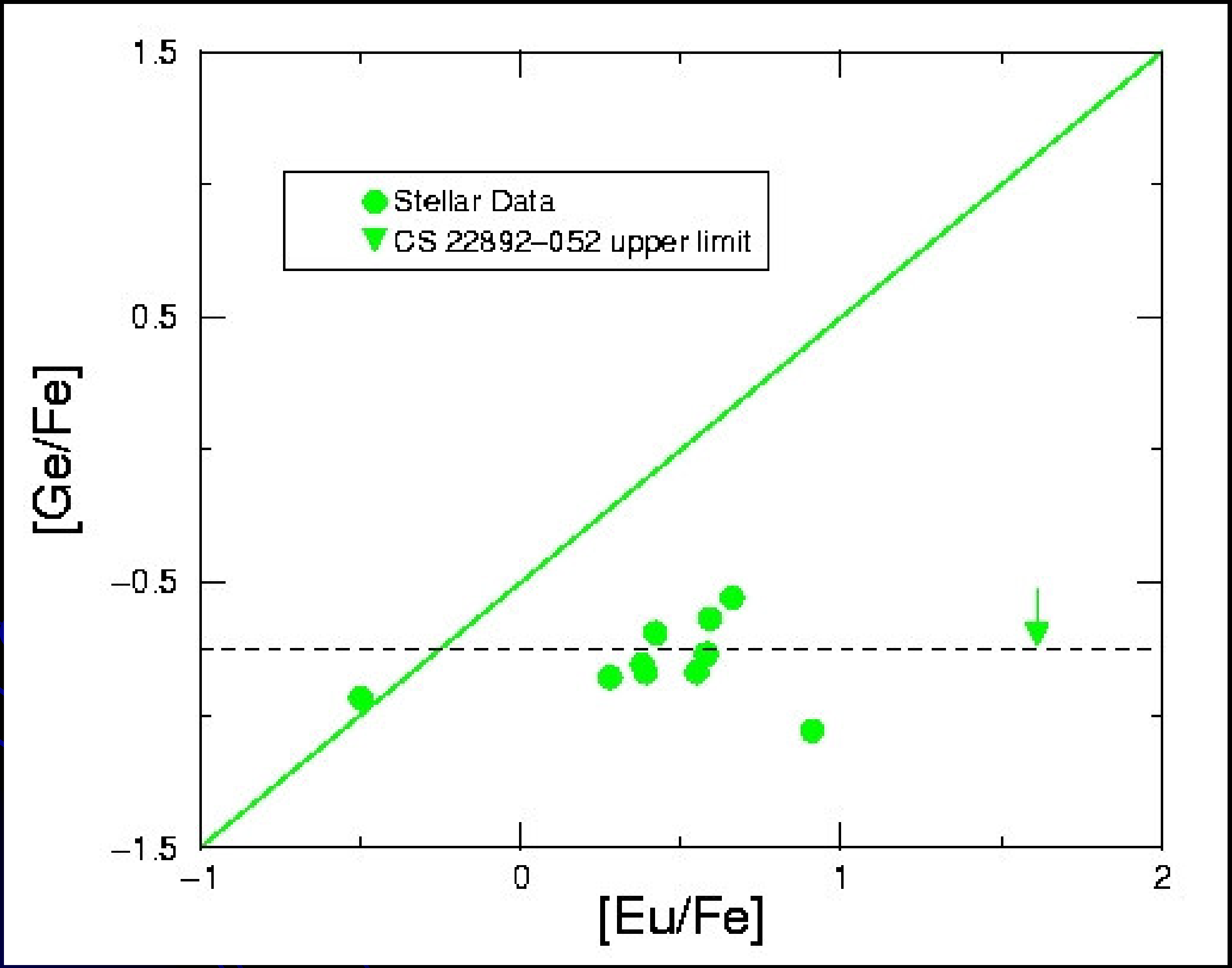
Challenge to theorists.

