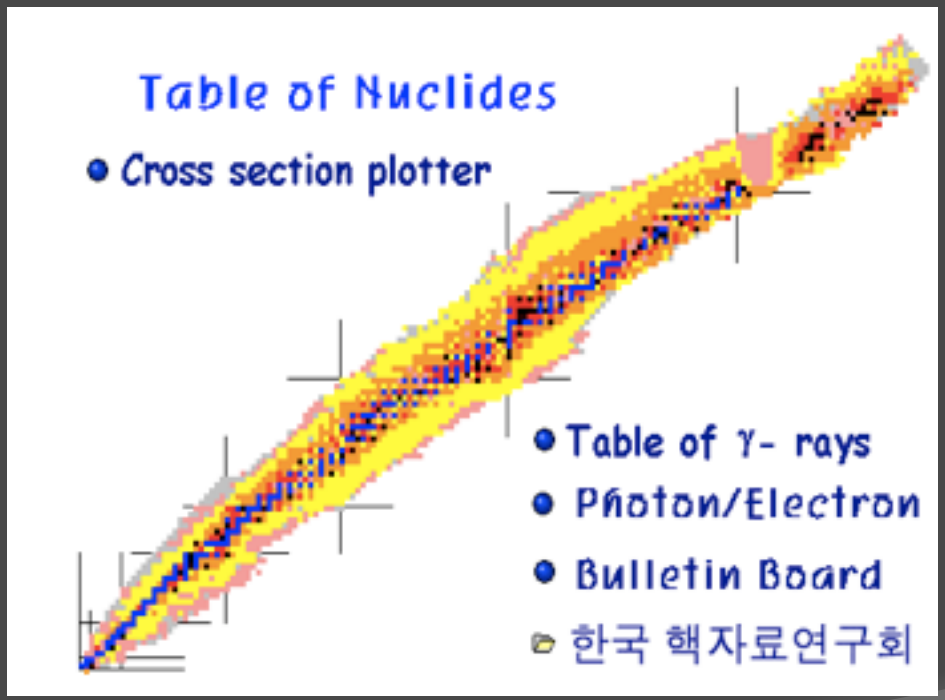
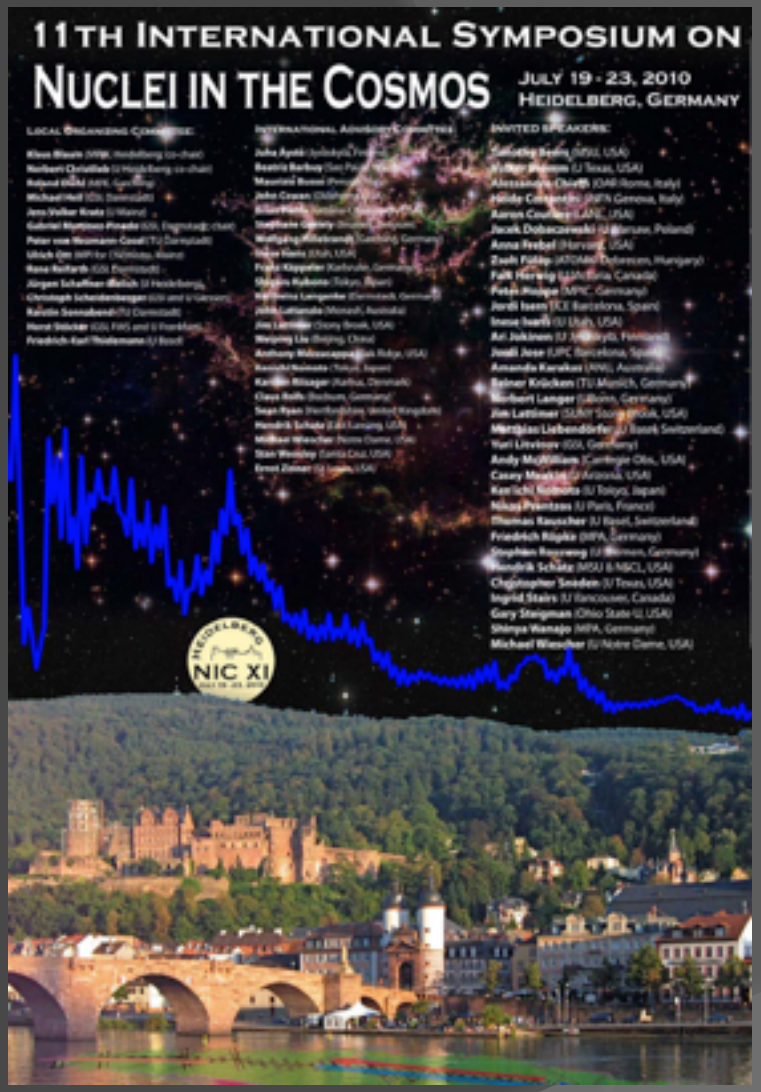
r-Process Enhanced Metal-Poor Stars





Chris Sneden
University of Texas, Austin

Outline

- r-process-rich stars: easy to find (sort-of)
- patterns in some element groups known in detail
- discovery of radioactive thorium and uranium
- deeper exploration of r-process limits, but how?
- gaps in Periodic Table coverage
- new work on n-capture light/heavy abundance ratios
- something old, much new

thanks to all my collaborators

- John Cowan
- Jim Truran
- Scott Burles
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- Inese Ivans
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- Angela Bragaglia
- Norbert Christlieb
- Beatriz Barbuy
- Anna Marino
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- Jennifer Johnson
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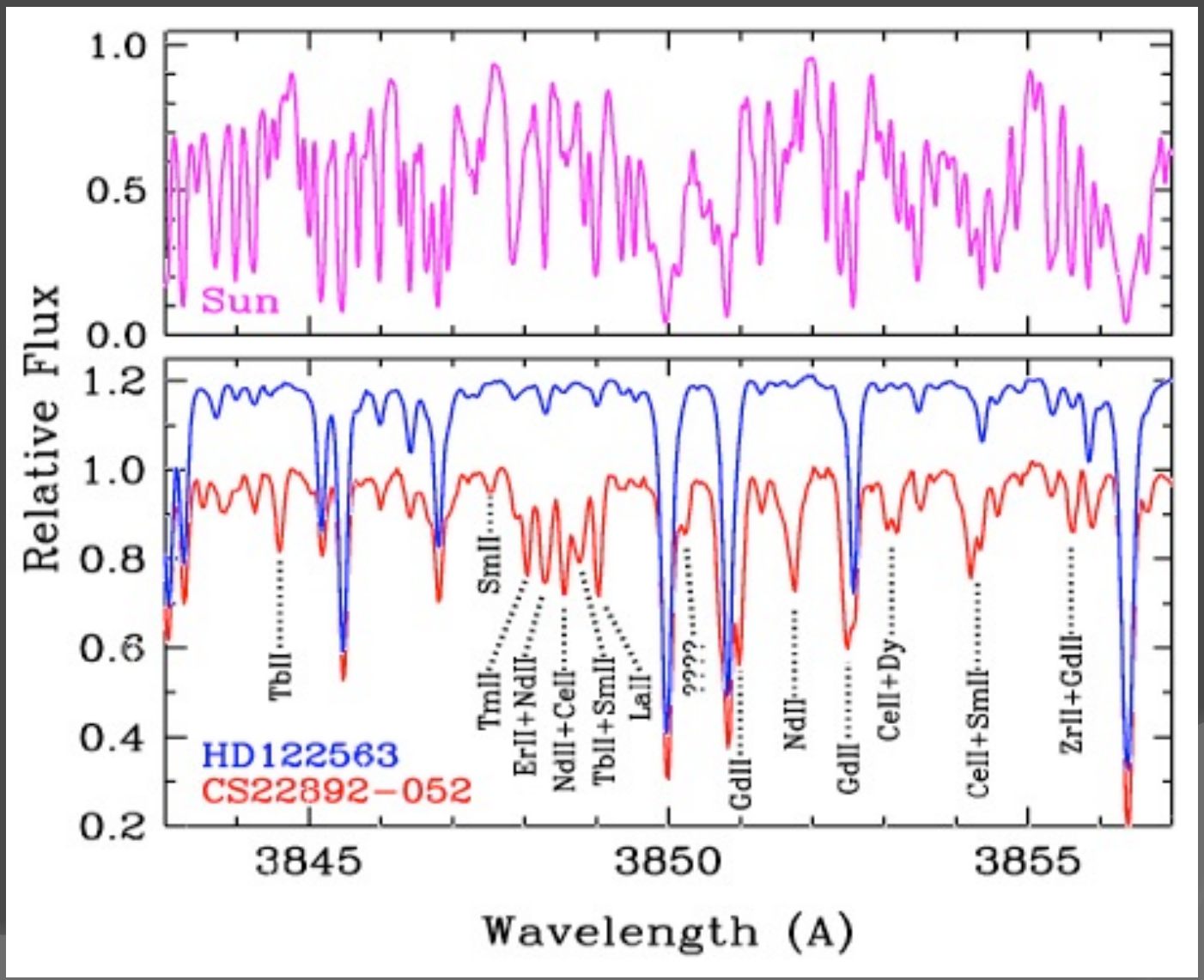
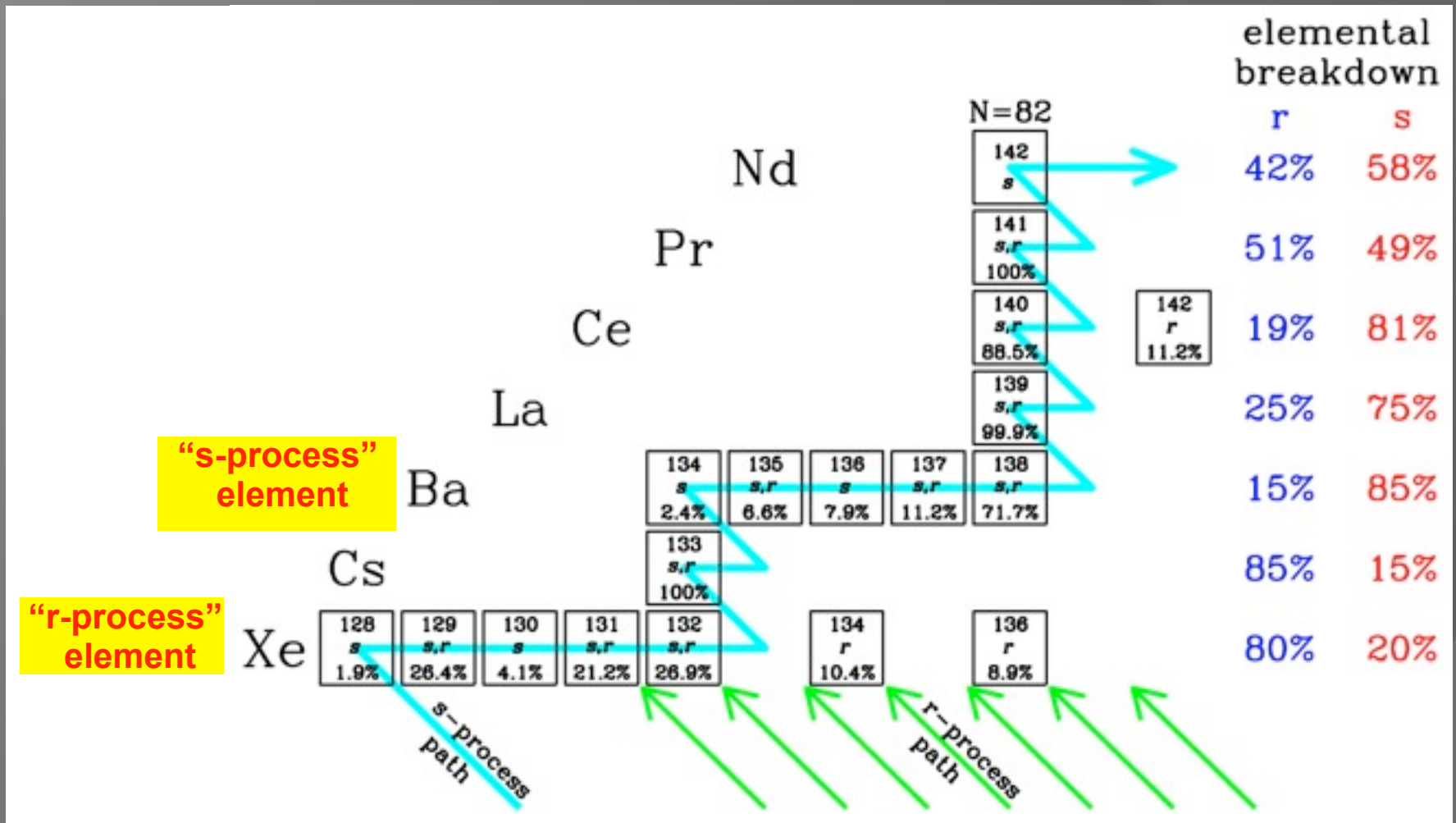
- Bernd Pfeiffer
- Eugenio Carretta
- Karl-Ludwig Kratz
- Francesca Primas
- Sara Lucatello
- Taft Armandroff
- Andy McWilliam
- Roberto Gallino
- Evan Kirby
- Vanessa Hill
- Ian Roederer
- Christian Johnson
- Sloane Simmons
- Valentina D'Orazi
- Ian Thompson
- Patrick Francois

$$[A/B] = \log_{10}(N_A/N_B)_{star} - \log_{10}(N_A/N_B)_{Sun}$$
$$\log \varepsilon(A) = \log_{10}(N_A/N_H) + 12.0$$
$$\log N_{Si}(A) = \log_{10}(N_A/N_{Si}) + 12.0$$

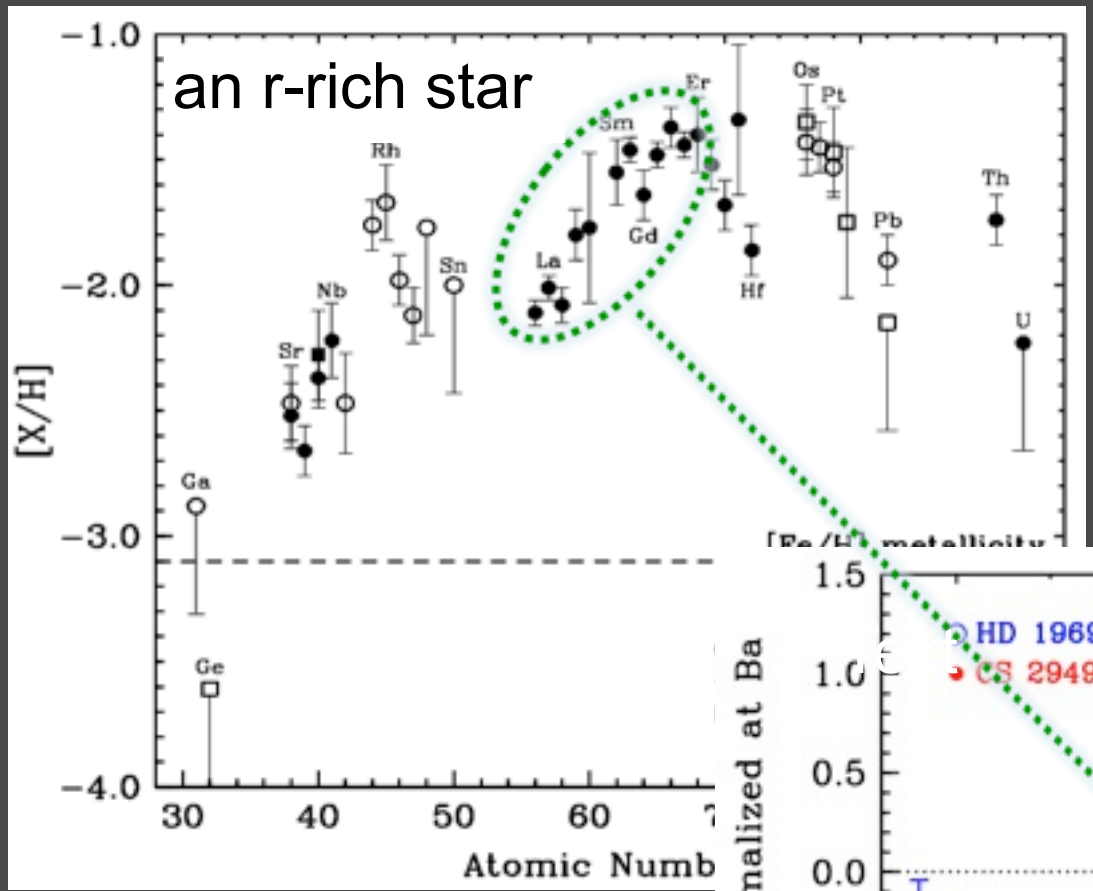
r-process-rich metal-poor stars: candy shop for spectroscopists



