Heavy & light neutron-capture elements in halo stars: what a difference the right theoretician makes …

Chris Sneden

University of Texas

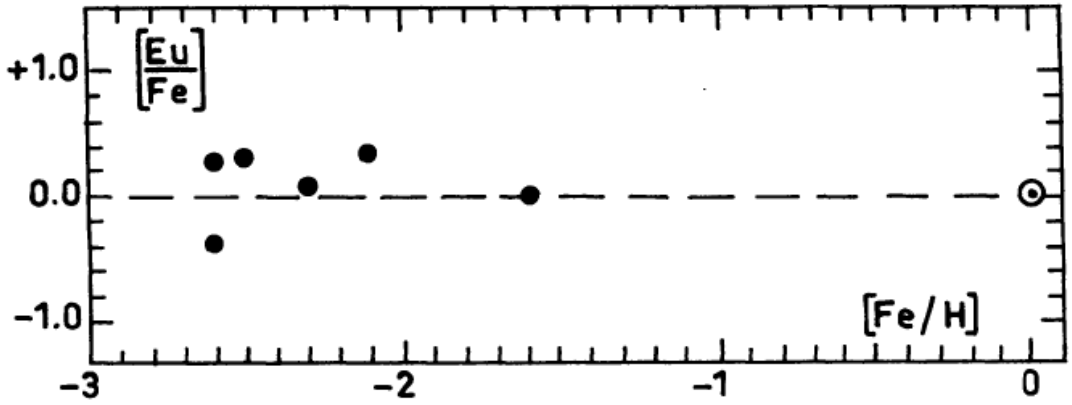
The abundance paper that really started things

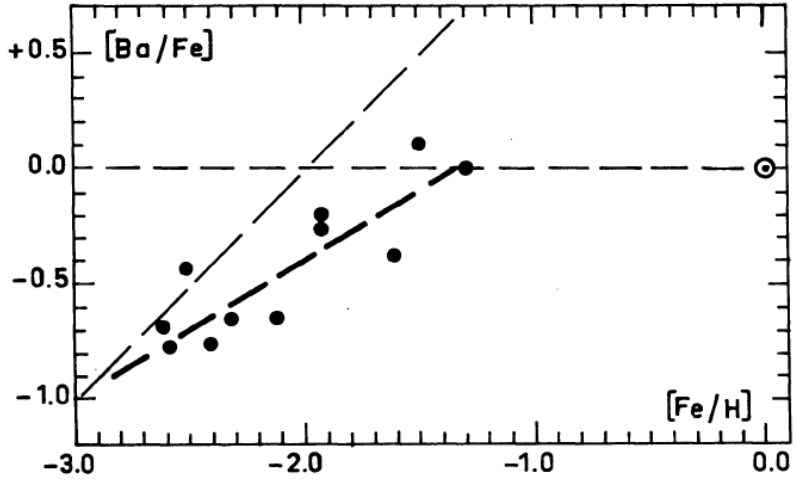
Nucleosynthesis in the Galaxy and the Chemical Composition of Old Halo Stars*

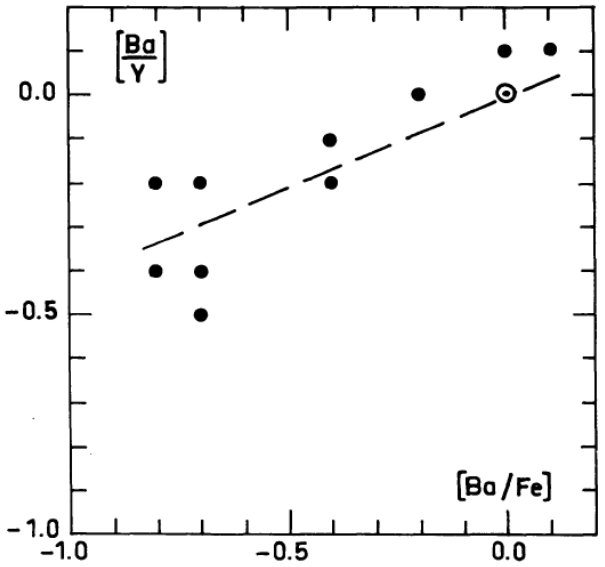
M. Spite and F. Spite

D.E.P.E.G., Observatoire de Paris-Meudon, F-92190 Meudon, France

Astron. Astrophys. 67, 23—31 (1978)







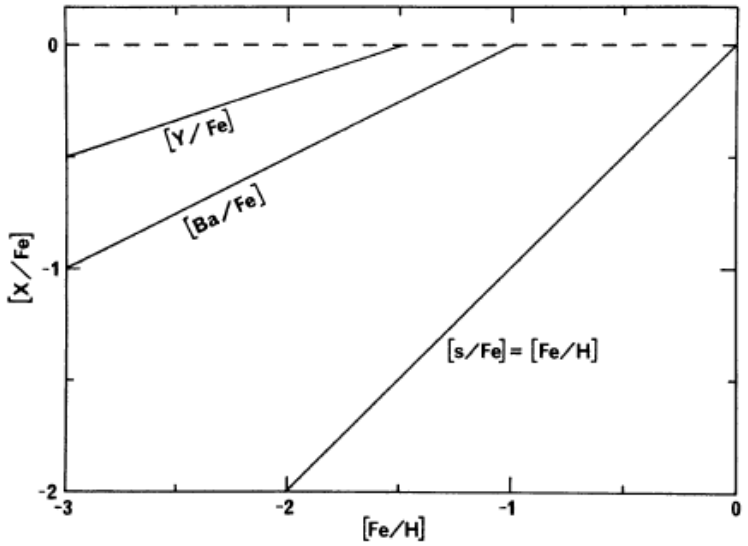
Leading to a pioneering interpretation

Astron. Astrophys. 97, 391–393 (1981)

A New Interpretation of the Heavy Element Abundances in Metal-deficient Stars

J. W. Truran*

Institute of Astronomy, University of Cambridge, Cambridge, England and Department of Astronomy, University of Illinois, Urbana, Illinois 61801, USA



IV. Conclusions

We emphasize the following general conclusions:

(i) The heavy element abundance patterns observed in the most metal-deficient stars in our galaxy may be understood in a simple and direct manner if the elements heavier than iron are assumed to represent products of *r*-process nucleosynthesis. The associated variations of [Y/Fe] and [Ba/Fe] with [Fe/H] are precisely what one would expect if the *r*-process nuclei represent primary nucleosynthesis products; this would be the case if they were formed as a consequence of the ejection of highly neutronized matter in supernova events.