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

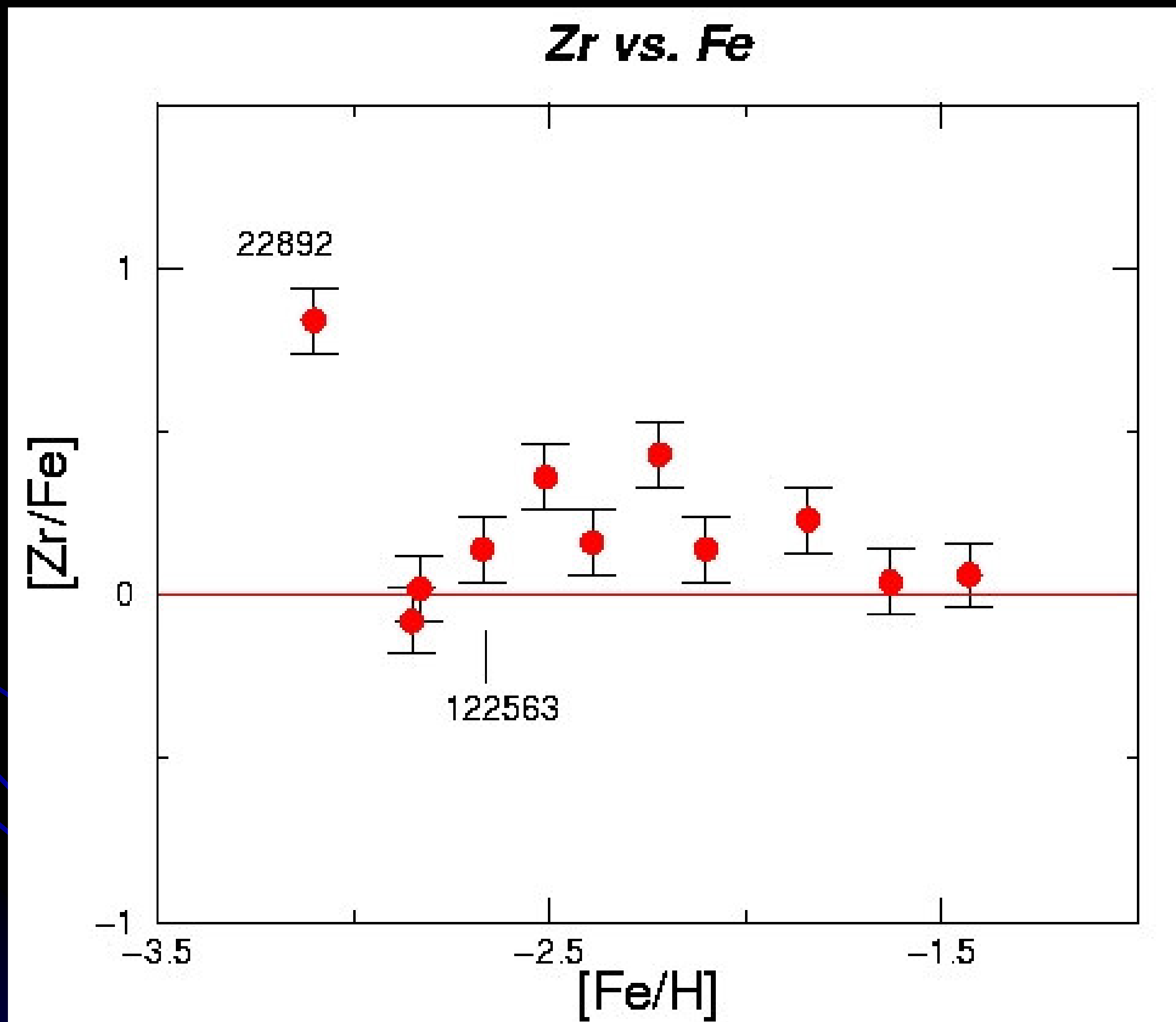


Ge ∝̸ Eu

JC et al. (2005)