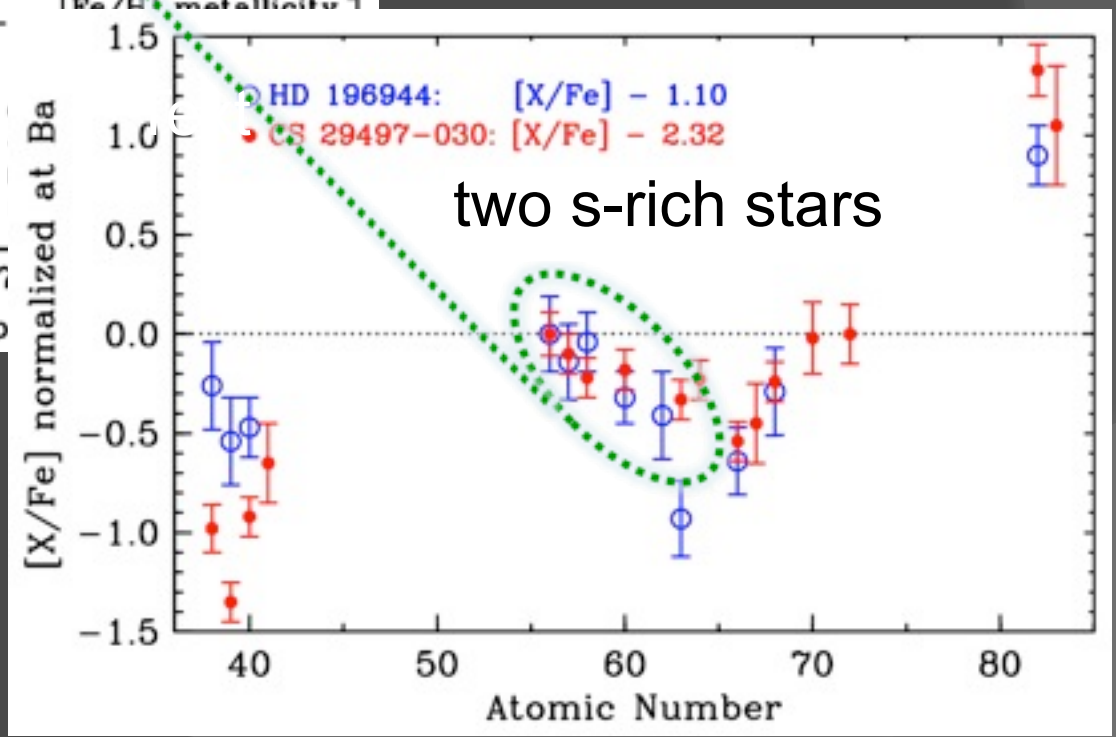
detailed look at r- and s-process paths



Sneden, Cowan, & Gallino 2008



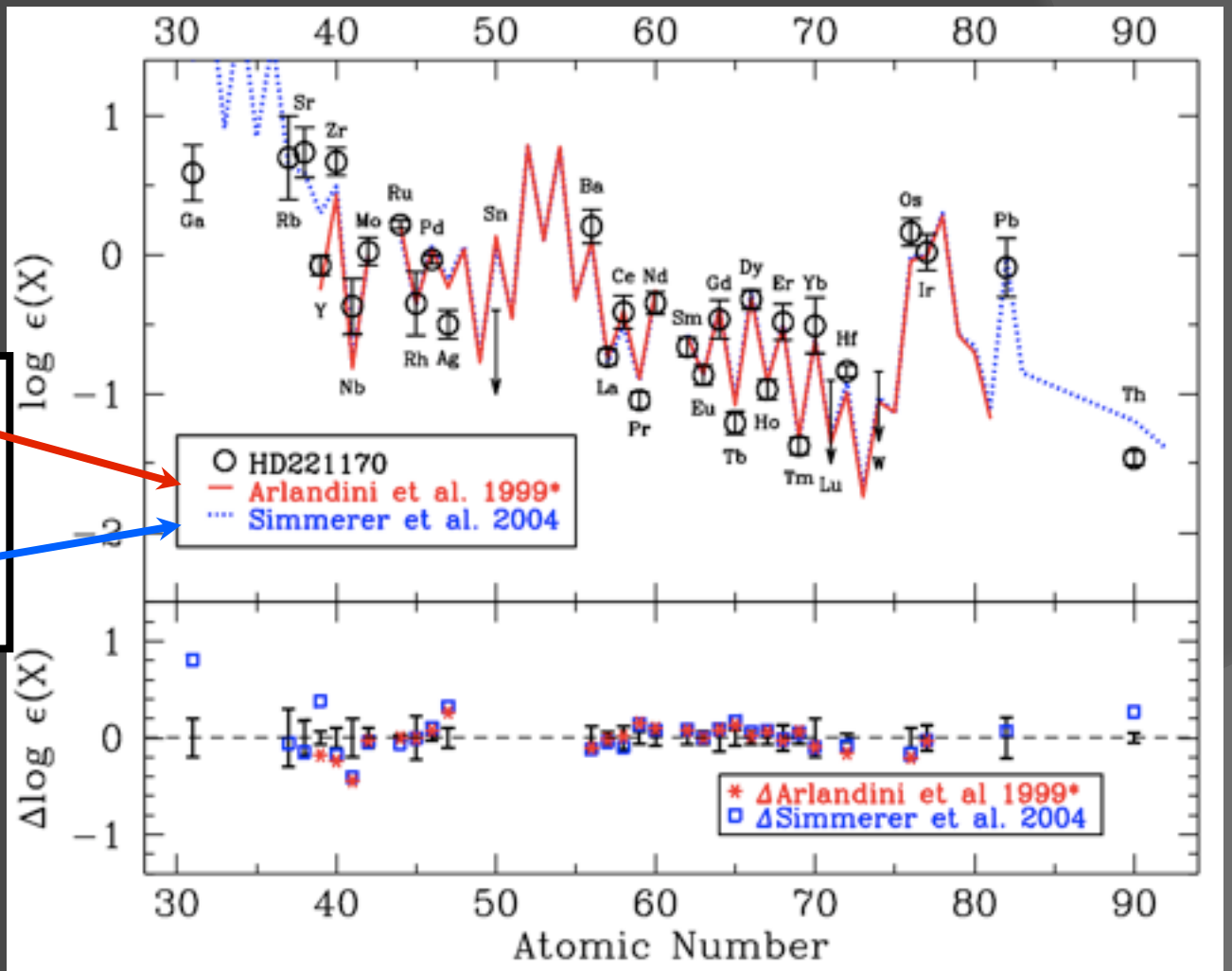
happily, the patterns are very different in r-rich and s-rich low metallicity stars