(ii) Given this *r*-process interpretation of the heavy element distributions, it follows that the abundances observed in the most metal-deficient stars can be explained on the basis of nucleosynthesis contributions from a single prior generation of massive stars, either galactic or pregalactic in nature.

my own initial foray into n-capture elements

THE ASTROPHYSICAL JOURNAL, **267**:757–778, 1983 April 15

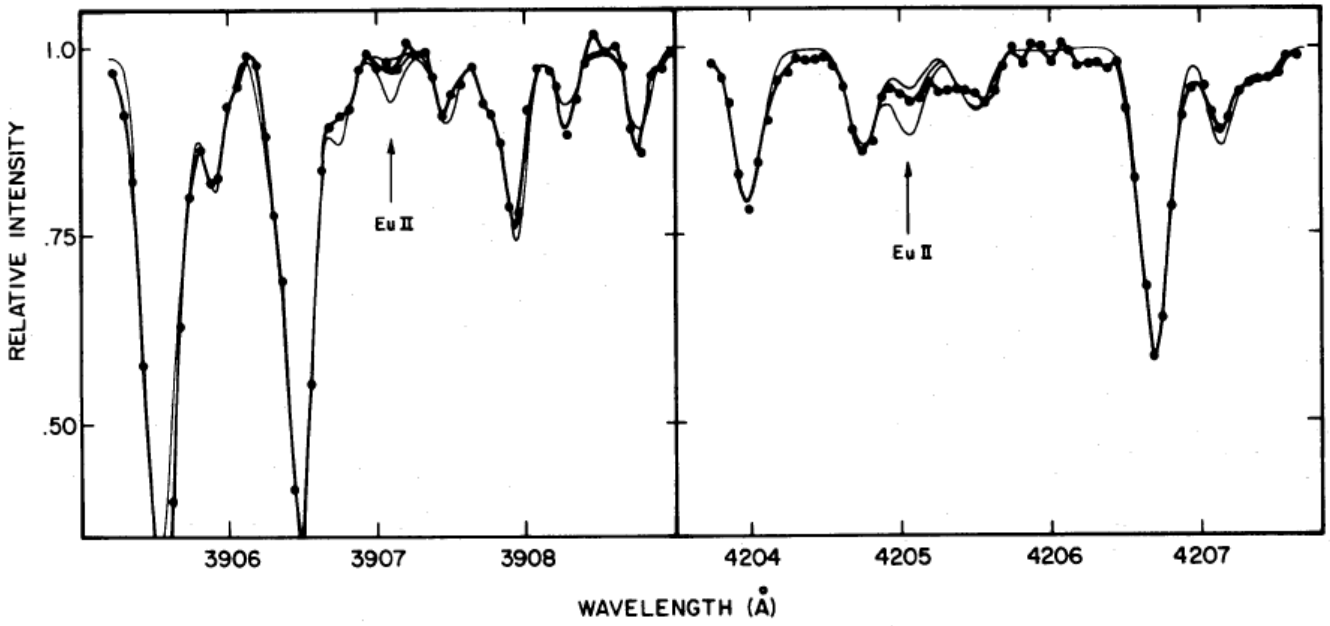
THE *r*- AND *s*-PROCESS NUCLEI IN THE EARLY HISTORY OF THE GALAXY: HD 122563

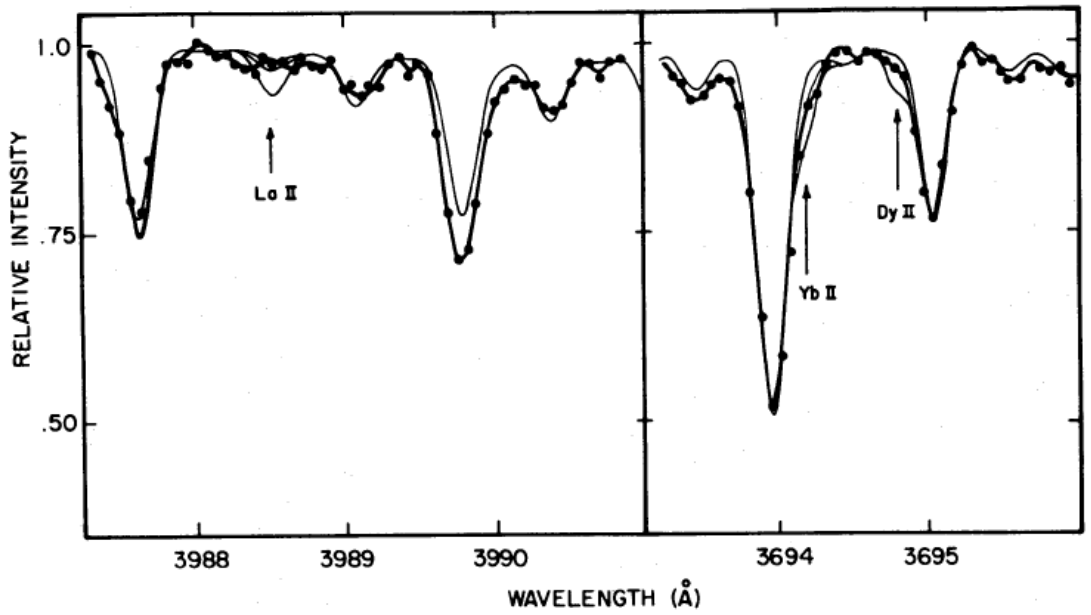
CHRISTOPHER SNEDEN AND M. PARTHASARATHY
Department of Astronomy, University of Texas at Austin
Received 1982 July 26; accepted 1982 October 7