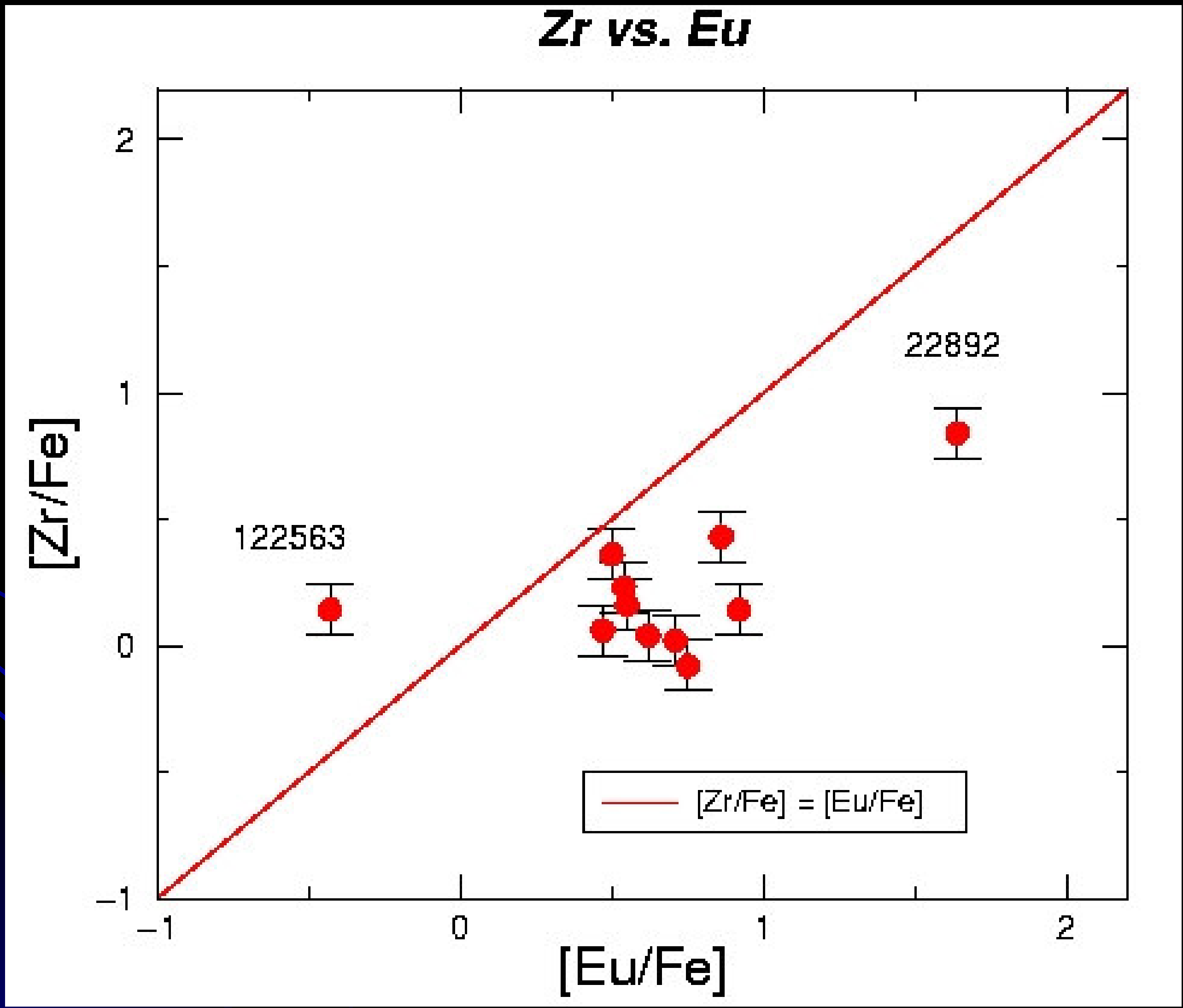
$[A/B] = \log_{10}(A/B)_{star} - \log_{10}(A/B)_{sun}$