with good abundances, r-process predictions can be really confronted

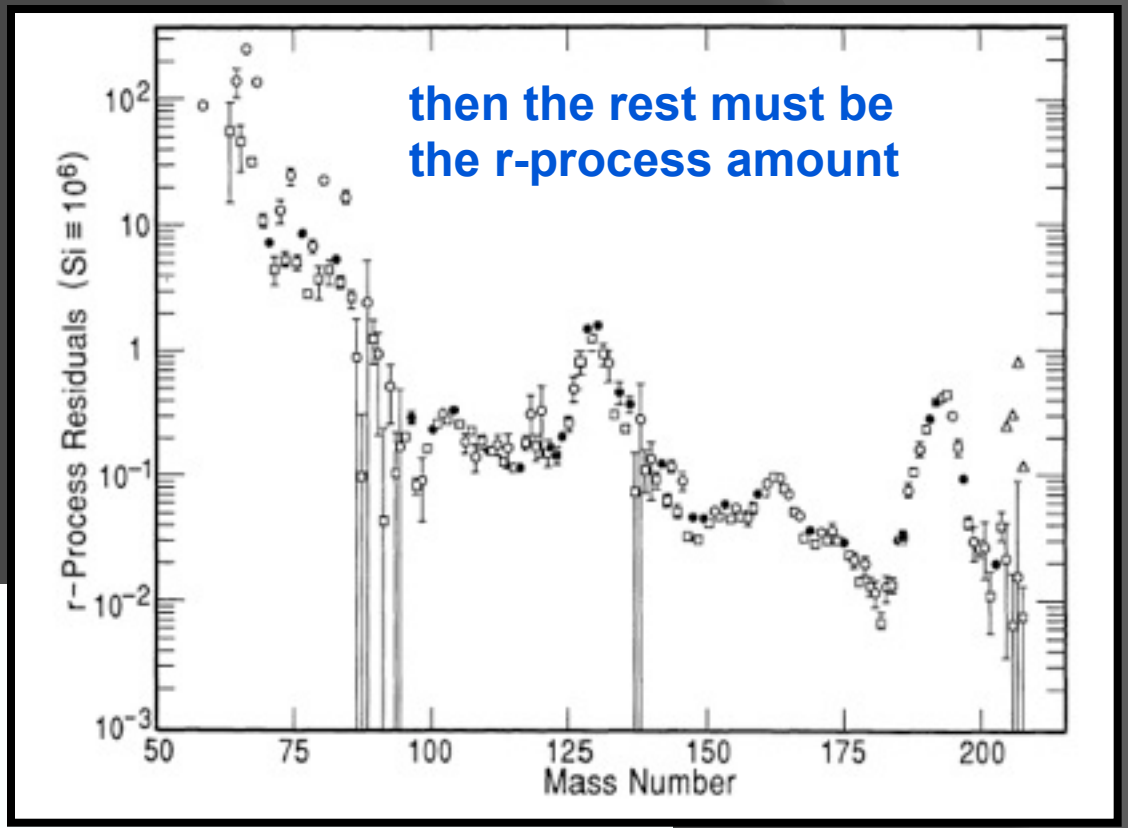
AGB model s-process prediction

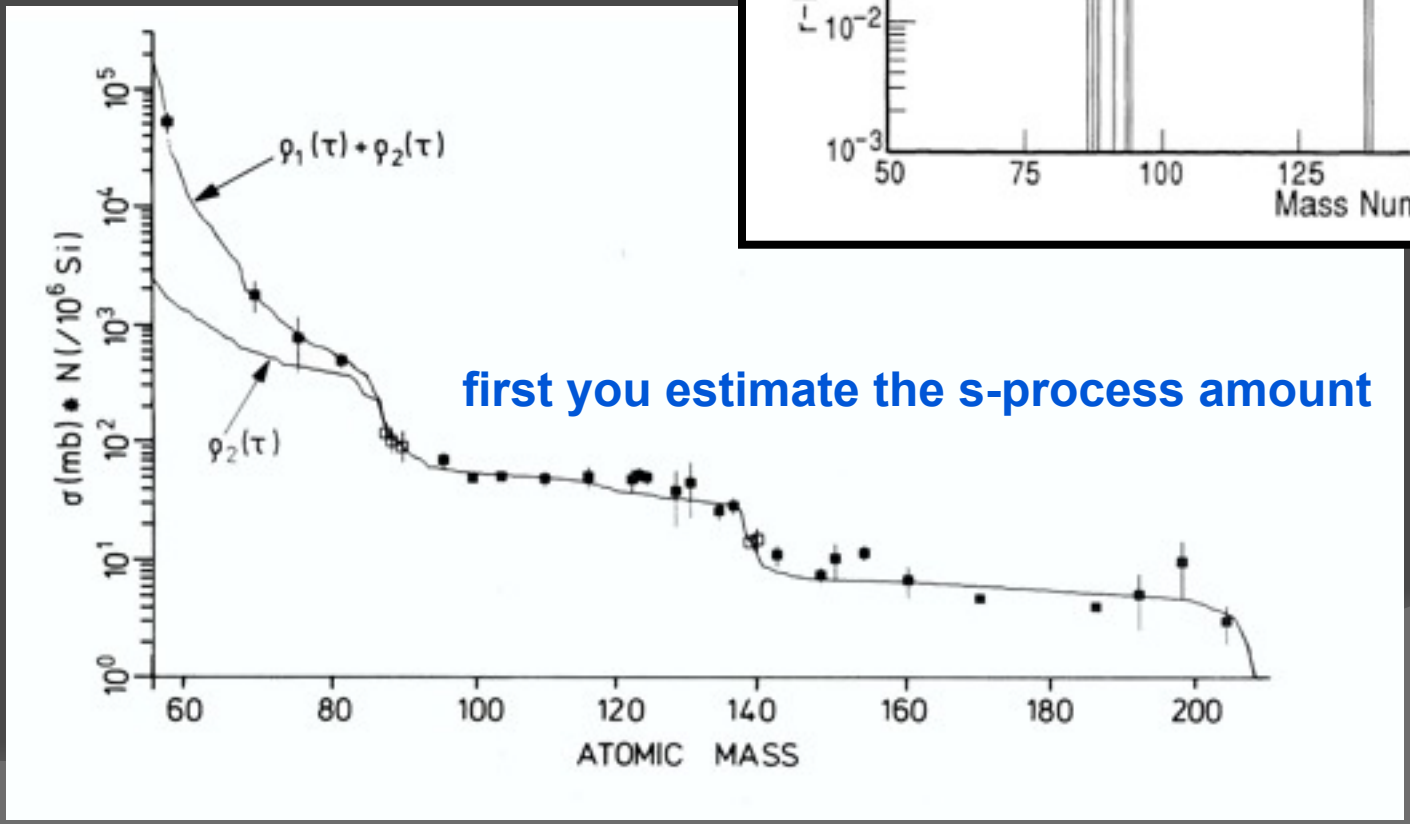
Empirical s-process estimation



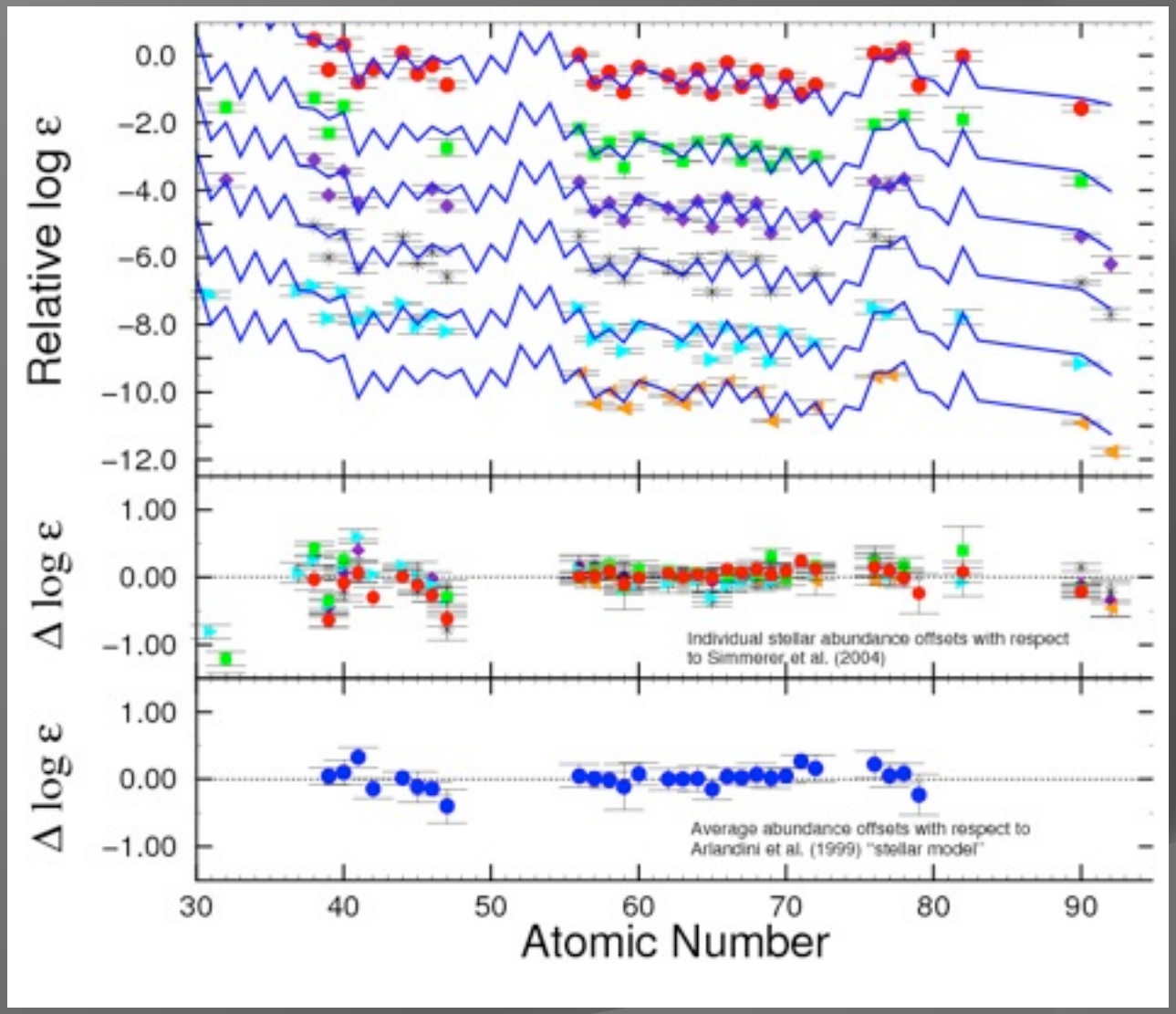
Ivans et al. 2006

But for too long we have relied on inferred r-process solar-system abundances





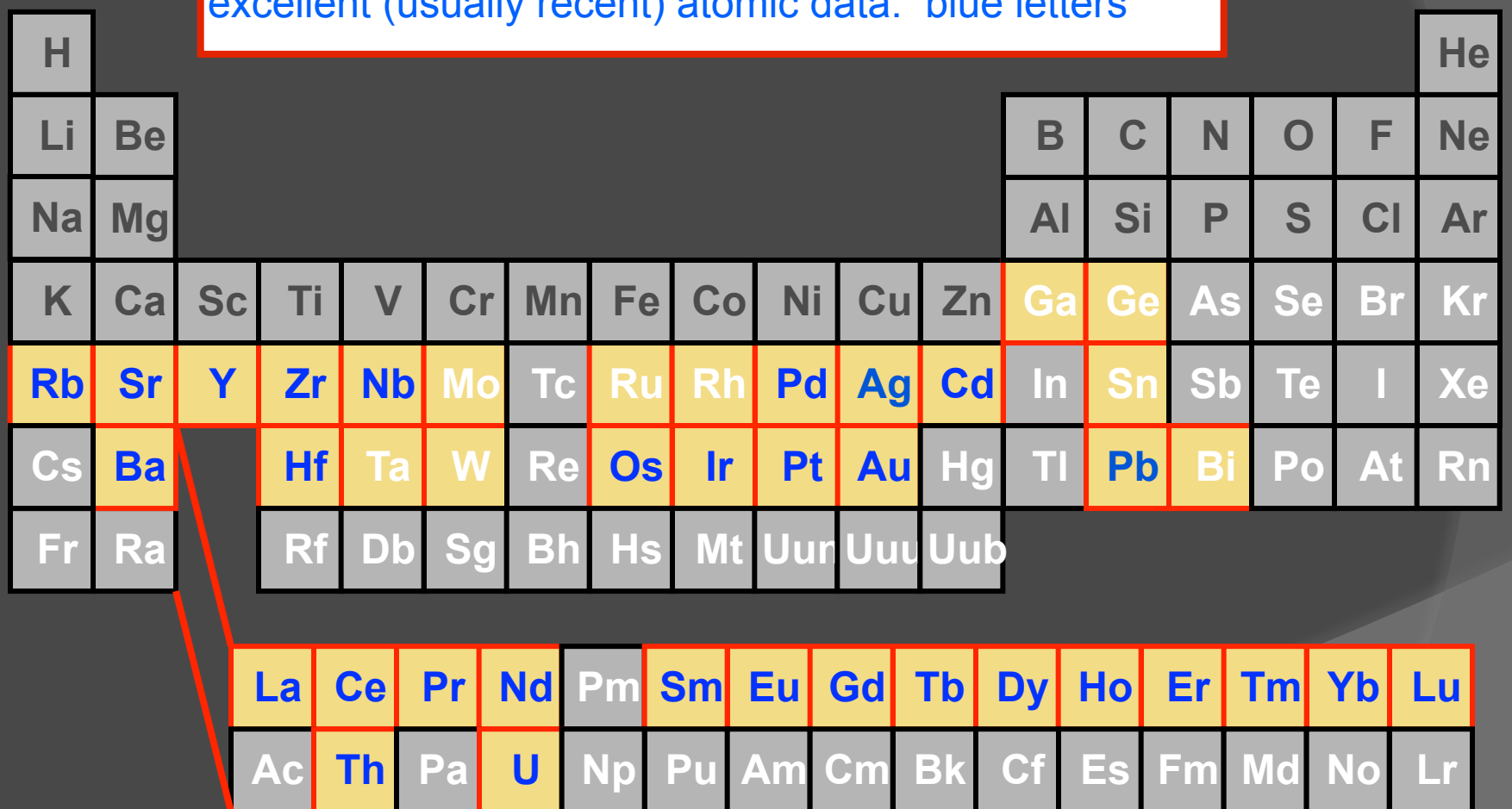
n-capture compositions of well-studied r-rich stars: Così fan tutte??



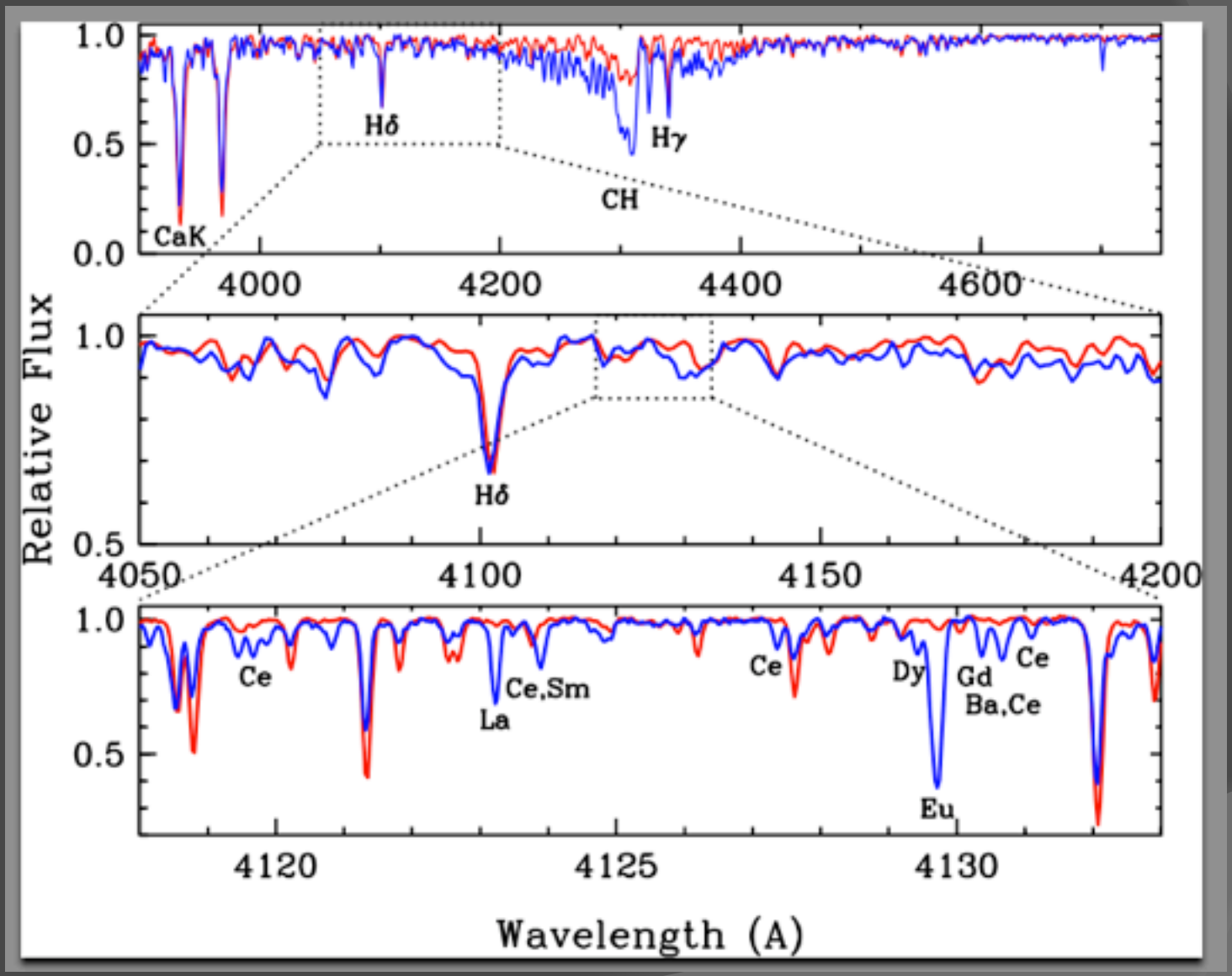
Sneden, Cowan & Gallino 2008

the unsung heroes are the lab atomic physicists: Lund, Liege, Wisconsin, ...

light element: black letters
undetectable n-capture elements: white letters
excellent (usually recent) atomic data: blue letters



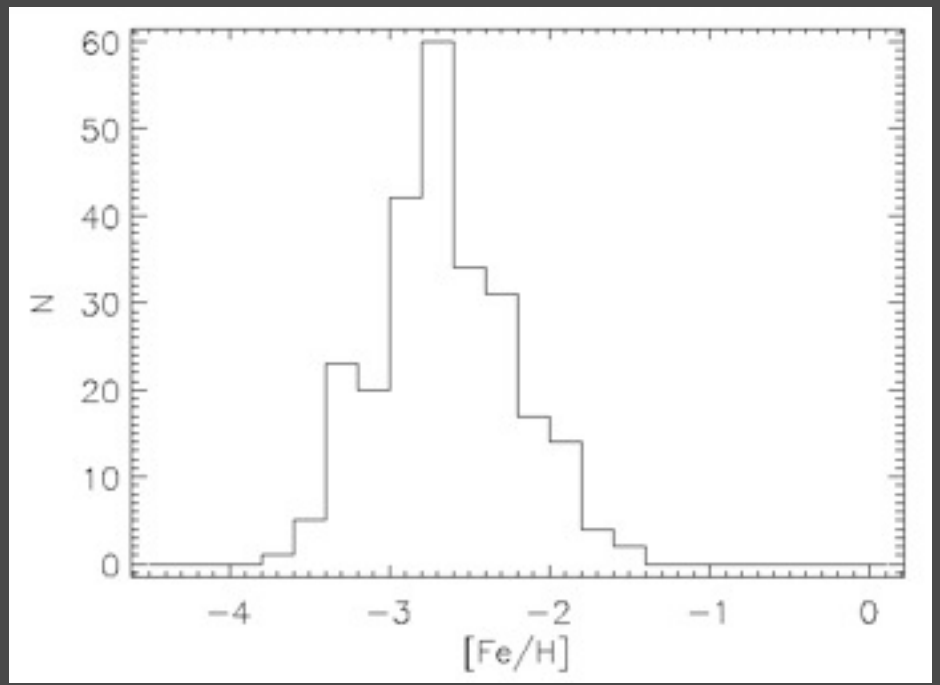
r-process-rich stars are not trivial to find

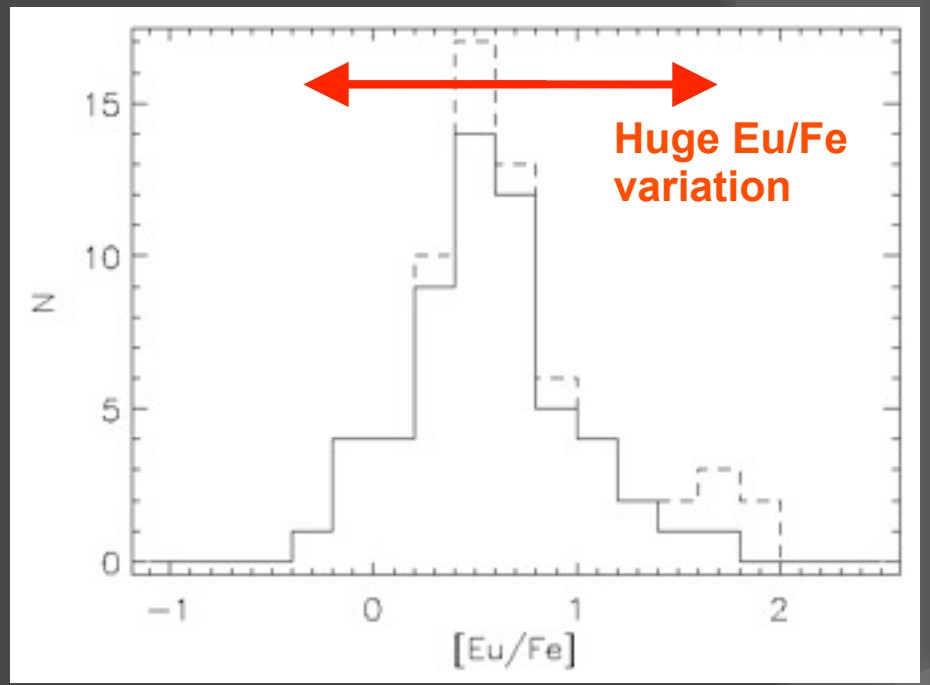


Sneden, Cowan & Gallino 2008

Hamburg-ESO (HES) r-process survey: an important addition to the statistics

Here are the distributions

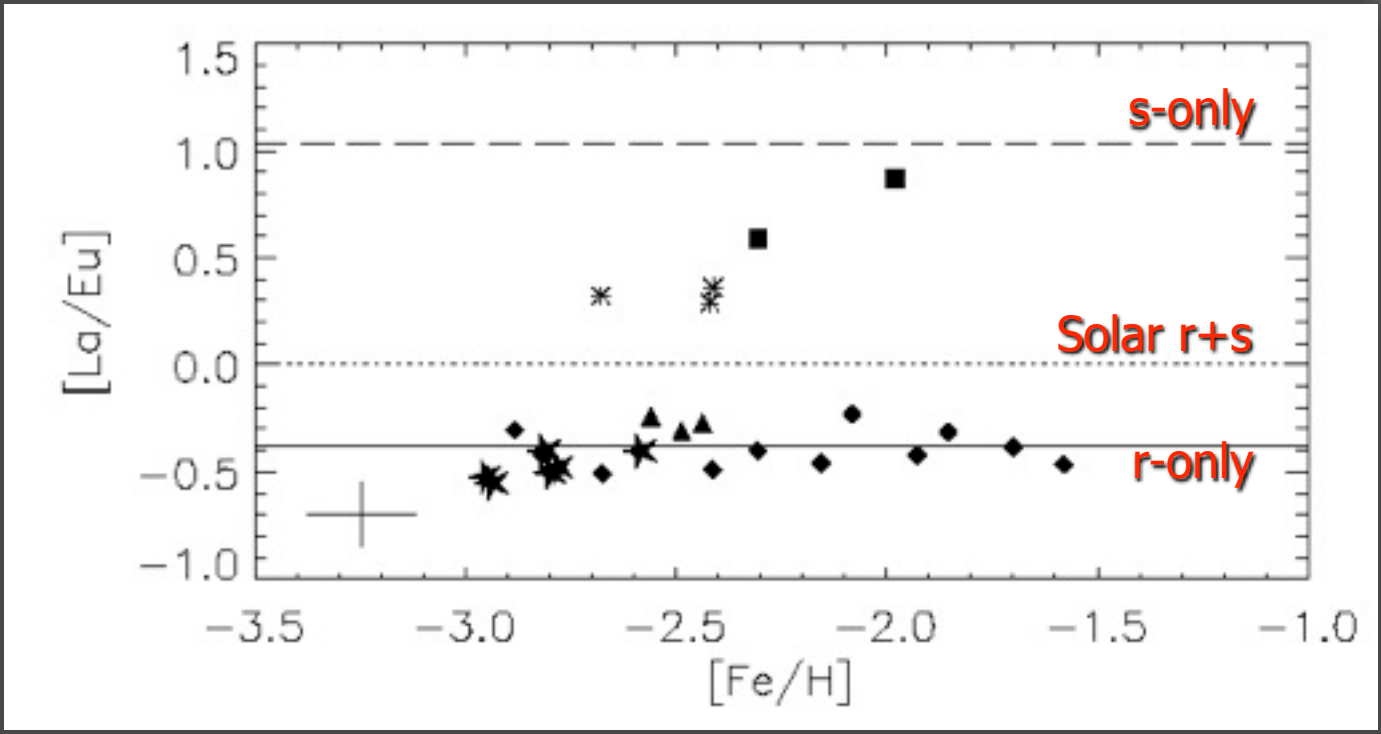


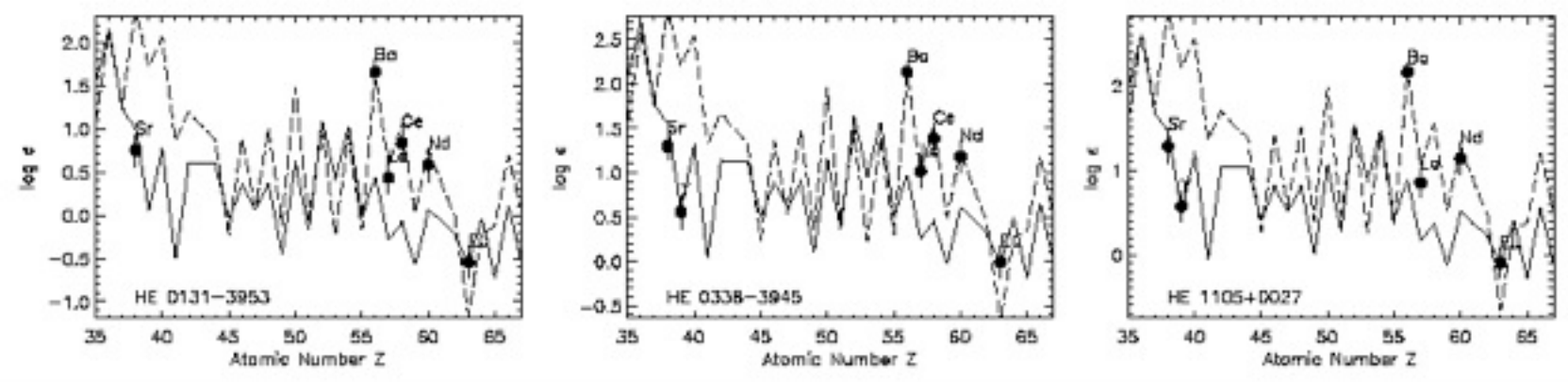


- 253-star "snapshot" detailed survey (R ~ 20,000, S/N ~ 50)
- small number of n-capture elements; approximate abundances
- stars with very strong CH bands discarded from sample (for now)
- 8 new stars with [Eu/Fe]>+1.0 and 35 more with [Eu/Fe]>+0.3