ABSTRACT

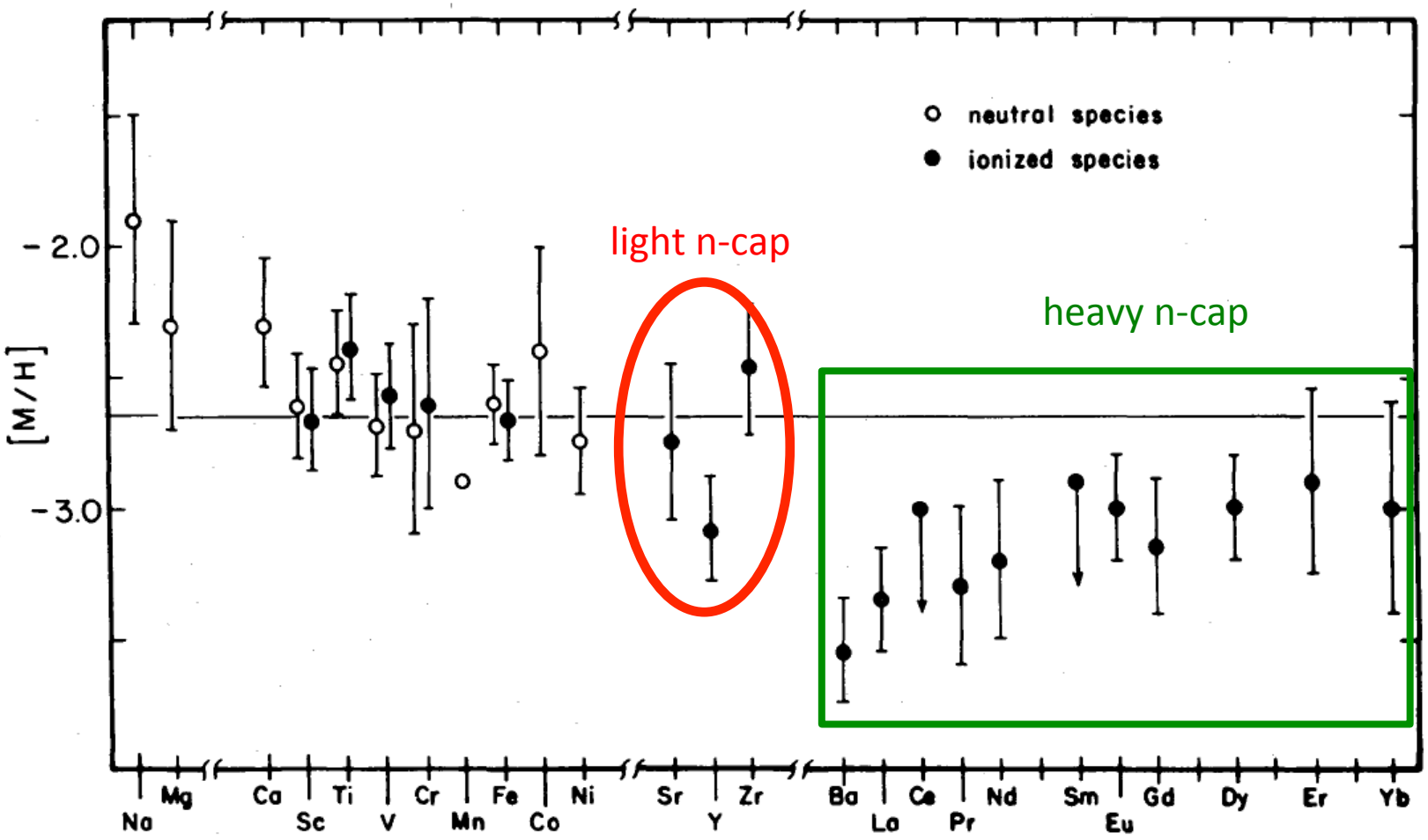
New high-resolution, high signal-to-noise spectra in the blue and ultraviolet spectral regions have been obtained for the extremely metal-poor giant star HD 122563. A complete model atmosphere, spectrum synthesis analysis of this star has been performed, employing a large number of weak iron-peak species lines and laboratory oscillator strengths. Spectral features of many rare earth elements have been detected in the ultraviolet. The large overdeficiency of nearly a factor of 10 for the *s*-process element barium is confirmed and is shown to extend to the other *s*-process elements La, Ce, Pr, Nd, and Sm. The *r*-process elements Eu, Gd, Dy, and possibly Er and Yb are less deficient than the *s*-process elements but do exhibit lower ratios with respect to iron-peak elements than in the Sun. A supplementary differential analysis of HD 122563 with respect to the Sun shows that the heavy-element abundances are not very model-atmosphere dependent. The heavy-element abundances can be understood with nucleosynthesis models in which the progenitors of this star produce mainly *r*-process isotopes. A small contribution of the *s*-process to the creation of the elements Sr, Y, Zr, and possibly Ba is not ruled out, but such traditional *s*-process elements as La, Pr, and Nd appear to have been made in the *r*-process in stellar generations prior to the formation of HD 122563.