Zr as a Function of Metallicity



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

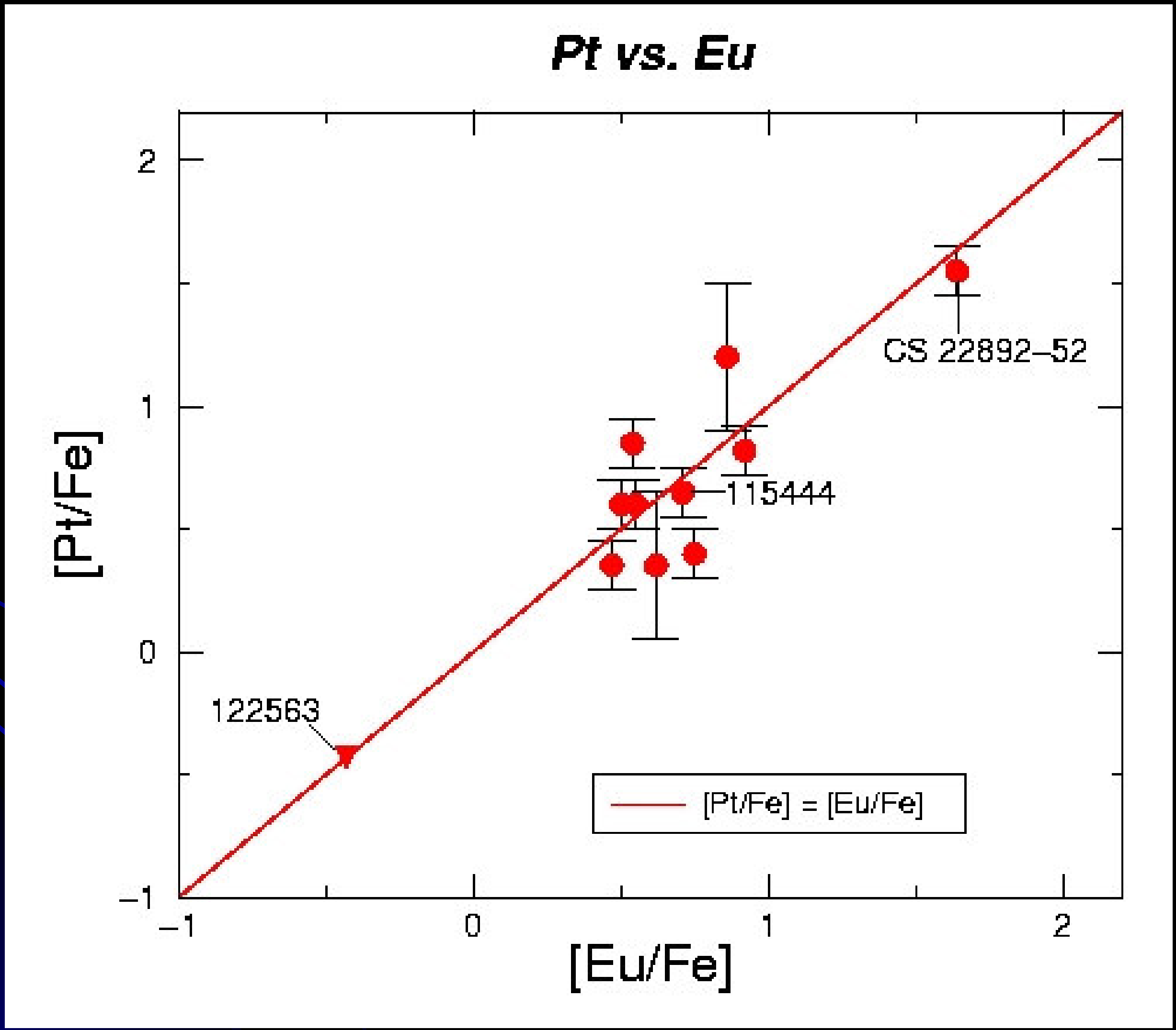