Barklem et al. 2005

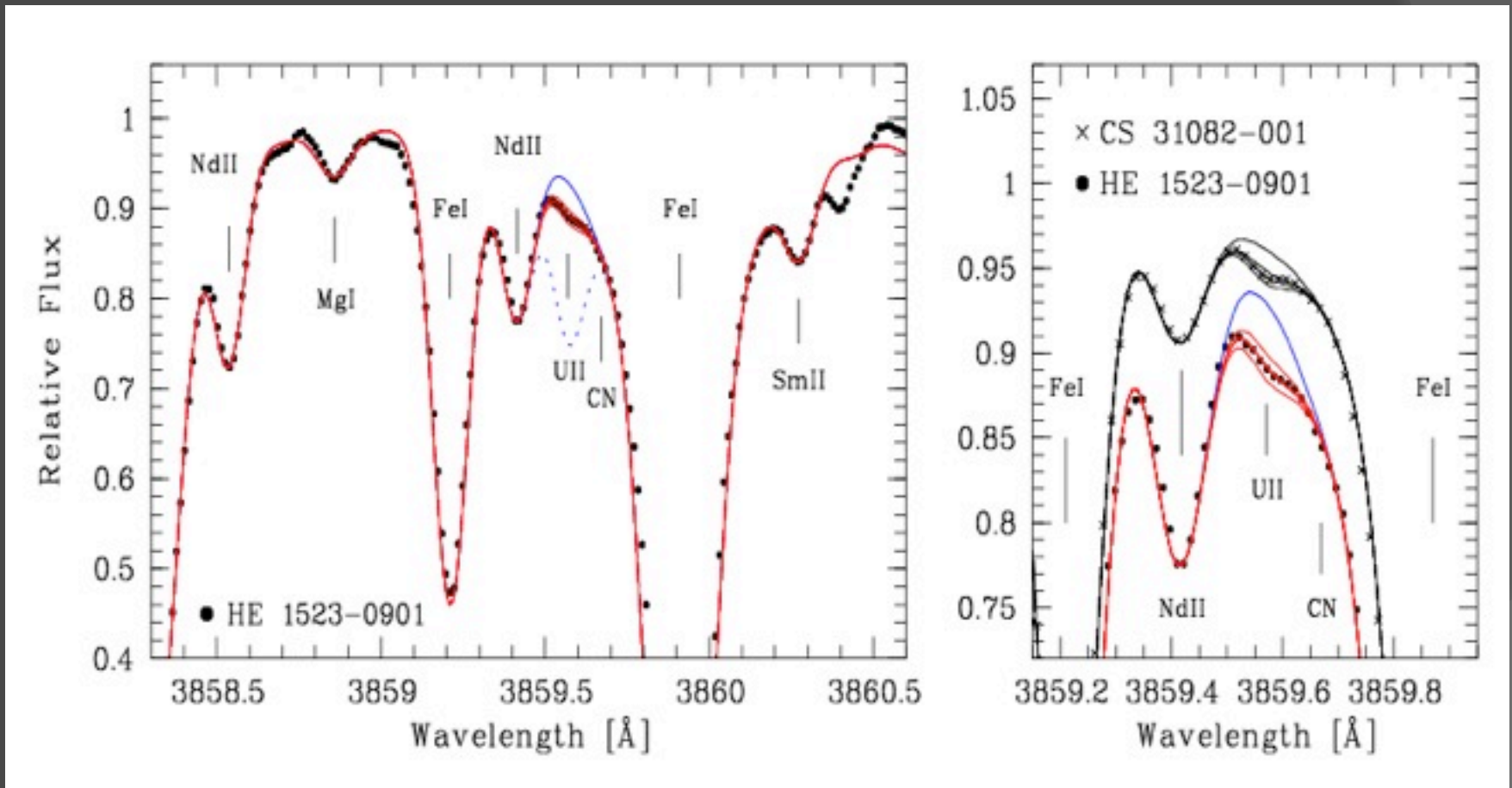
HES: mostly "r-rich" stars; a few "s" ones





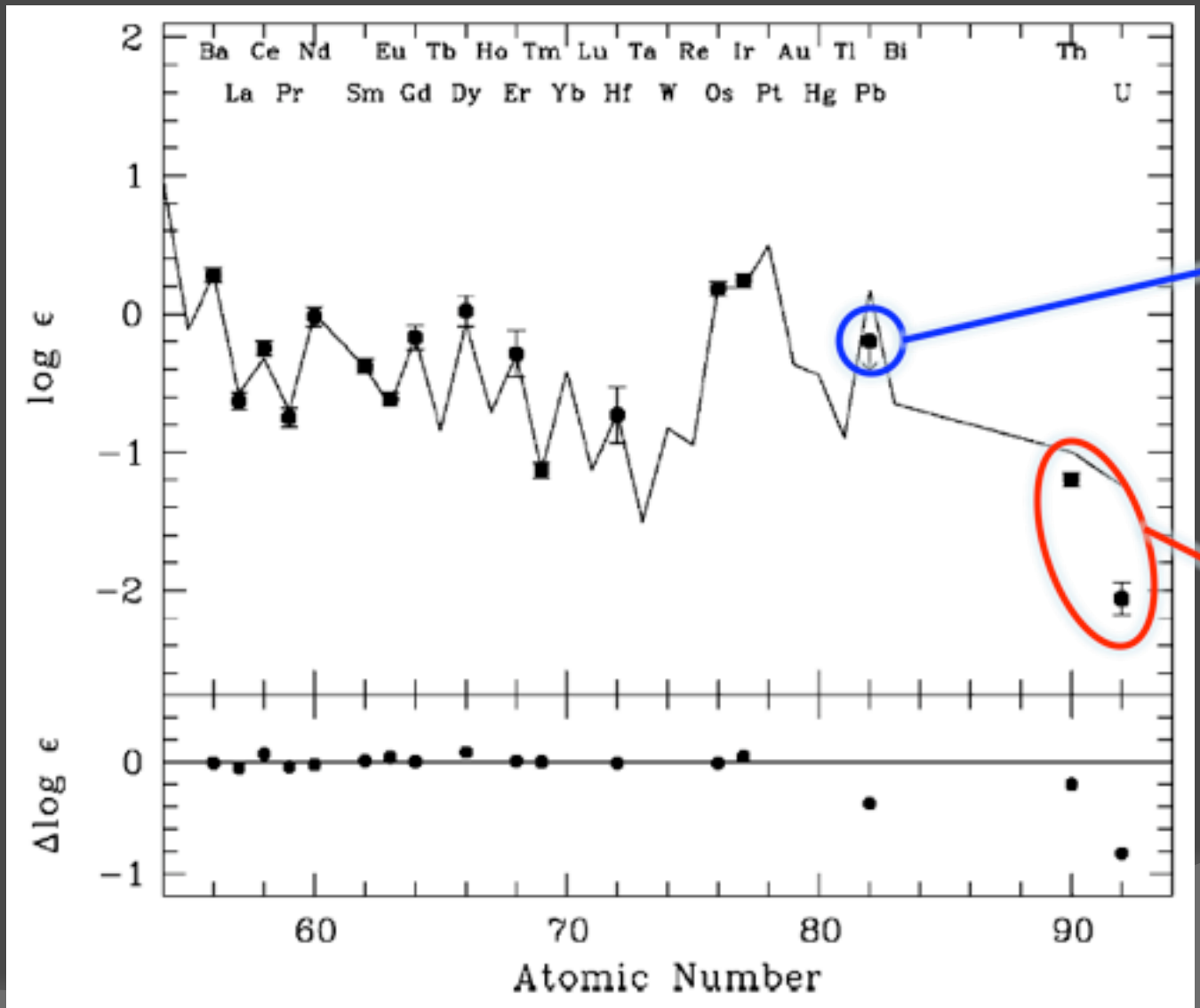
Barklem et al. 2005; dashed lines are scaled solar-system s-only abundances

Thorium/Uranium detections promise alternate Galactic ages



Frebel et al. 2007

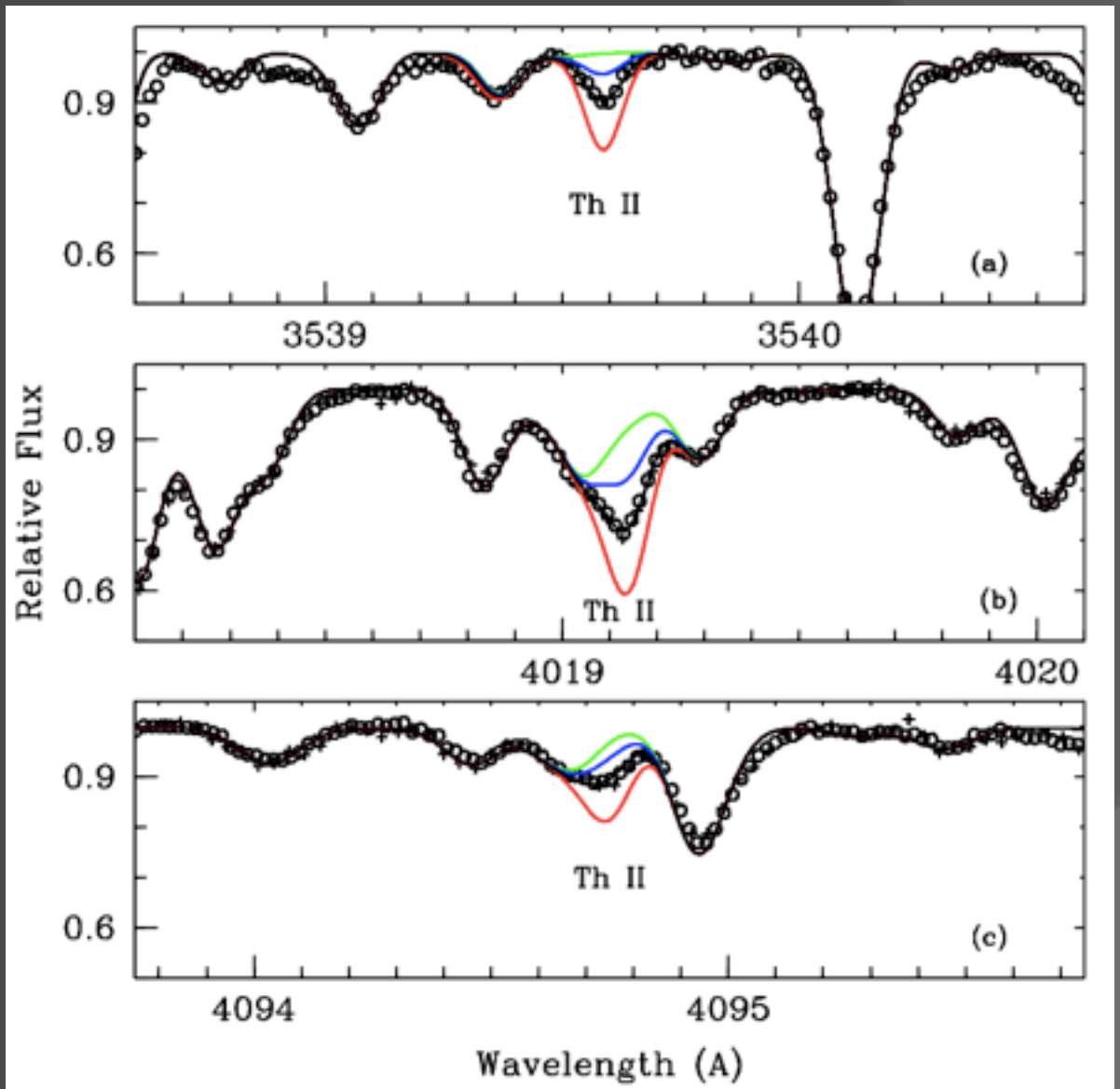
leading to possible radioactive "ages"



Persistent question: why is Pb usually so low?

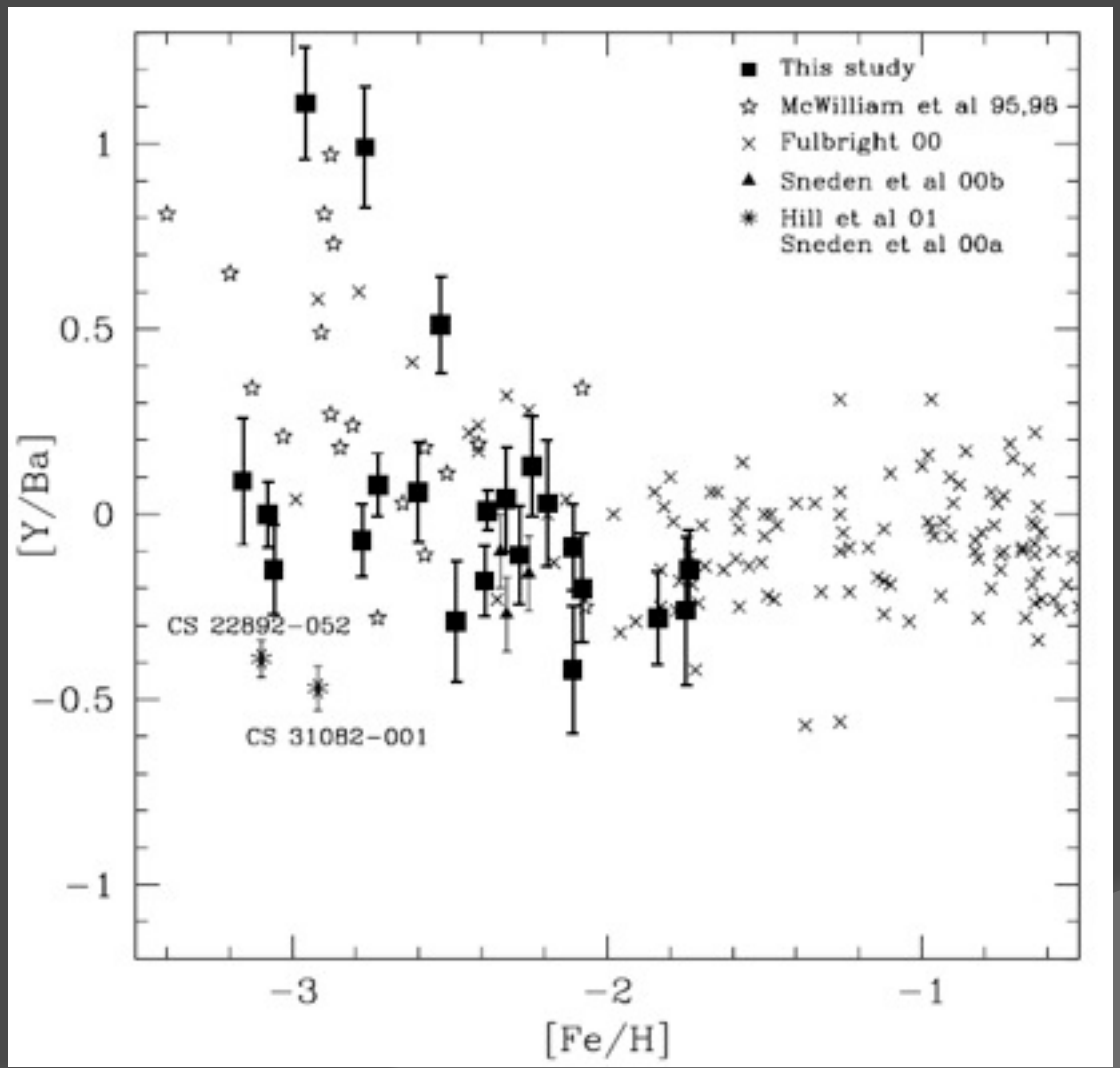
U/Th ratio should be best age indicator, if both elements can be detected reliably