Working on this star was not easy …



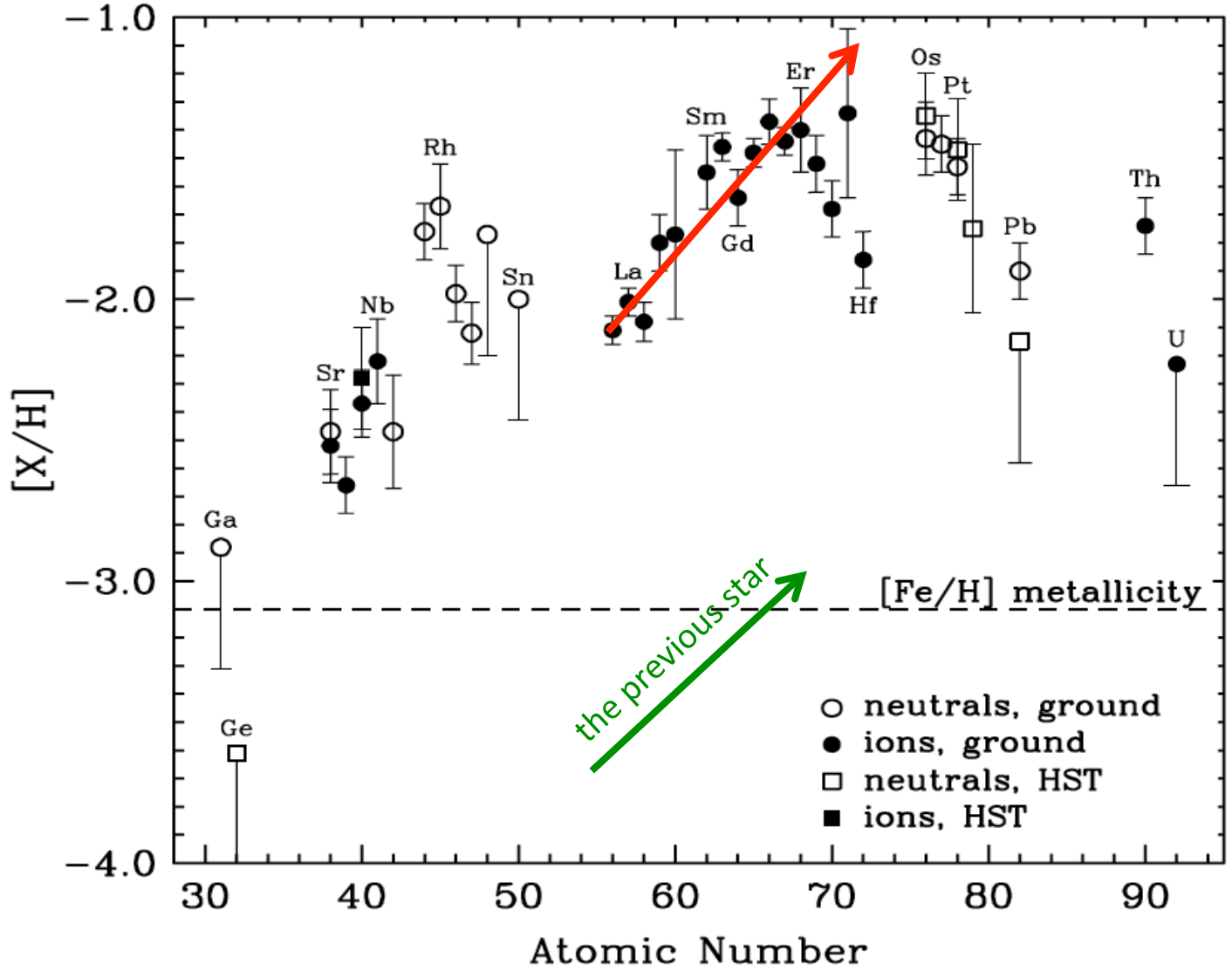


But the result was unmistakable .. sort-of



alas … this was the extent of the interpretation

and with perfect hindsight we see the r-process trend



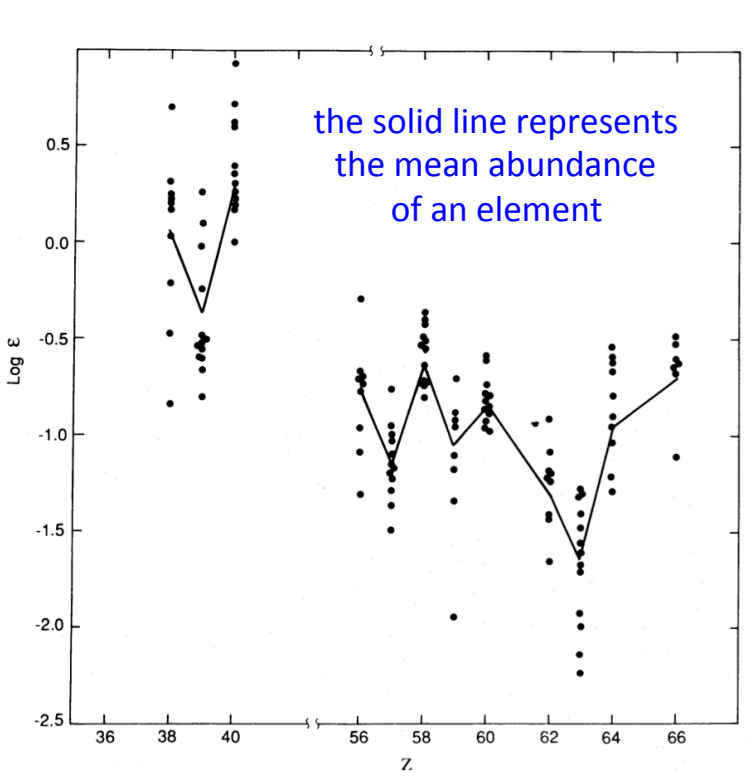
Sneden, Cowan et al. 2003

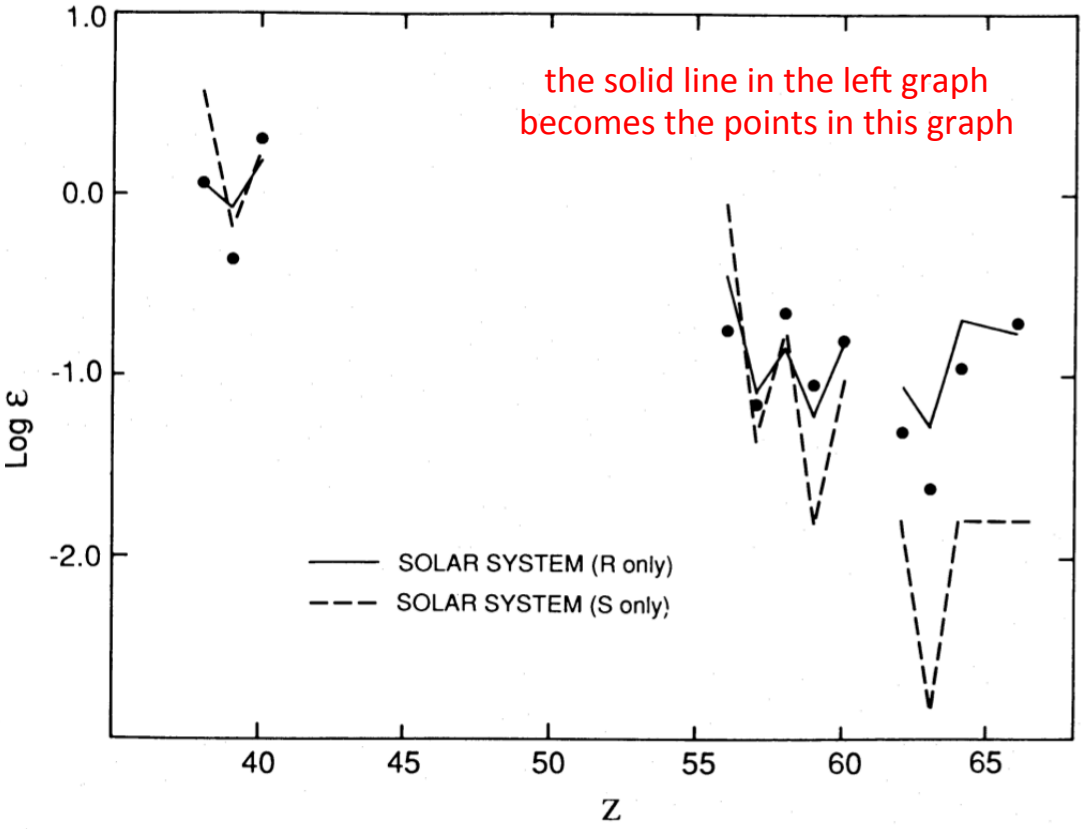
John's 1st abundance work

THE ASTROPHYSICAL JOURNAL, 327:298–320, 1988 April 1

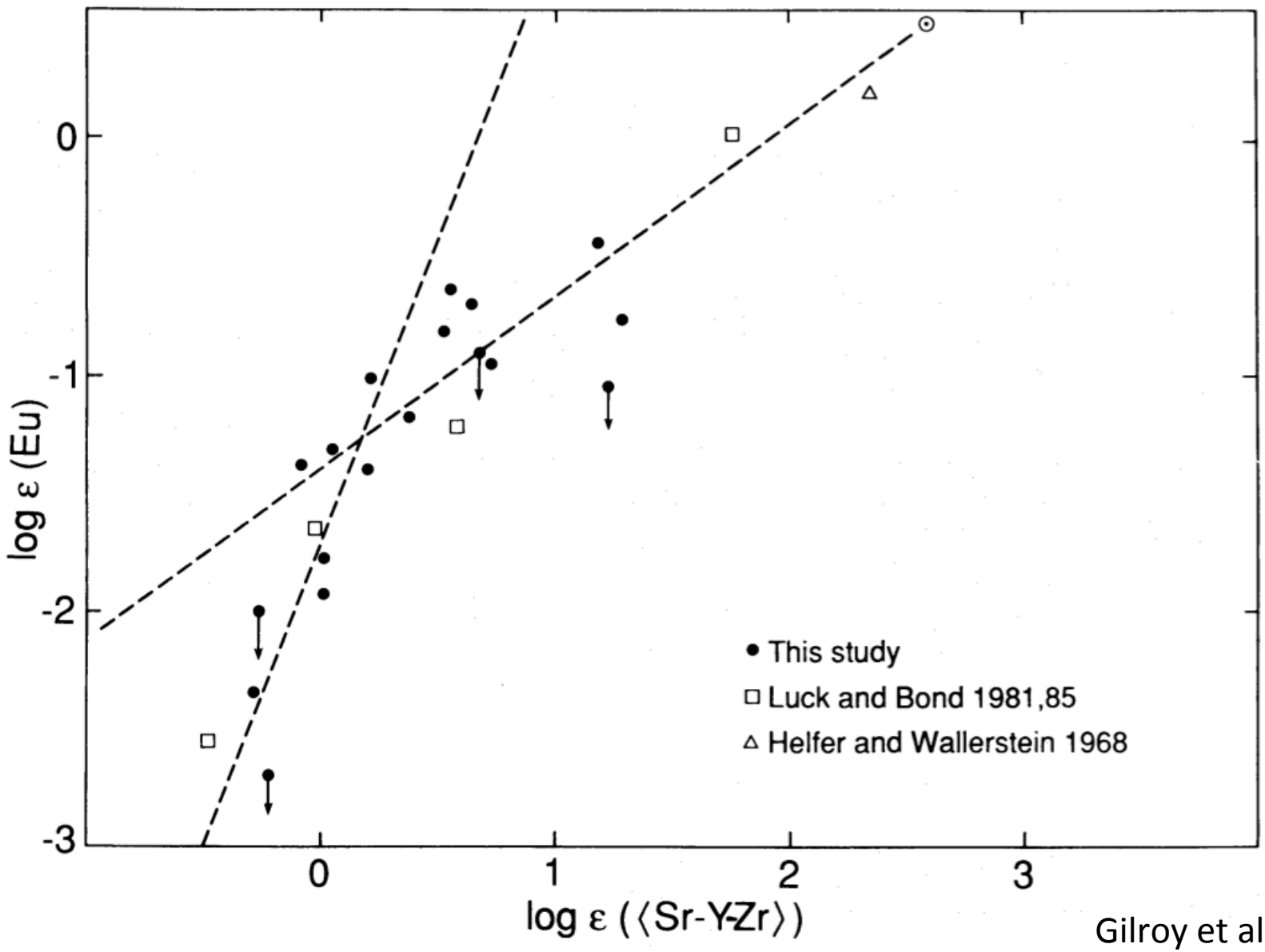
ABUNDANCES OF NEUTRON CAPTURE ELEMENTS IN POPULATION II STARS