Zr and Eu Abundances in Halo Stars



Zr ∝̸ Eu

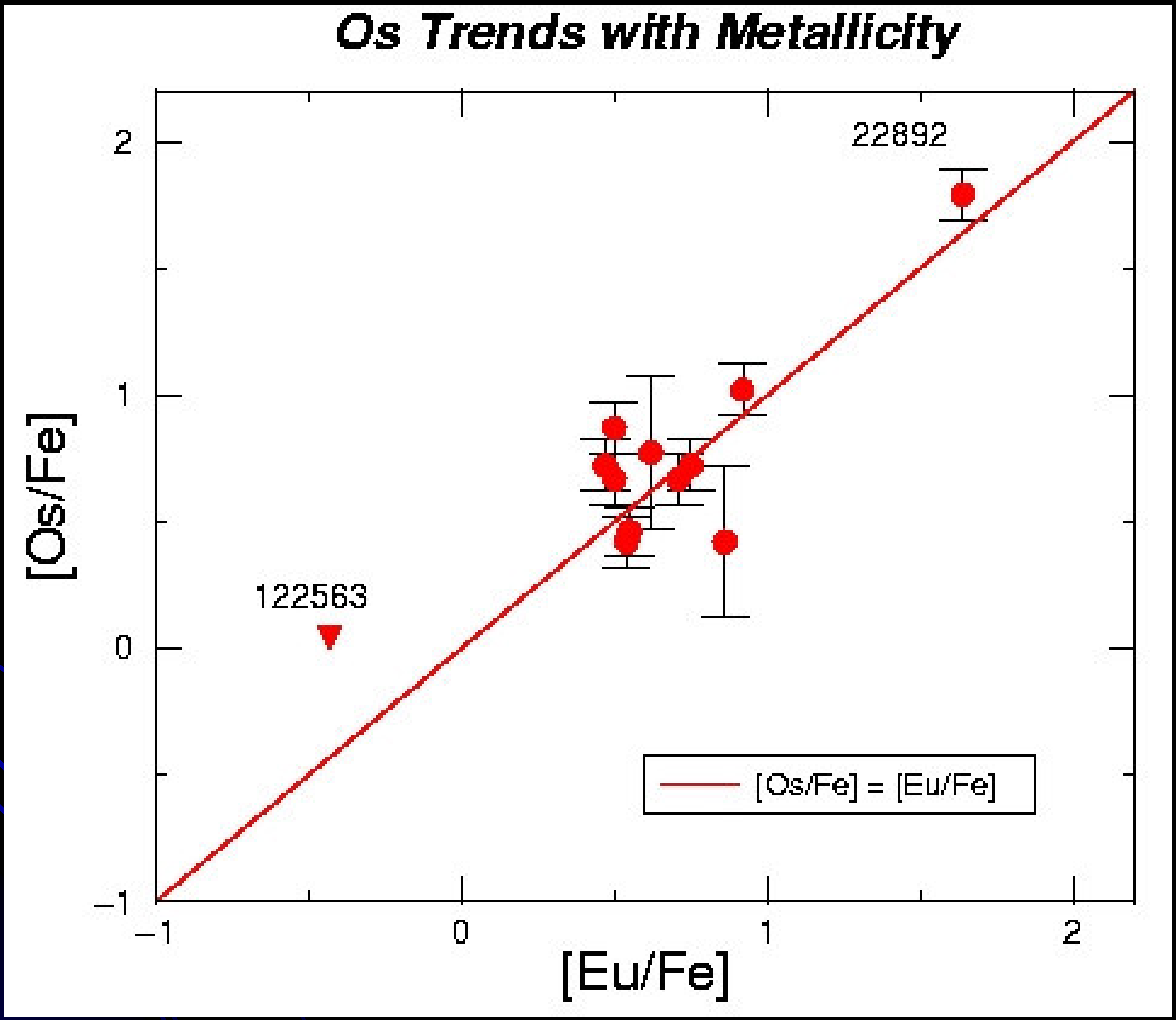
Both n-cap elements but not from same source?