BUT, critical element thorium is a struggle even in the best cases



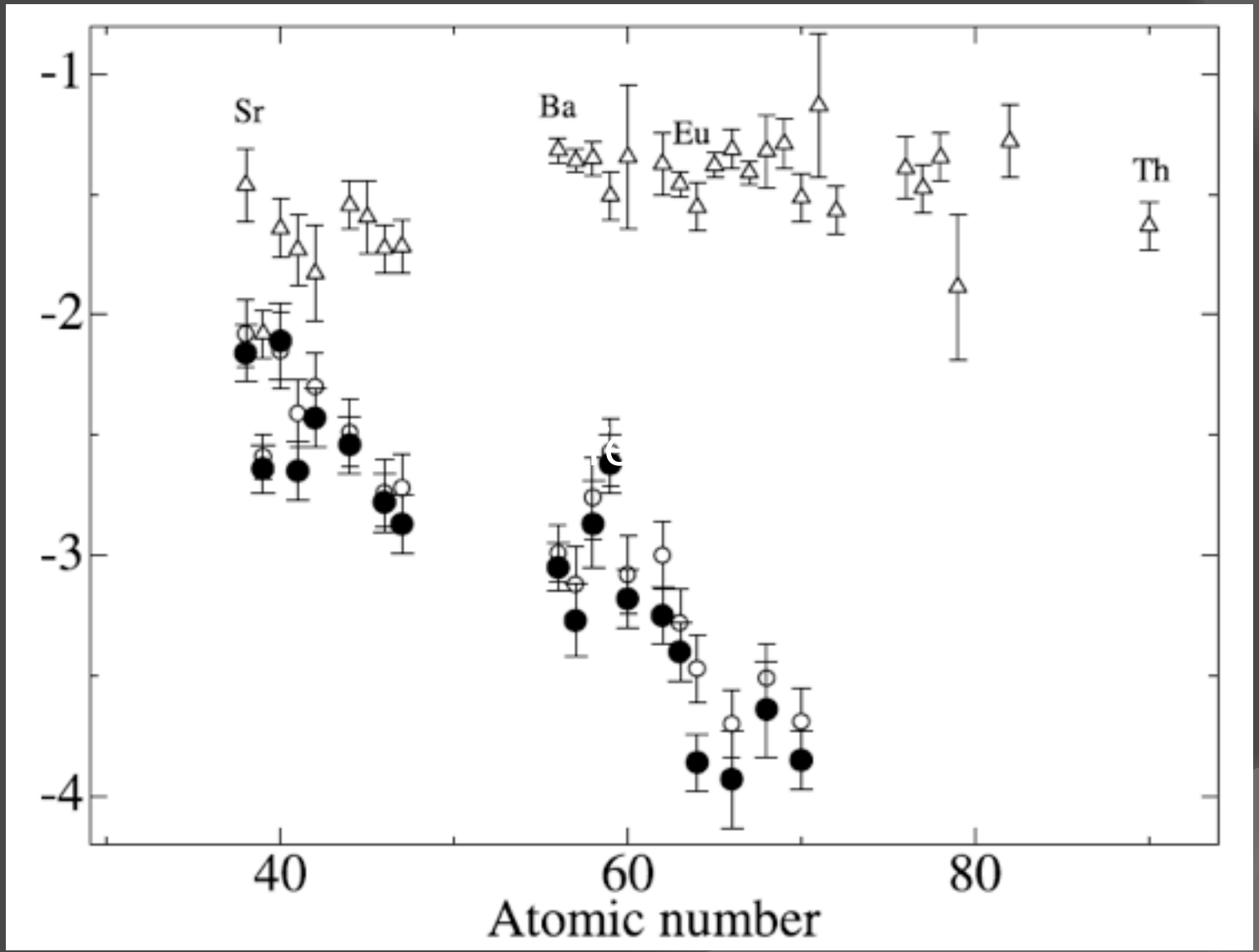
Ivans et al. 2006

Beyond simplest r-process results: de-coupling of the heavy/light elements



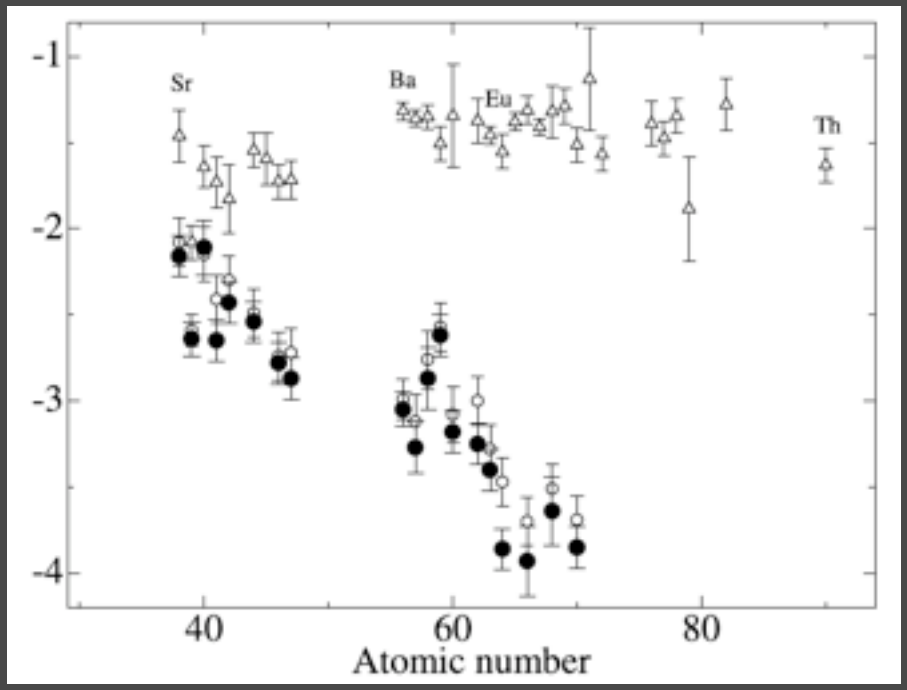
Johnson & Bolte 2002

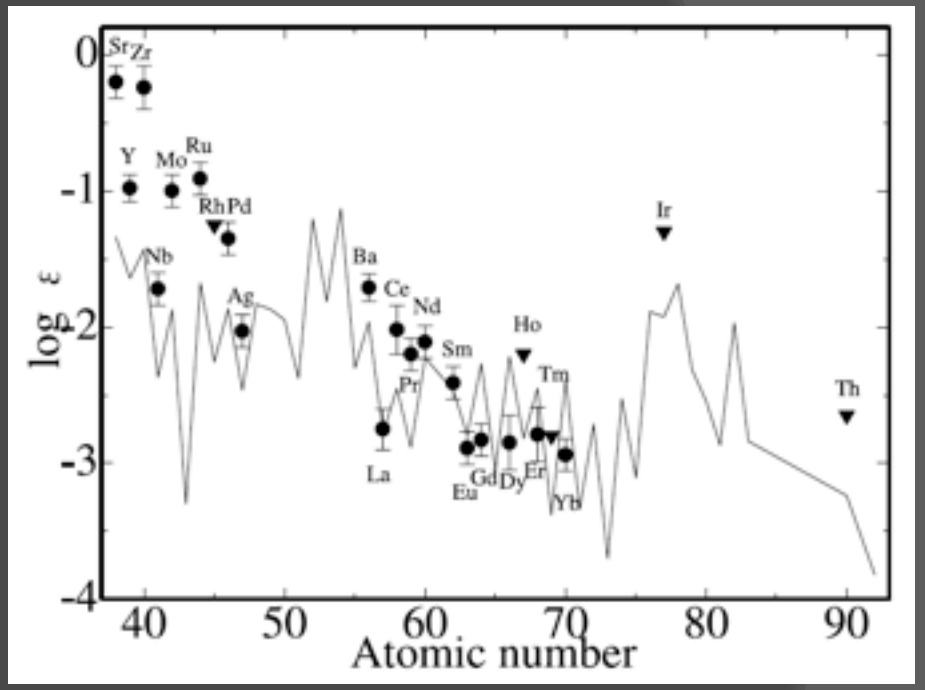
significant step forward: light vs heavy



Honda et al. 2007

But not (maybe) signaling an s-process

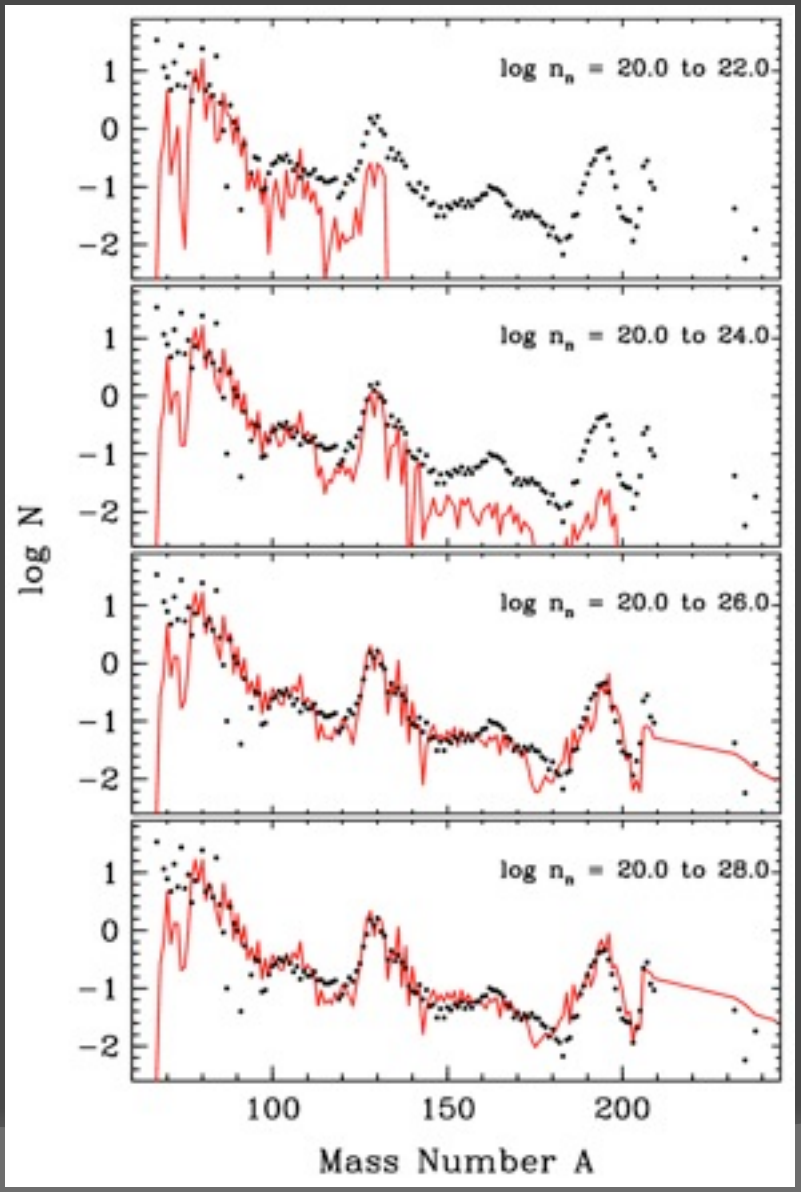


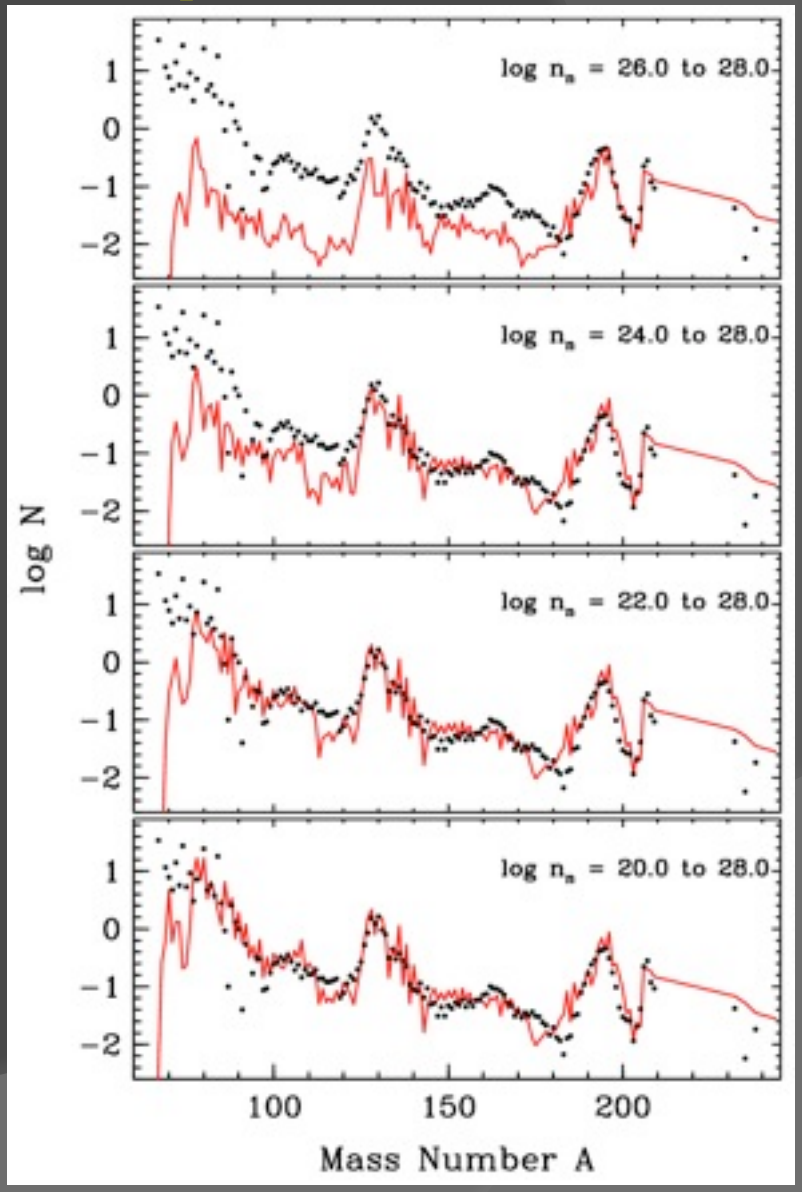


we conclude that the deviation of the abundances of heavy neutron-capture elements in HD 88609, and probably in HD 122563, from the main r-process pattern is not a result of contamination of the s-process yields, but implies that the weak r-process produces a different abundance pattern of heavy neutron-capture elements from that produced by the main r-process.