KALPANA KRISHNASWAMY GILROY AND CHRISTOPHER SNEDEN[1]
Department of Astronomy and McDonald Observatory, University of Texas at Austin
CATHERINE A. PILACHOWSKI
Kitt Peak National Observatory, National Optical Astronomy Observatories
AND
JOHN J. COWAN
Department of Physics and Astronomy, University of Oklahoma
Received 1987 August 24; accepted 1987 September 28



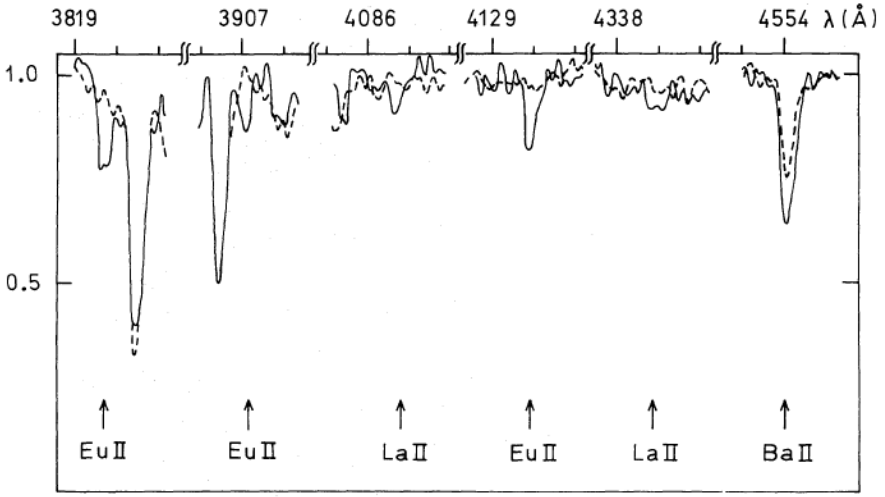


Showing hints of the light/heavy mismatch



Gilroy et al. 1988

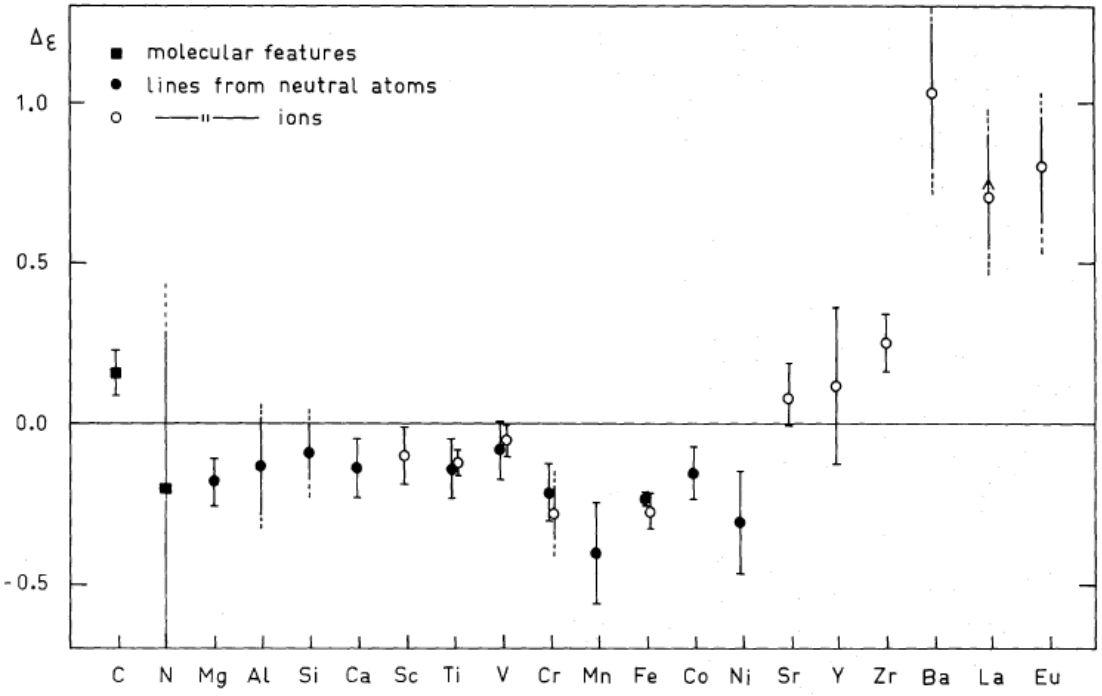
The first legitimate r-process-rich star