N-Capture Element Correlations



Pt ∝ Eu

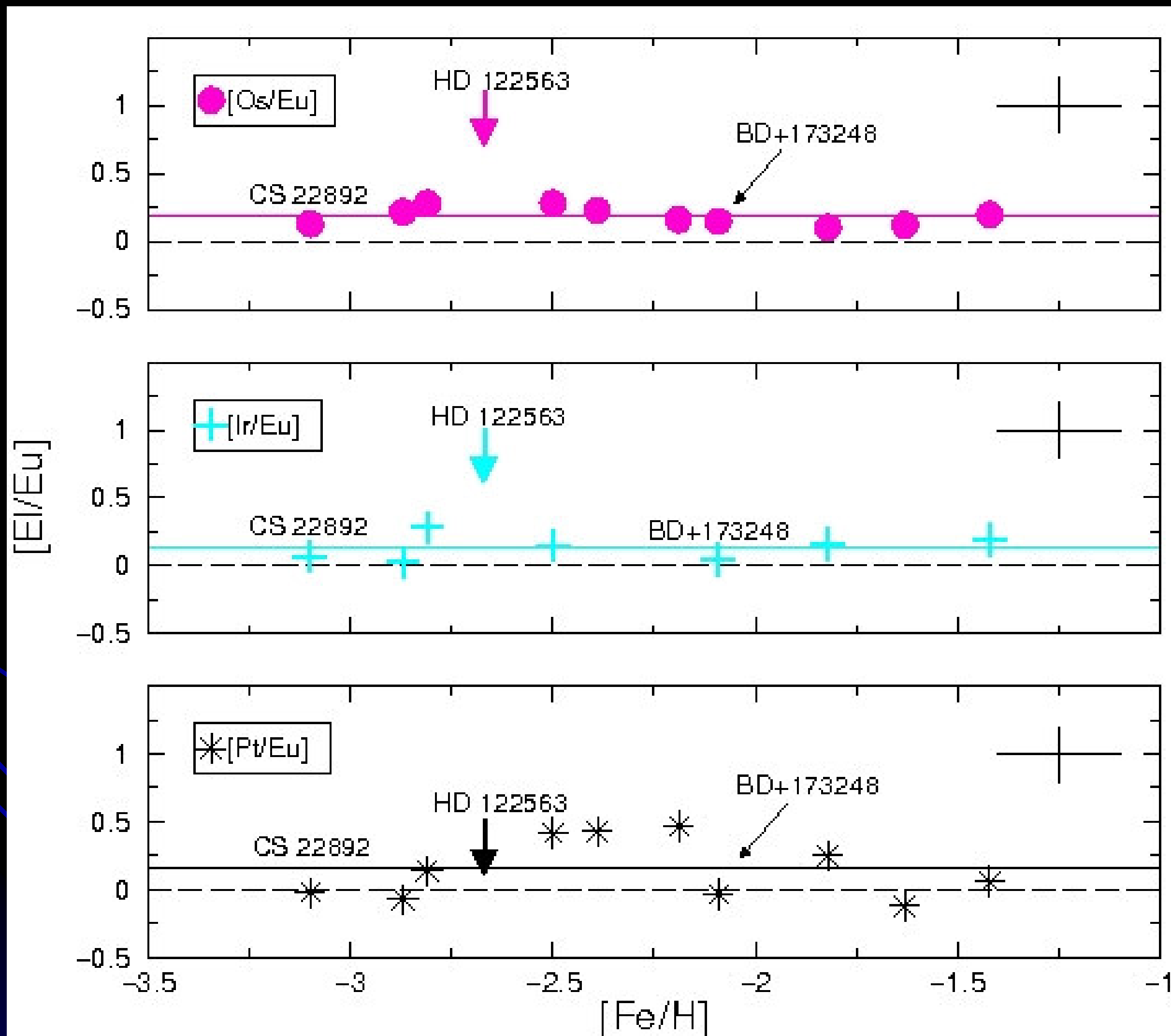
N-Capture Element Correlations



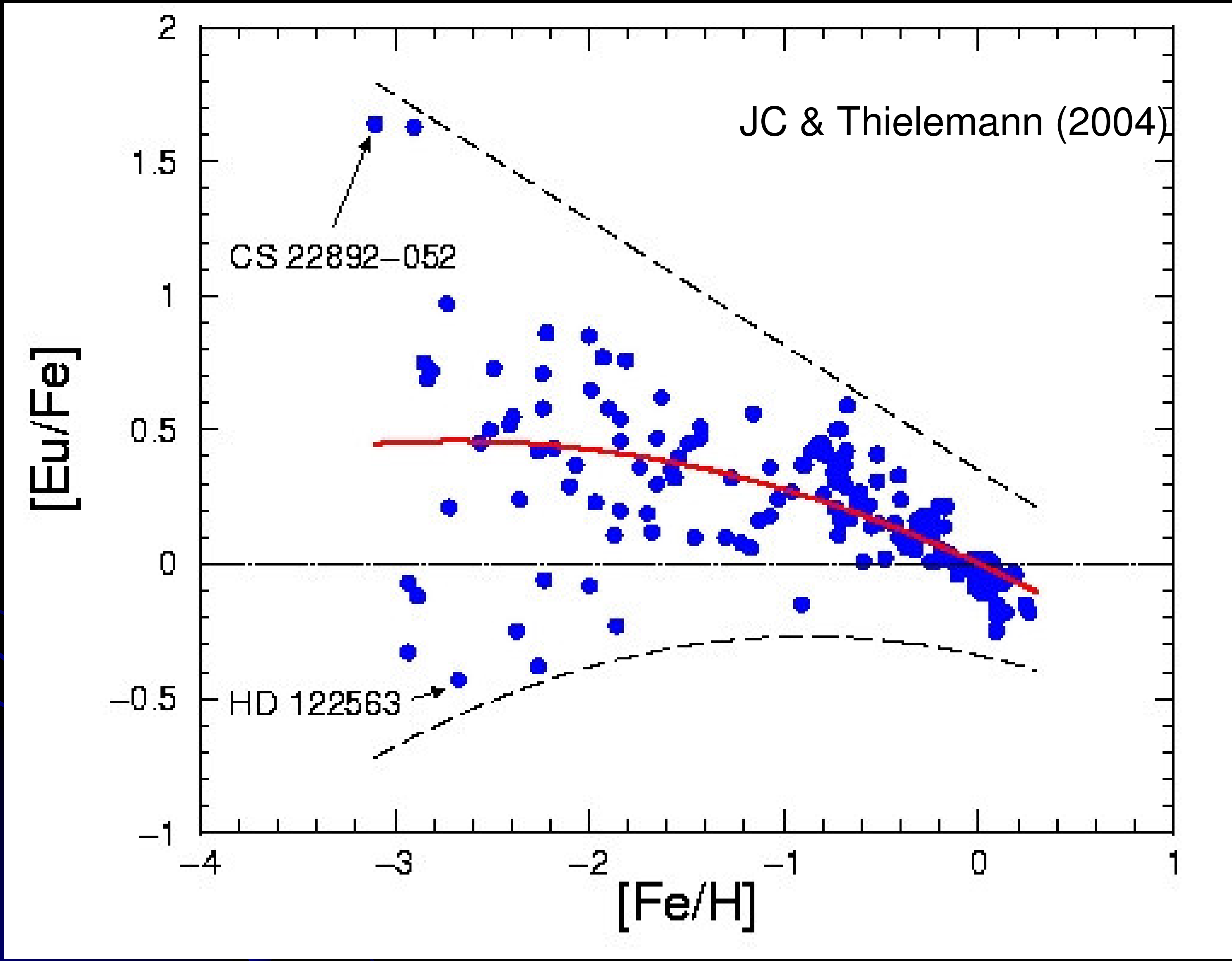
Os ∝ Eu

N-Capture Element Correlations

3rd r-process peak elements correlate with Eu.