Honda et al. 2007

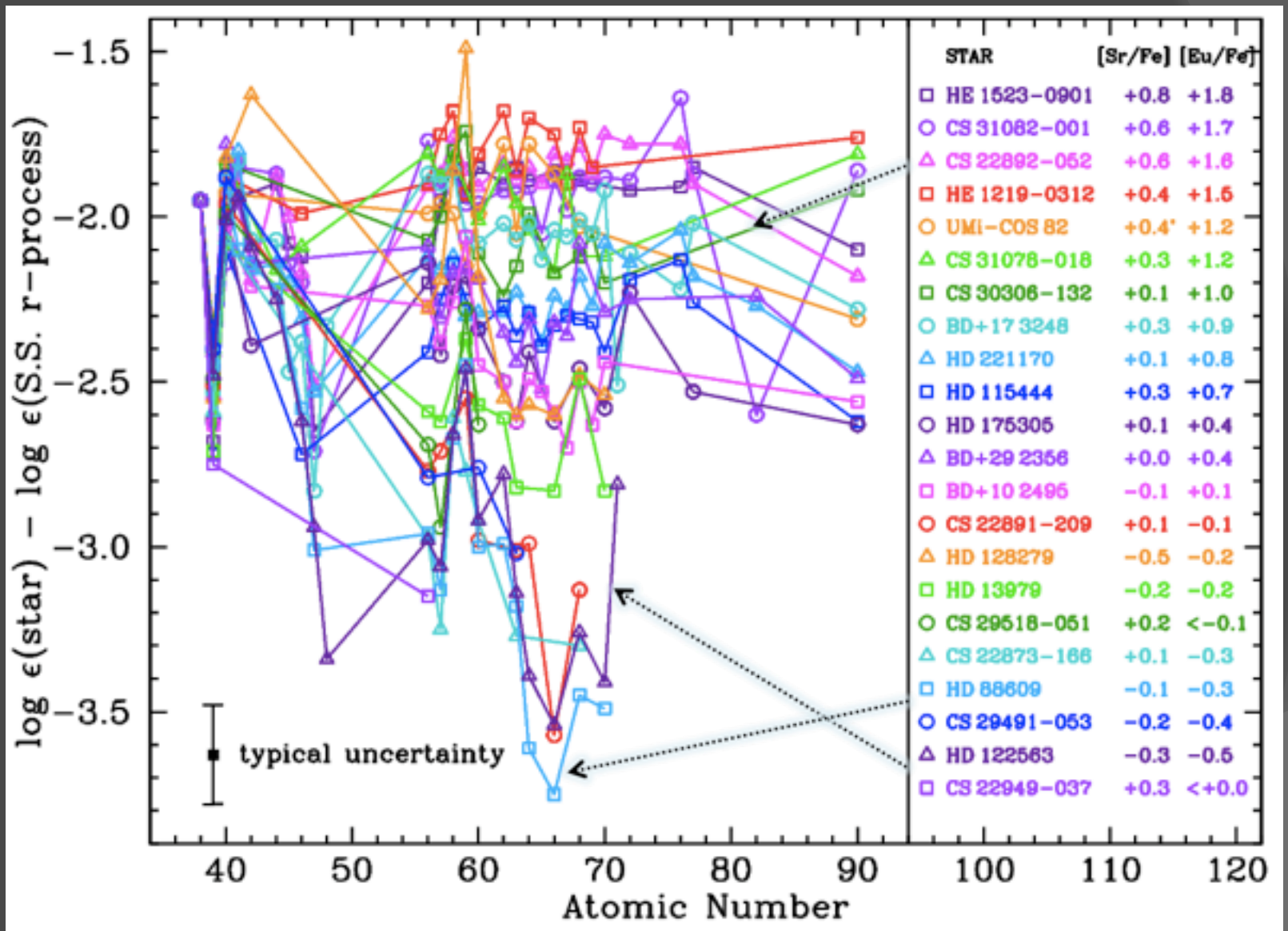
can be understood from various densities in r-process syntheses





Kratz et al. 2007

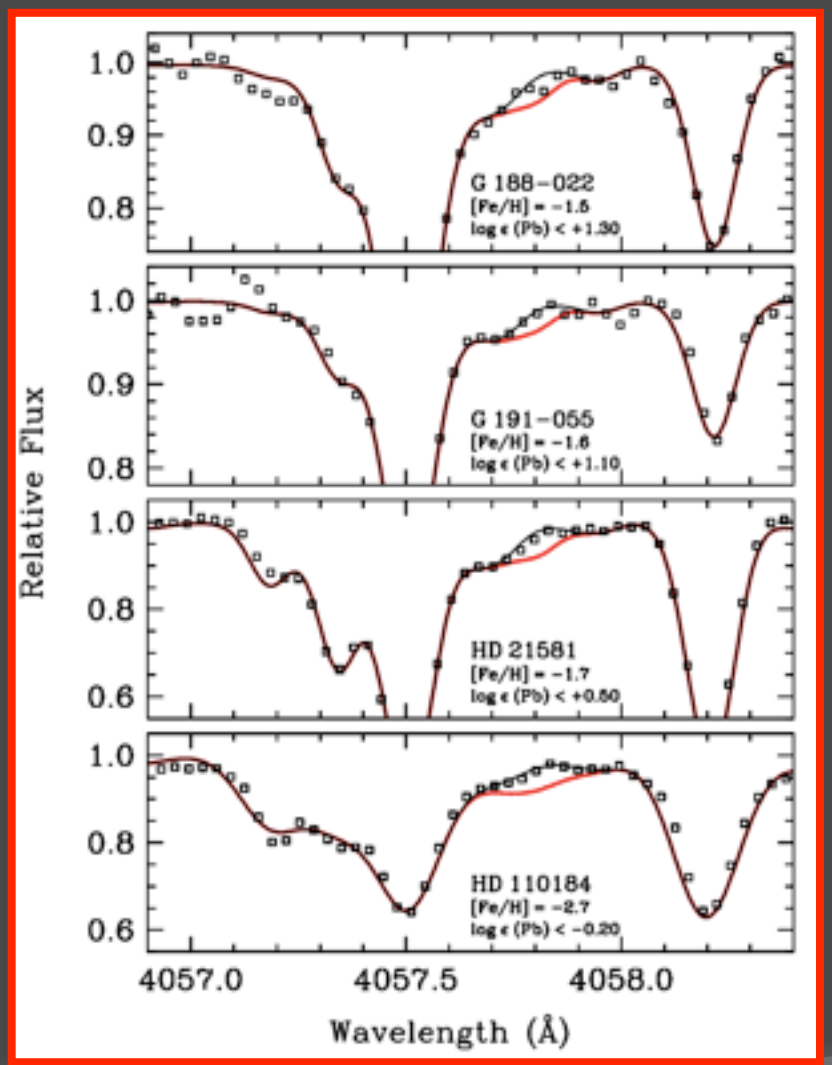
abundance distribution variations: "normal"



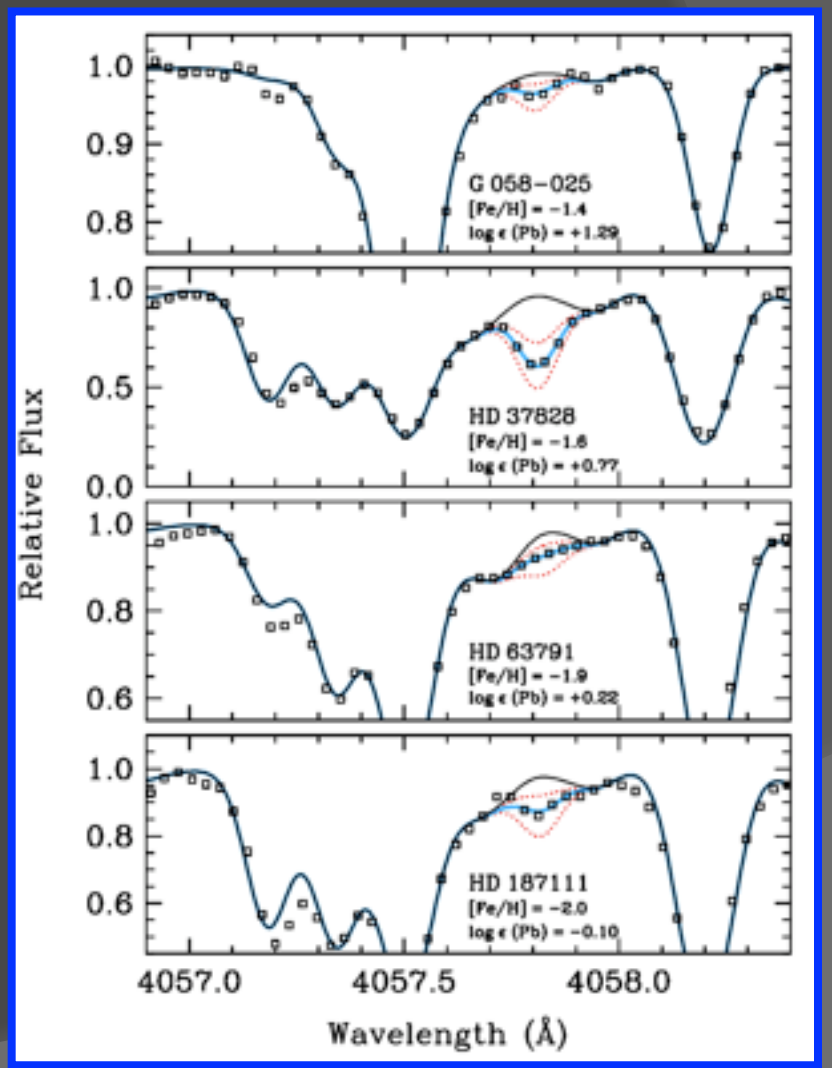
Roederer et al 2010

Is lead the key?

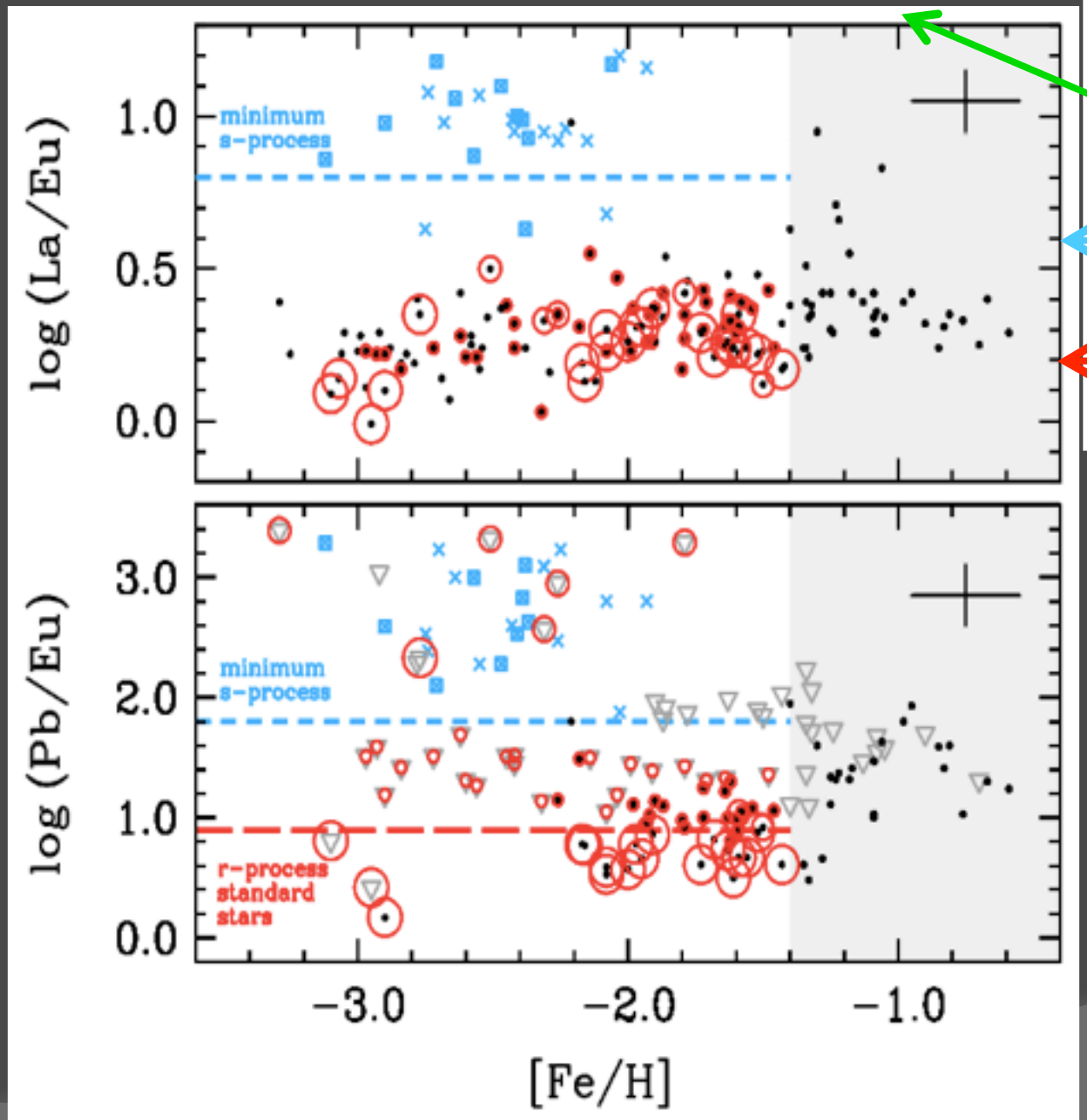
no Pb ➔ r-rich?



yes Pb ➔ s-contribution for sure



Roederer et al 2010



REMEMBER:
log ε(La/Eu)

= +1.5
(solar s-only)

= +0.6
(solar total)

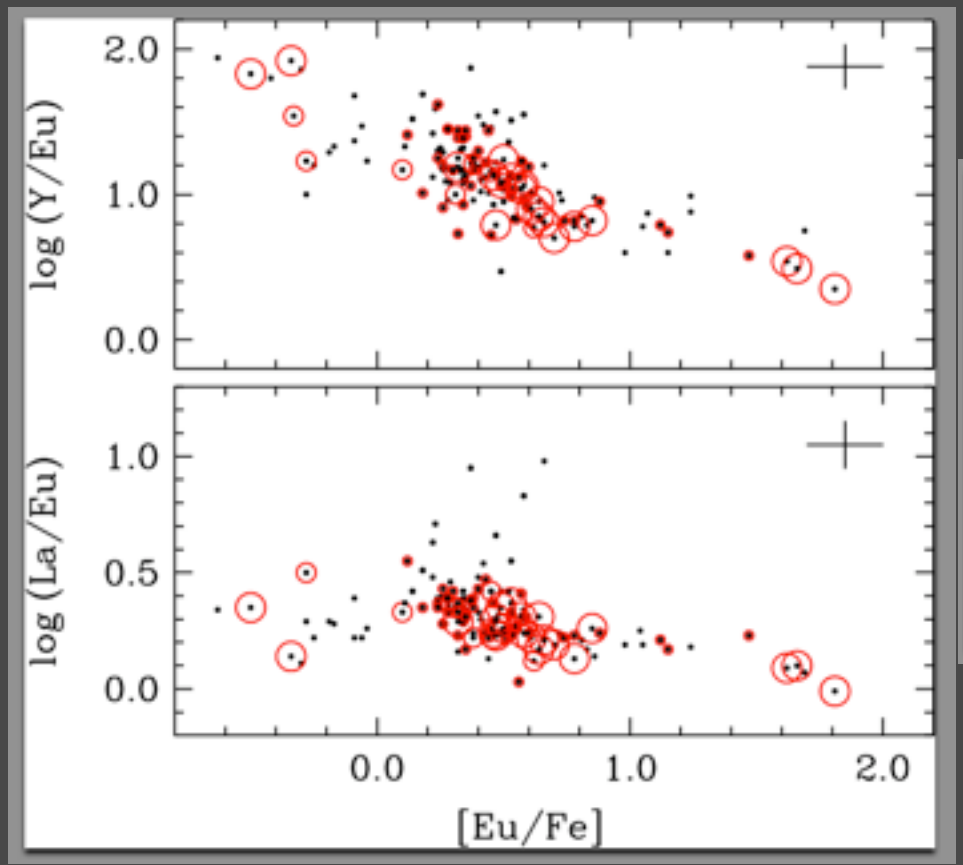
= +0.2
(solar r-only)

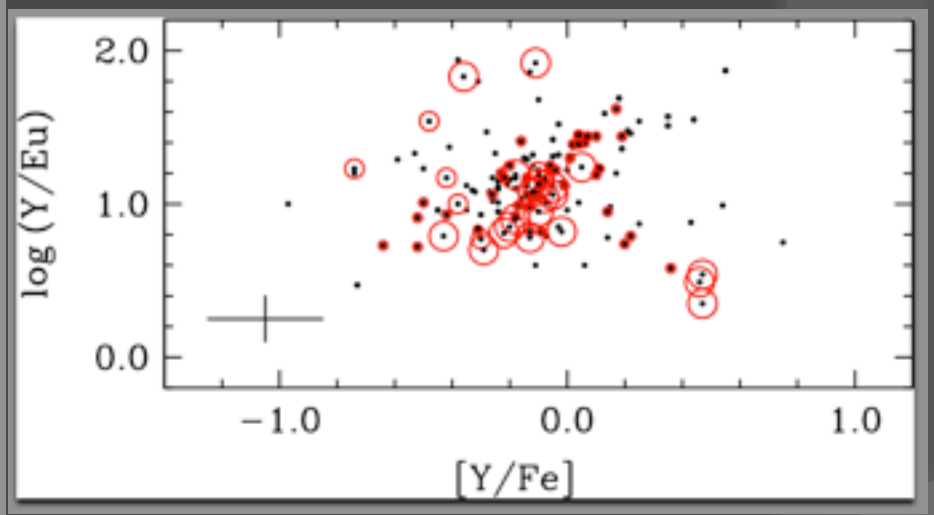
No Pb =
no s-process

= r-rich?