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

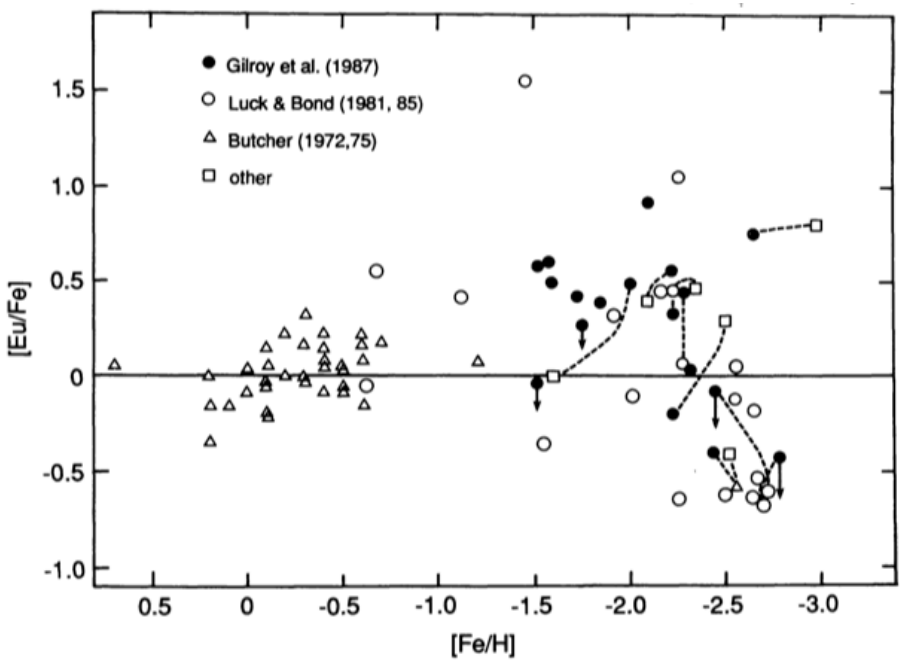
HD 115444 – a barium star of extreme Population II

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



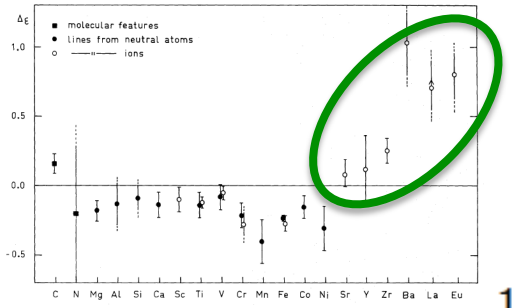
Mapping out conclusions that stick today

For example, in figure 1 we have plotted the ratio [Eu/Fe] versus [Fe/H]. Three principal conclusions may be drawn from this figure. 1) *Eu often is overabundant in metal-poor stars relative to Fe*, especially in the range $-1.5 \leq$ [Fe/H] < -2.5. Eu may be made in bulk only in the r-process, and so these relative overabundances clearly demonstrate the existence of substantial r-process synthesis (presumably by high-mass supernovae) early in the history of the galaxy. 2) *[Eu/Fe] displays a considerable star-to-star scatter*, perhaps increasing with decreasing [Fe/H]. This result supports the common ideas that the r-process elements and the Fe-peak elements probably were synthesized by stars of different masses, and that the Galaxy was largely unmixed during the early formation of the halo. 3) *[Eu/Fe] may begin to decline below [Fe/H] ≈ -2.5*. The data here are intriguing but scant, and suggest that the first Galactic nucleosynthesis events may not have been able to manufacture this element (and those of similar Z?) very efficiently.