Eu Abundance Scatter in the Galaxy



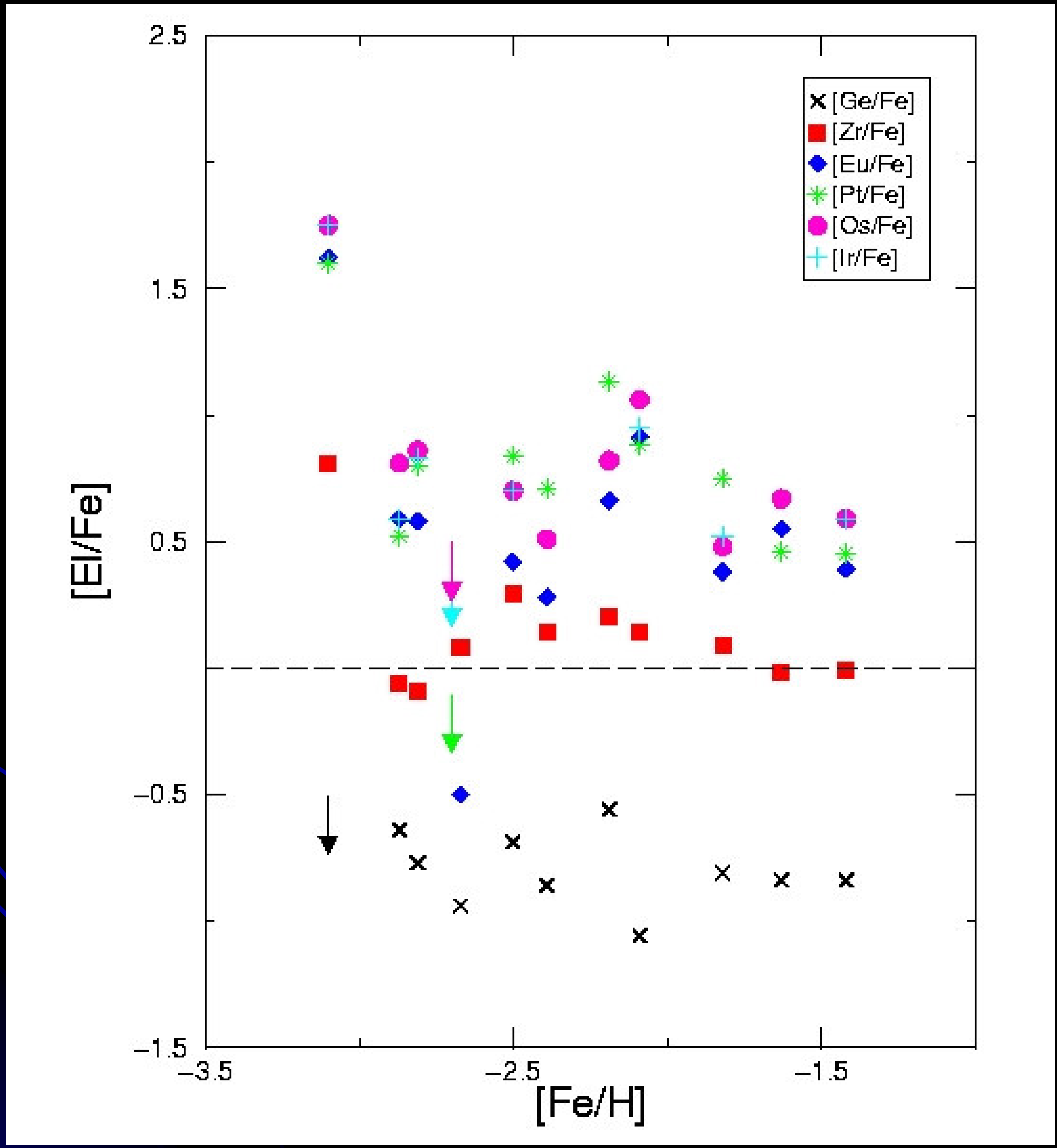
First seen by Gilroy et al. (88). Single SNe at early times?

Early Galaxy chemically inhomogeneous and unmixed.