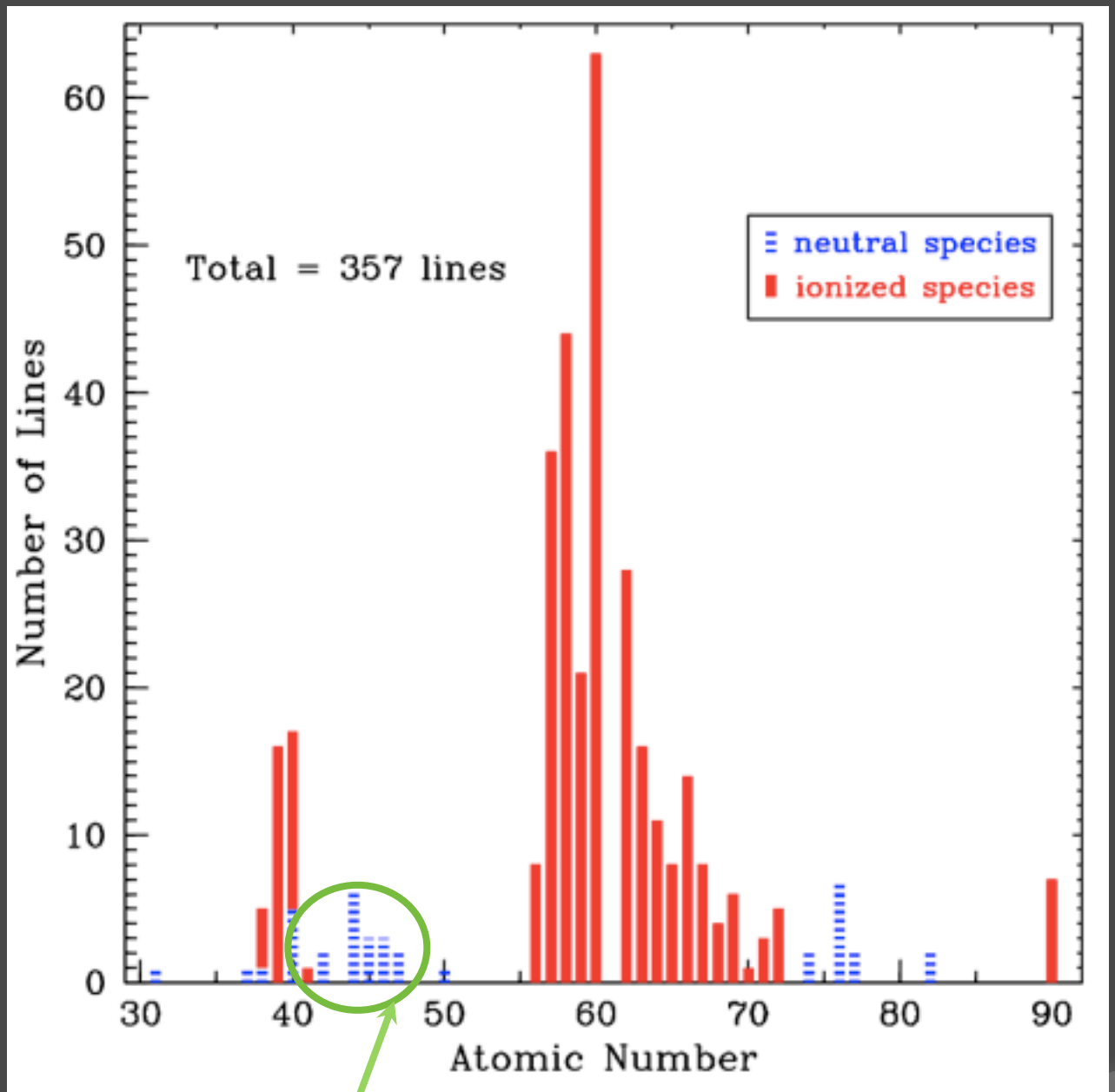
Roederer et al 2010

The variations probably are dominated by the heavy elements





Roederer et al 2010



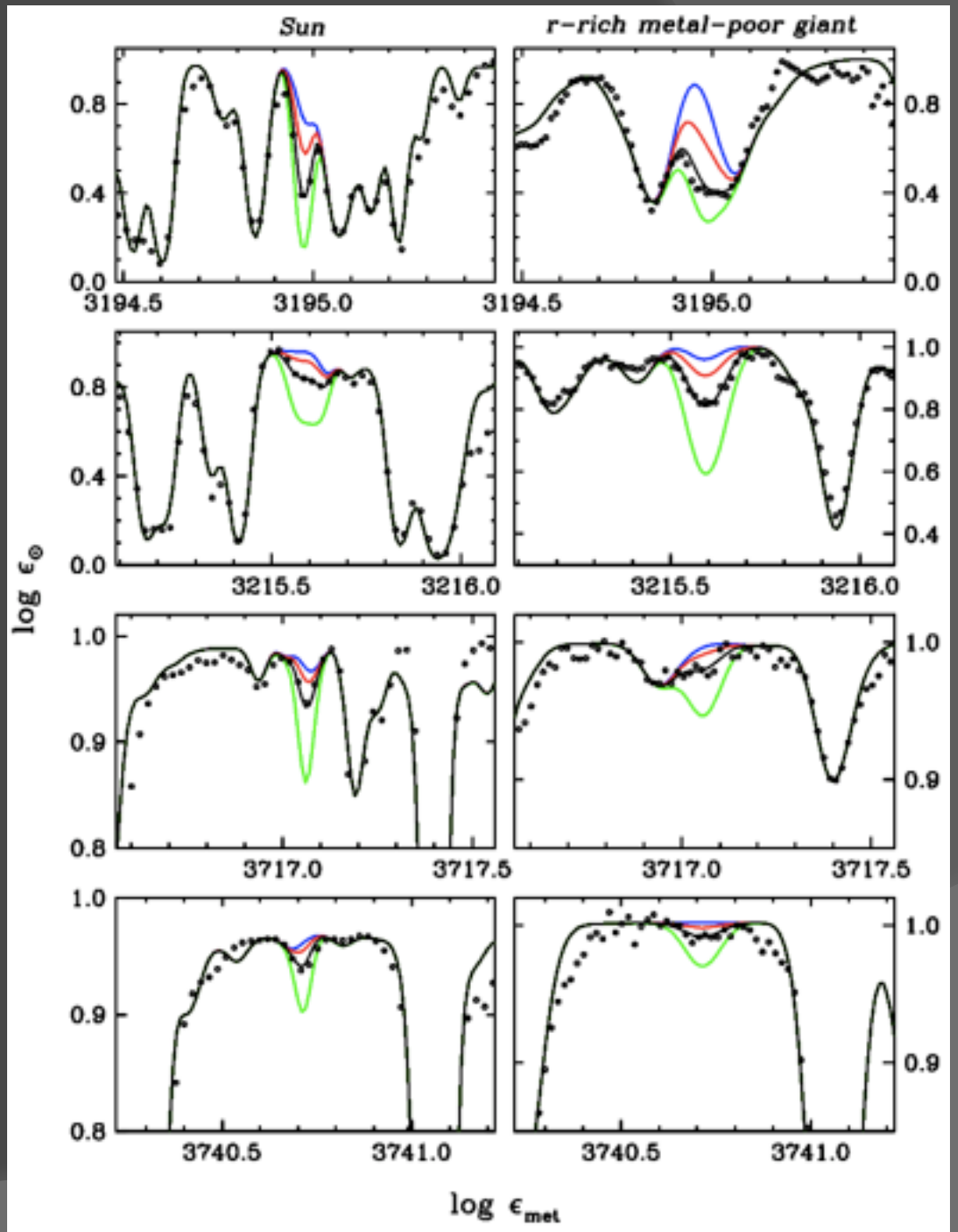
this element domain is the frontier

what are we REALLY observing in r-rich stars?

Ivans et al. 2006

Niobium, Z=41
Good luck!

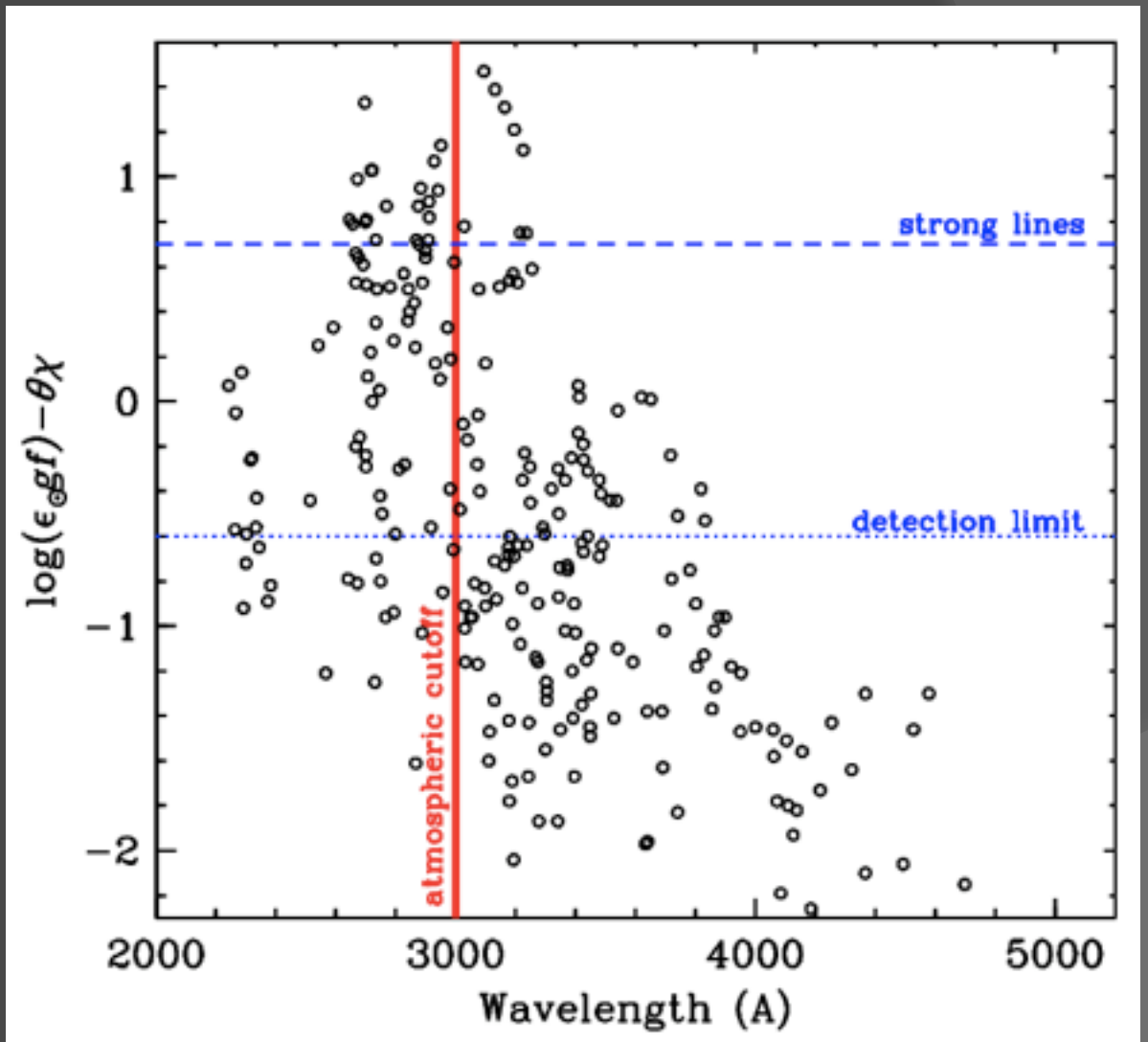
these are the best transitions in the most favorable detection cases



Nilsson et al. 2010

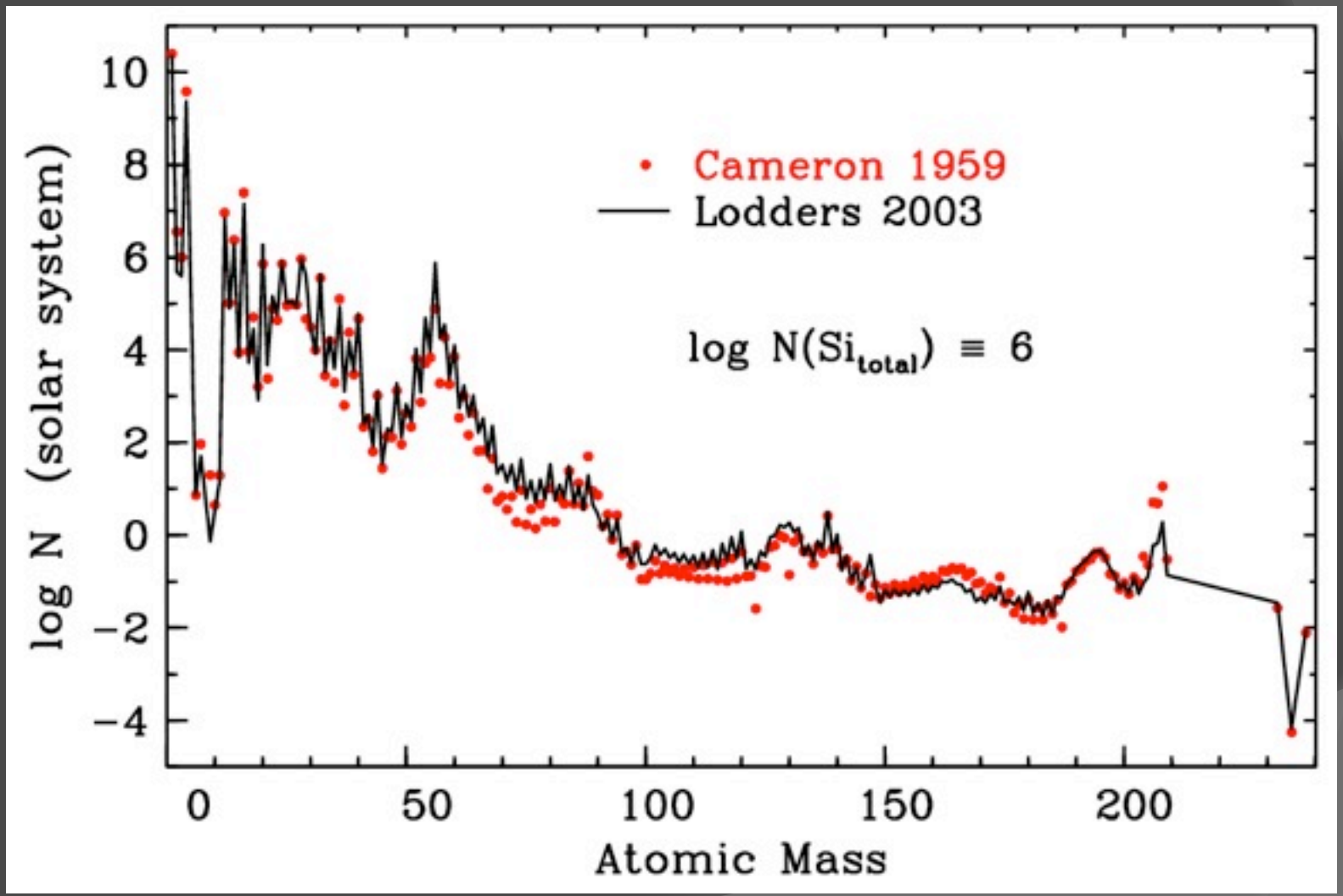
Why is Niobium such a challenge?