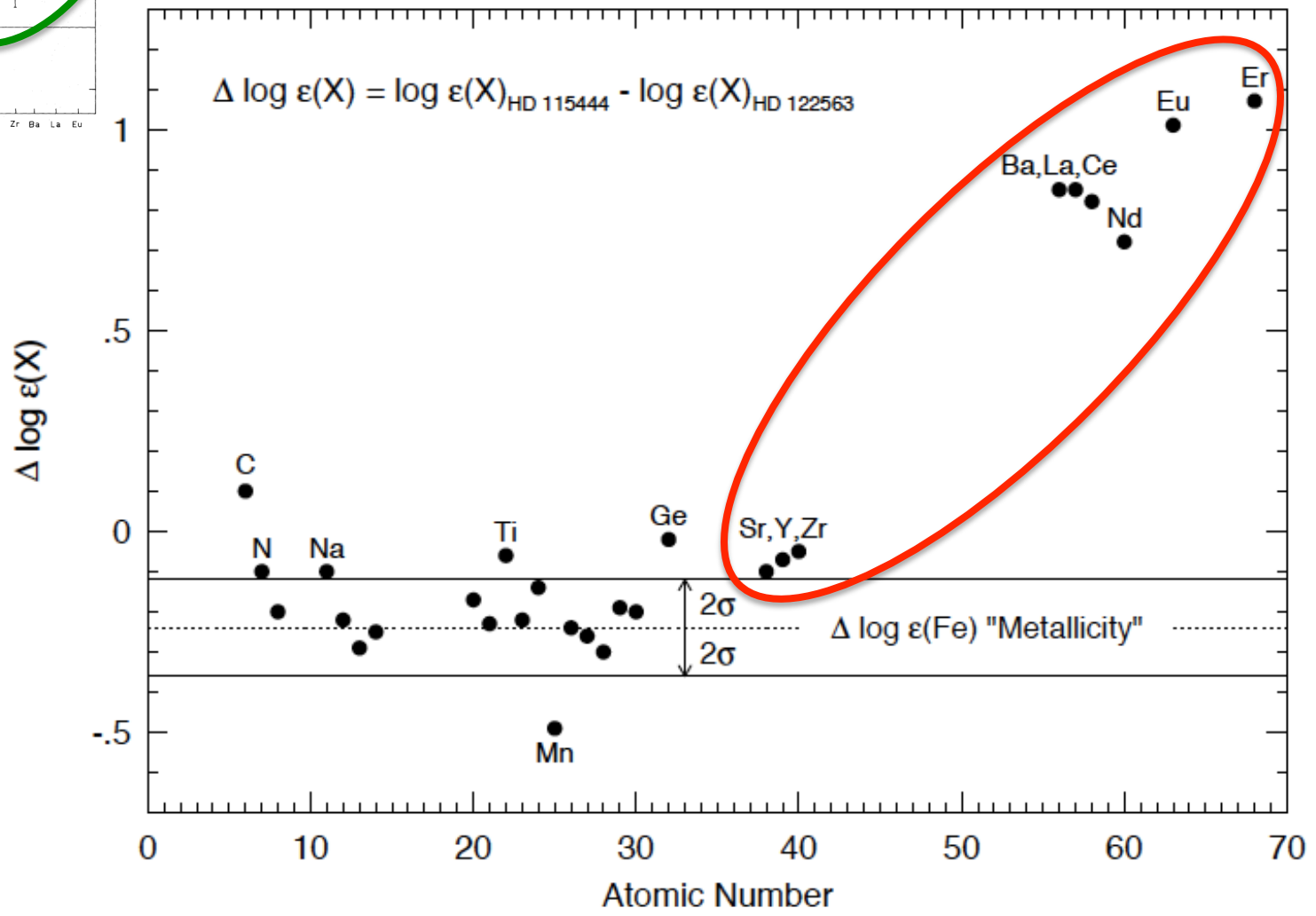
Sneden, Cowan et al. 1988

but disentangling this took additional work



original

modern



Westin, Cowan et al. 2000

Ba & Eu behaviors: an “early” attempt at global trends

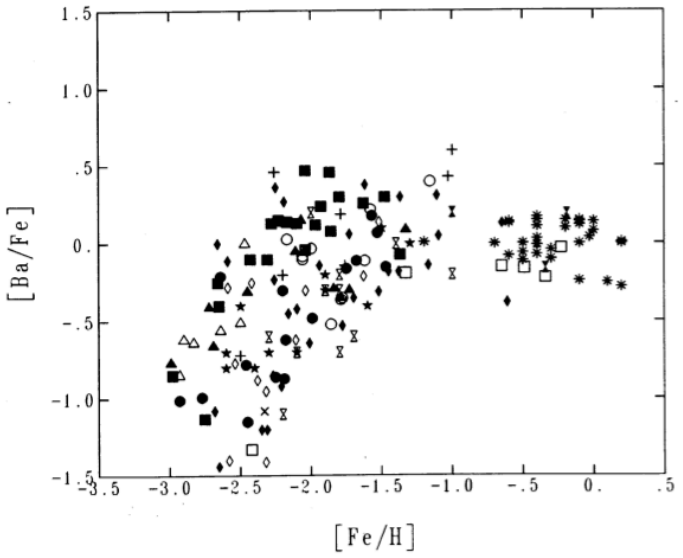


FIG. 5a

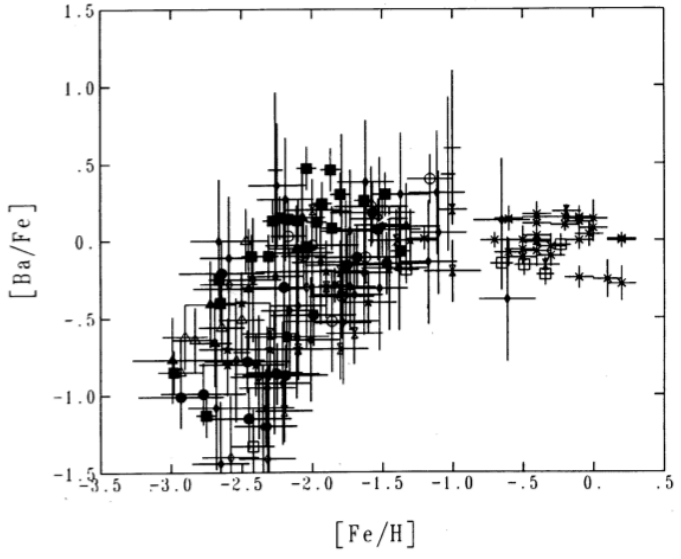
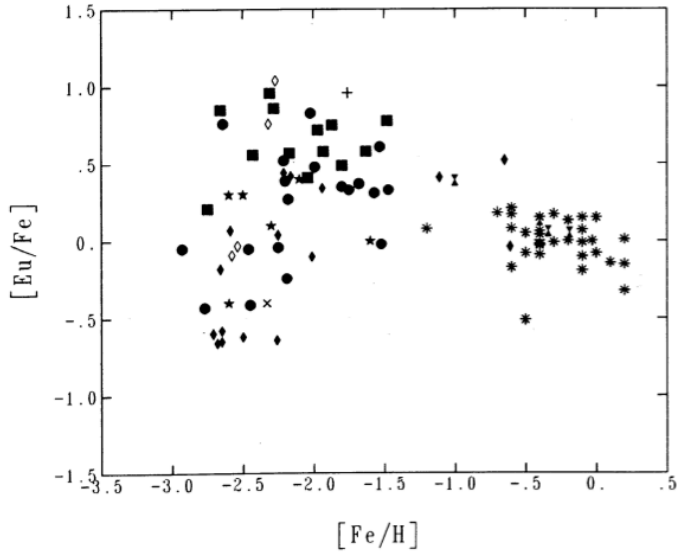
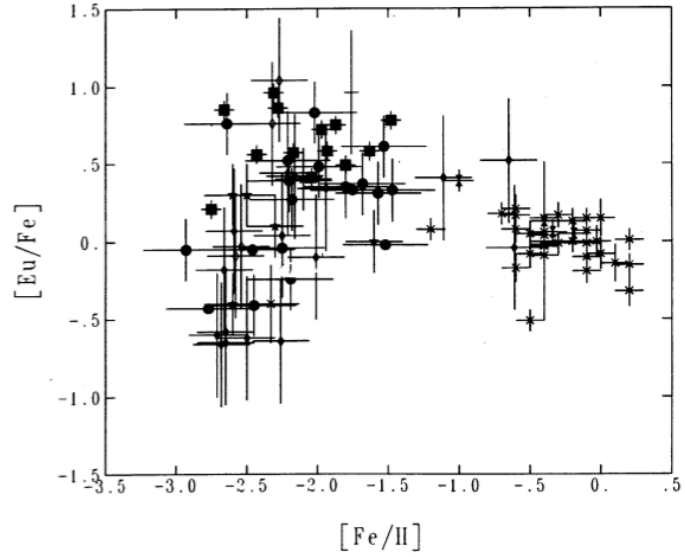