N-Capture Element Abundance Trends

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

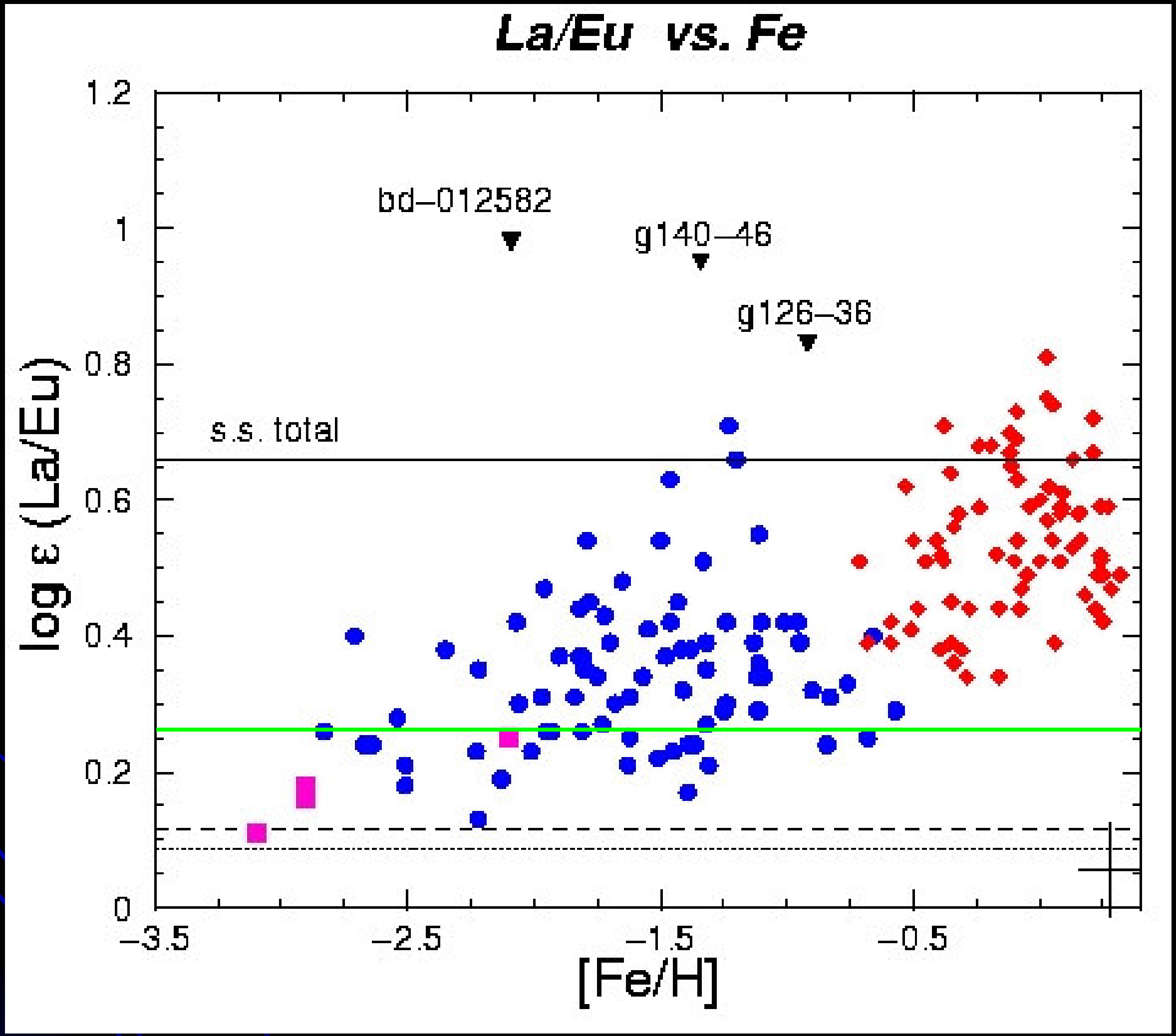
RARE



Ge & Zr show little scatter.

COMMON

R- and S-Process Abundance Trends



Simmerer et al. (2004)

r-process only

O'Brien et al. (2003)

Burris et al. (2000)

Some Concluding thoughts on: Element Synthesis

- Ge, thought of as an n-capture element, appears to be correlated with Fe at low metallicities
- Zr (like Sr & Y) complicated:
  - not correlated with metallicity or with heavier n-capture element abundances
  - not same origin as Eu, some primary (Travaglio et al. 2004)
- Element abundances from Z = 40-50 may be uniform in r-process rich stars, but below upper end
- Os,Ir,Pt correlated with Eu abundances

Some Concluding thoughts on: Nucleosynthesis Early in the Galaxy

- R-process elements observed in very metal-poor 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

Some Concluding Thoughts on: Abundance Trends in the Galaxy

- New Os-Pt abundance values show same scatter as [Eu/Fe] at low metallicity
- New La/Eu ratios more reliable than Ba/Eu:
  1. Show scatter
  2. Only most metal-poor stars show r-process only ratio
  3. Stresses importance of nuclear measurement
  4. Some "dusting" of s-process even at [Fe/H] < -2 ?

Challenges and New Directions

- R-process rich vs. r-process poor. Is the abundance pattern the same?
- What about Ge? How do you make it at very low [Fe/H]? α-rich process?
- How to make Zr? Several processes?
- Is the lighter n-capture pattern the same in all of the halo stars? Nuclear effect or 2 r-processes?
- What about Th & U in CS 31082-01? Actinide boost or fission recycling? How to explain the Pb abundance? How many more like it?