Simple: all reasonably strong lines are in the vacuum UV



Nilsson et al. 2010

Some perspective is needed: first a couple of old results



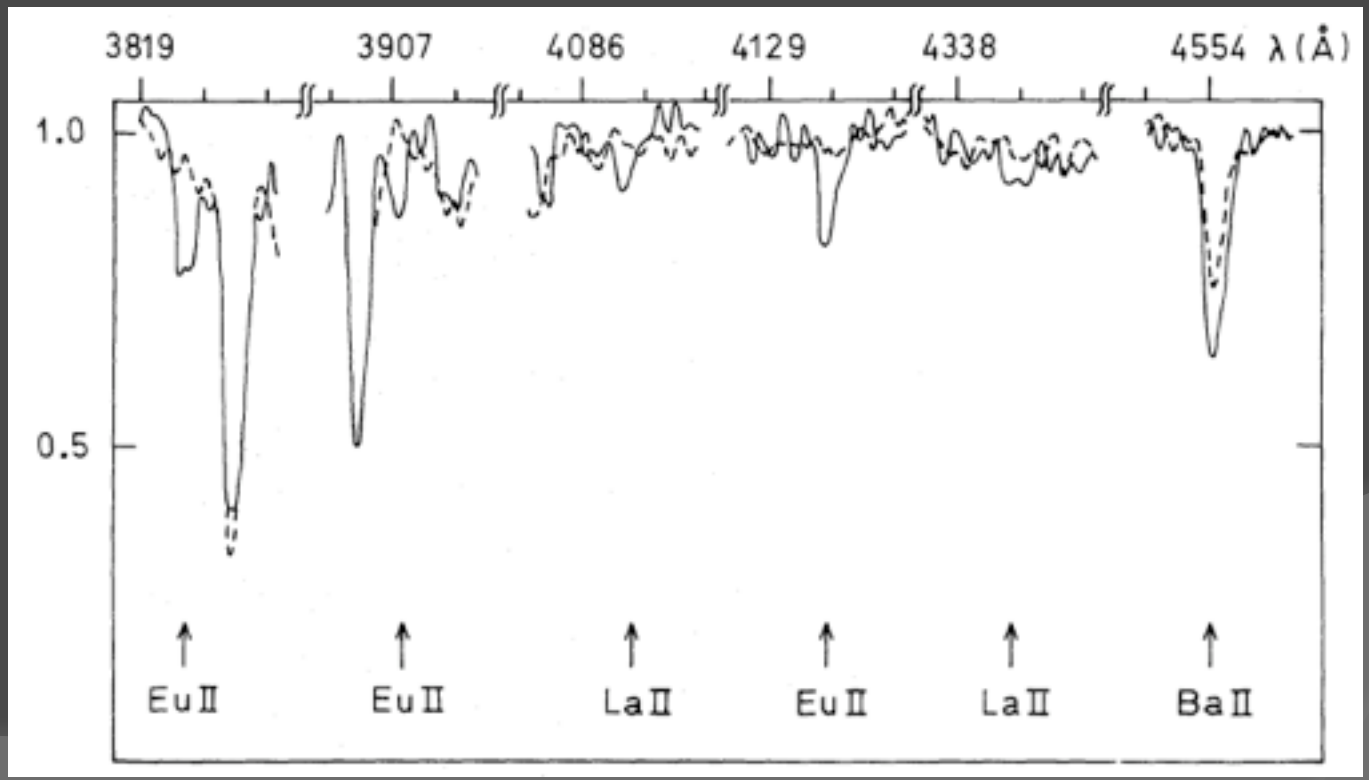
Sneden, Cowan, & Gallino 2008

second, r-rich stars aren't really a recent discovery

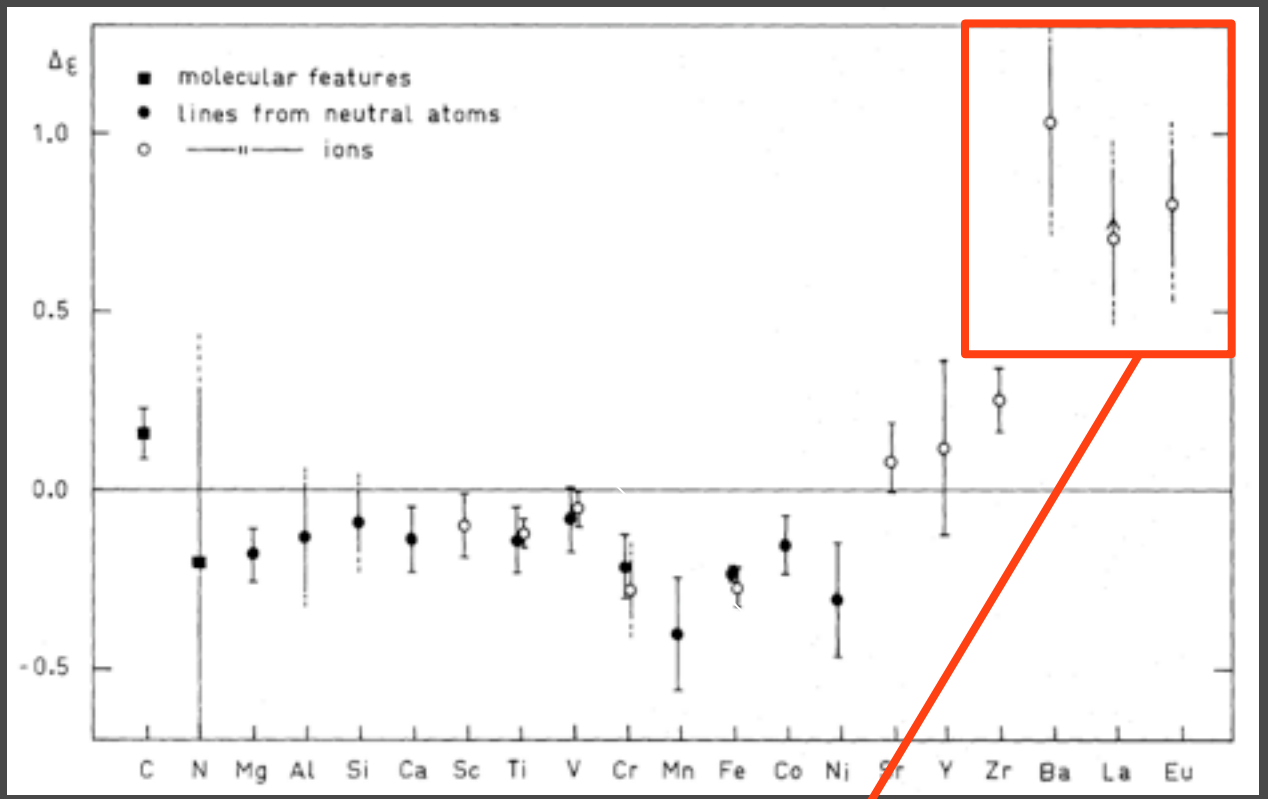
HD 115444 – a barium star of extreme Population II

R. & R. Griffin* *The Observatories, Madingley Road, Cambridge CB3 0HA*
B. Gustafsson and T. Vieira *Astronomiska Observatoriet, Box 515, S-751 20 Uppsala, Sweden*

Mon. Not. R. astr. Soc. (1982) **198**, 637–658



They knew that something was odd



"Another peculiarity of HD 115444 is its high Eu content relative to HD 122563. A high Eu abundance is not characteristic of Ba stars ... We probably have to interpret its high Eu abundance as a result of a supernova explosion, producing the r elements, in the prestellar gas or close to the star."

How about some new stuff? A sample:

A systematic study of extremely metal-poor stars with SDSS/Subaru
Aoki et al., NIC_XI_256
discovery of first r-rich main sequence star

Detailed abundance analysis of the r-process enhanced star HE 2327-5642
Mashonkina et al., NIC_XI_036
important to grind through analyses of more r-rich stars

Silver and Palladium - tracers of the weak r-process
Hansen & Primas, NIC_XI_393
Constraints on the weak r-process: Abundance of Palladium in mps
Francois et al., NIC_XI_392
links (cleanly?) with lighter n-capture elements
excellent correlation with neighboring silver

Thorium enrichment in the Milky Way Galaxy
Aoki & Honda, NIC_XI_266
use of long wavelength Th II line
small star-star [Th/Eu] scatter
actinide/lanthanide dispersion is relatively small

How about some new stuff? A sample:

The Influence of Neutron Capture Rates on the Rare Earth Peak
Mumpower et al., NIC_XI_235
sensitivity of r-process abundances to n-capture rates

Production of LEPP nuclei in supernova neutrino-driven winds
Montes & Arcones, NIC_XI_119
LEPP = light element primary process (Z~38-48 to me)
abundance predictions as a function of n/p

Nucleosynthesis from High-Entropy Hot-Bubbles of Sne; MPS Abundances
Izutani N.1, Umeda, NIC_XI_392
OK, more Fe-peak than n-capture elements
further exploration of n/p in explosive nucleosynthesis

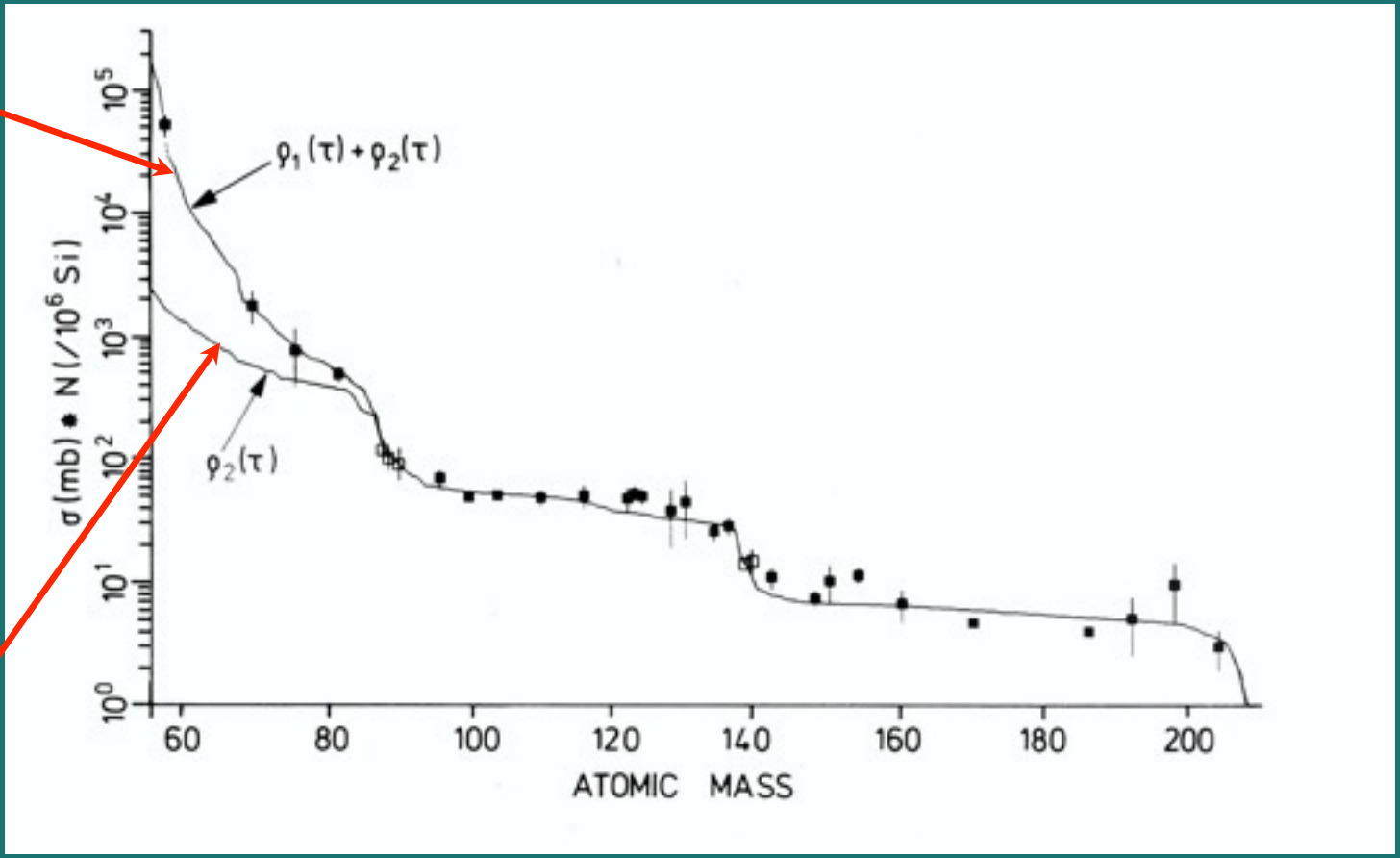
r-process Nucleosynthesis in Magnetically Dominated Core-Collapse SNe
Nishimura et al., NIC_XI_330
more and more attempts to bridge observation/theory gap

Summary

- much hard work has discovered many r-rich stars
- many papers now great star-star similarities; much credit due to atomic physicists
- More uniform surveys of La, Eu, Pb
- are actinide-boost stars really rare?
- Pb is a key; do not understand its synthesis
- must find more super-r-rich stars with U
- and, better understanding of Th/Eu ratios
- push observers/experimentalist/theorists to work together

Assessing the s-process contributions to solar-system n-capture abundances

"weak" s-process component

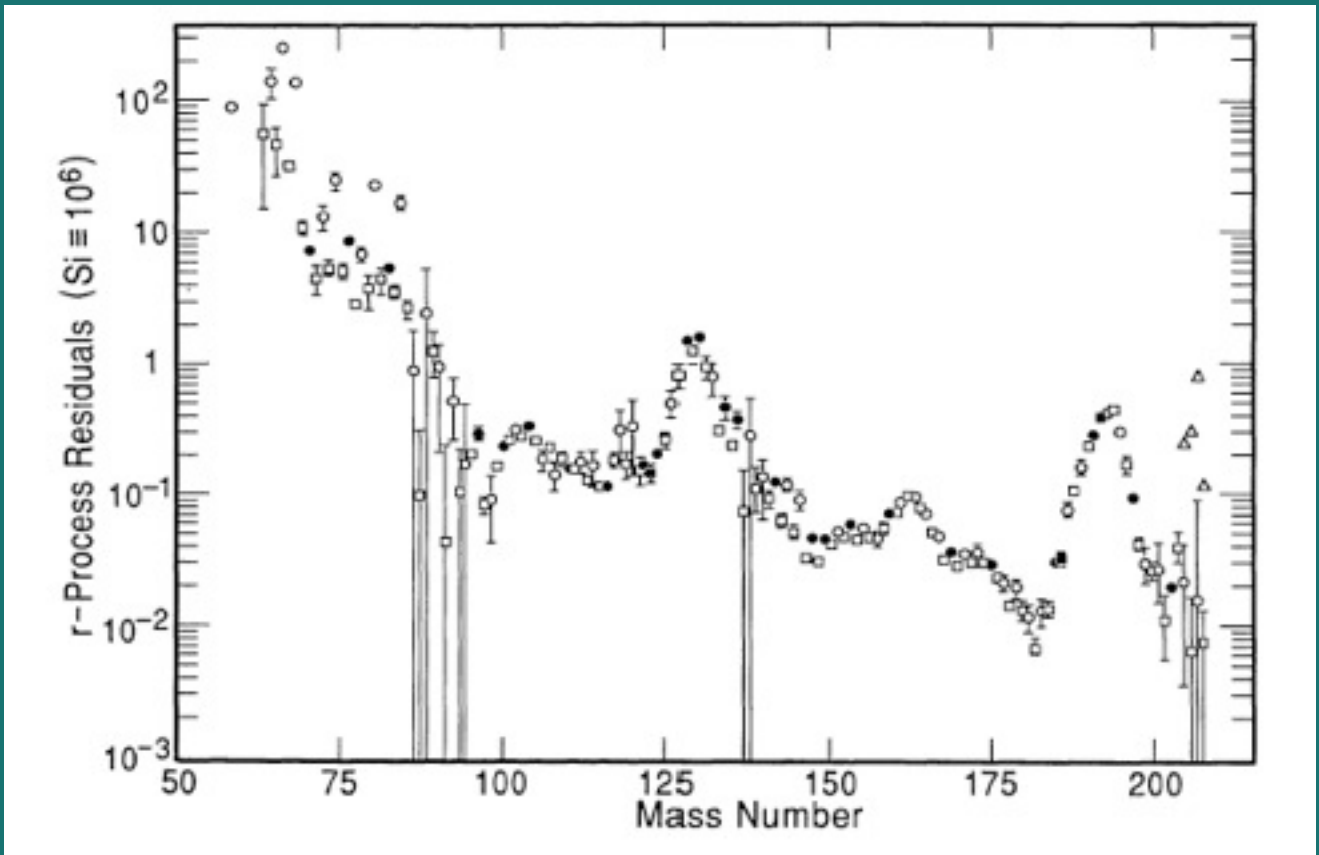


"main" s-process component

Filled symbols = s-process-only isotopes

Rolfs & Rodney (1988)

Solar-system r-process isotopic abundances: be cautious, as these are **RESIDUALS**



Filled symbols = abundances of *r*-process-only isotopes;
Open symbols = *r*-process abundances: isotopic totals *minus* *s*-process components

Cowan *et al.* (1991)