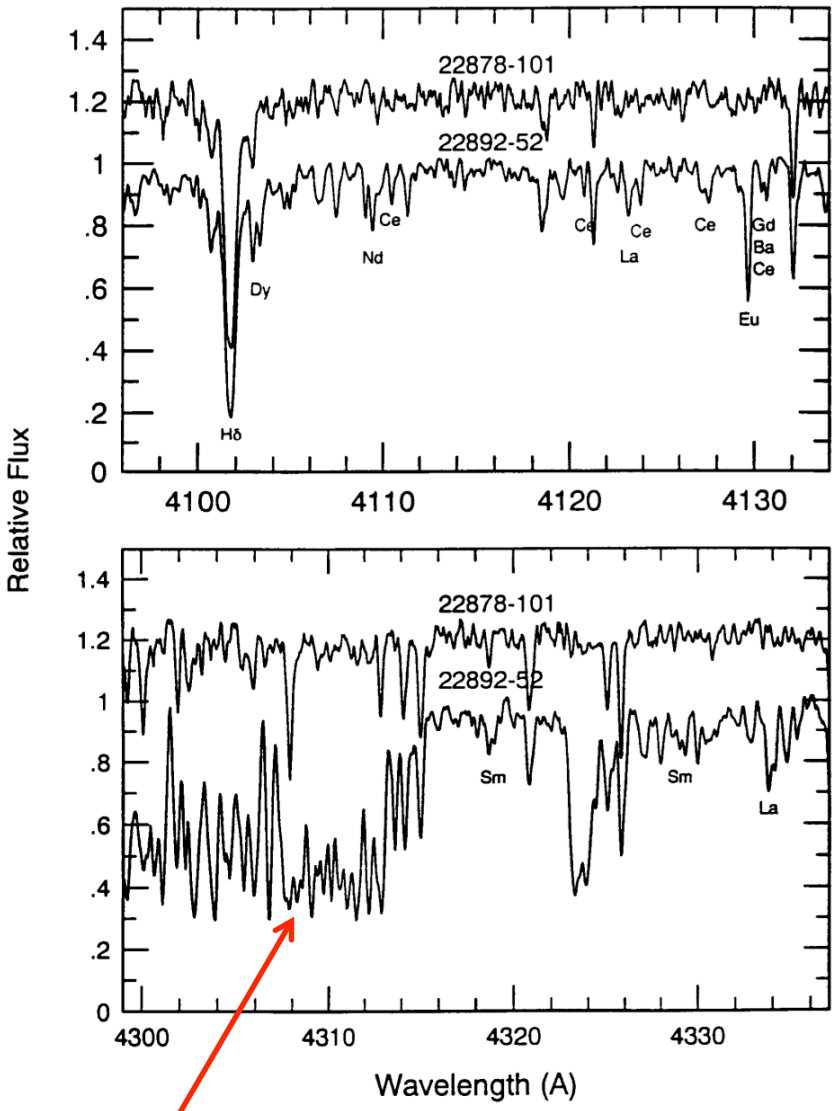
FIG. 5b



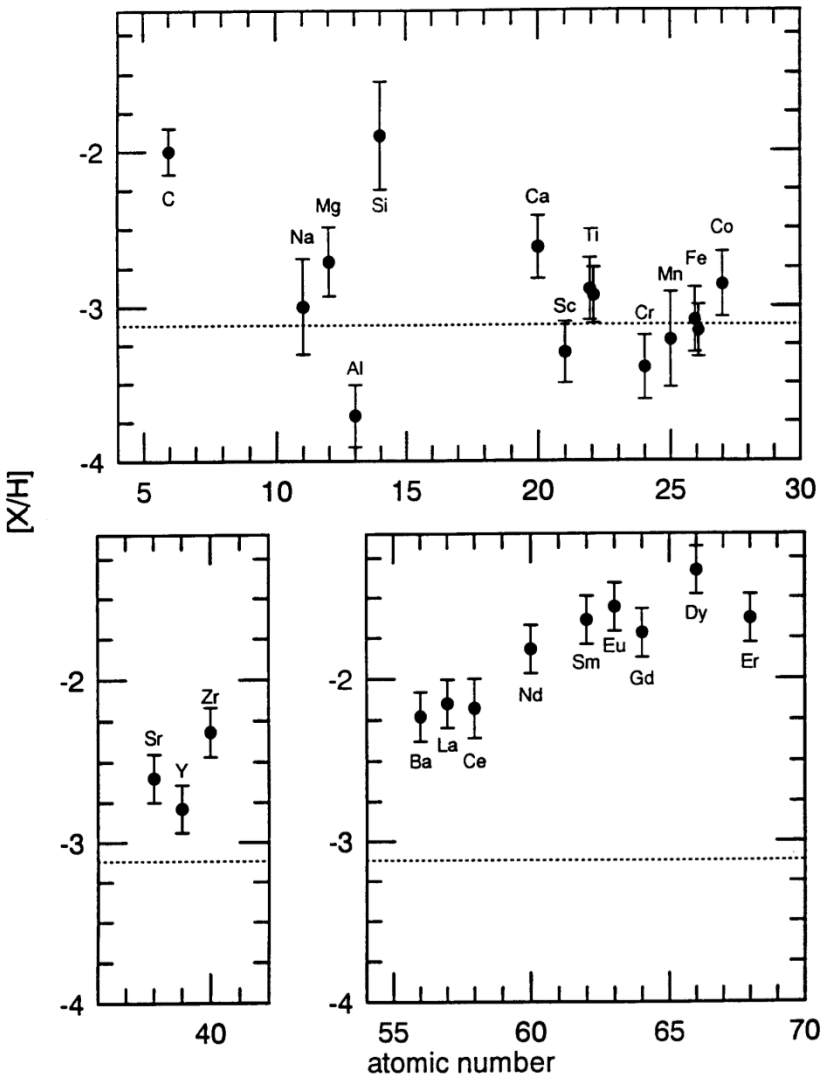


Mathews, Bazan, & Cowan 1992

The star that changed everything



High C abundance continues to be the weird aspect of this star



Sneden, Preston, McWilliam, Searle 1994

The theme of this conference?

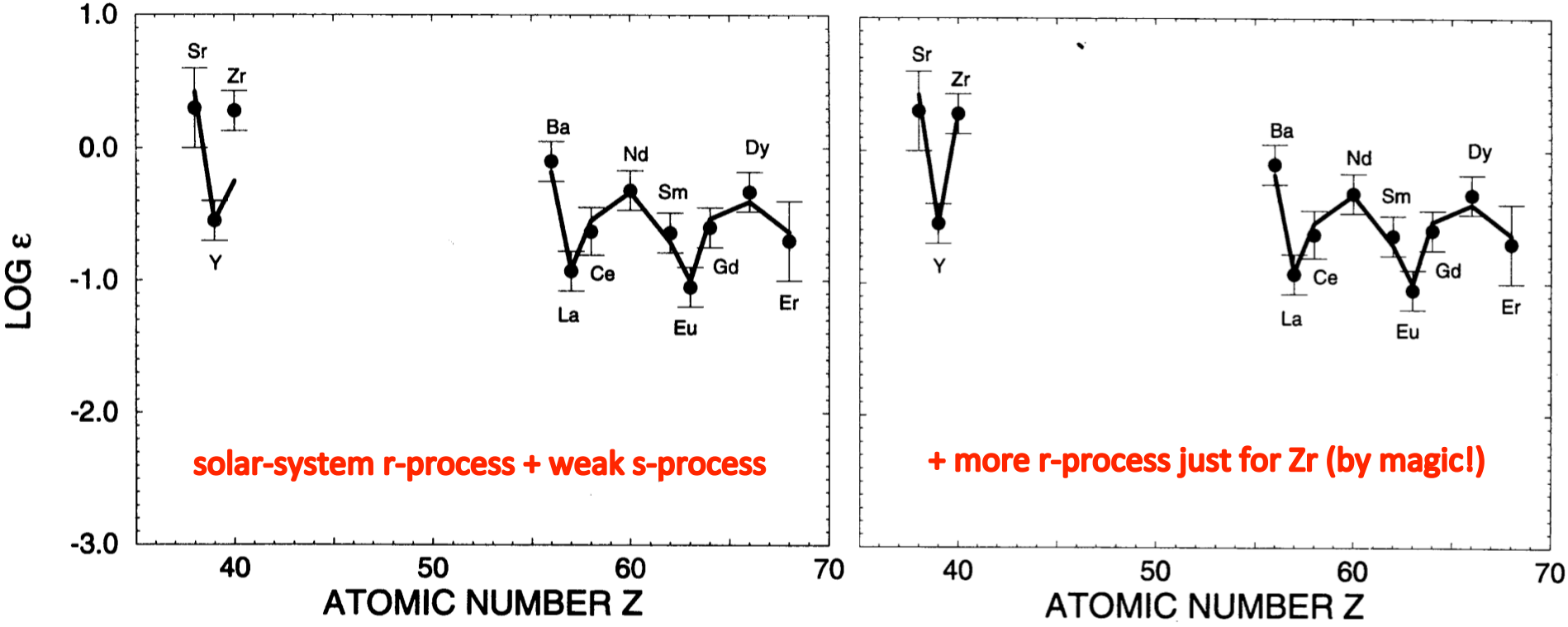
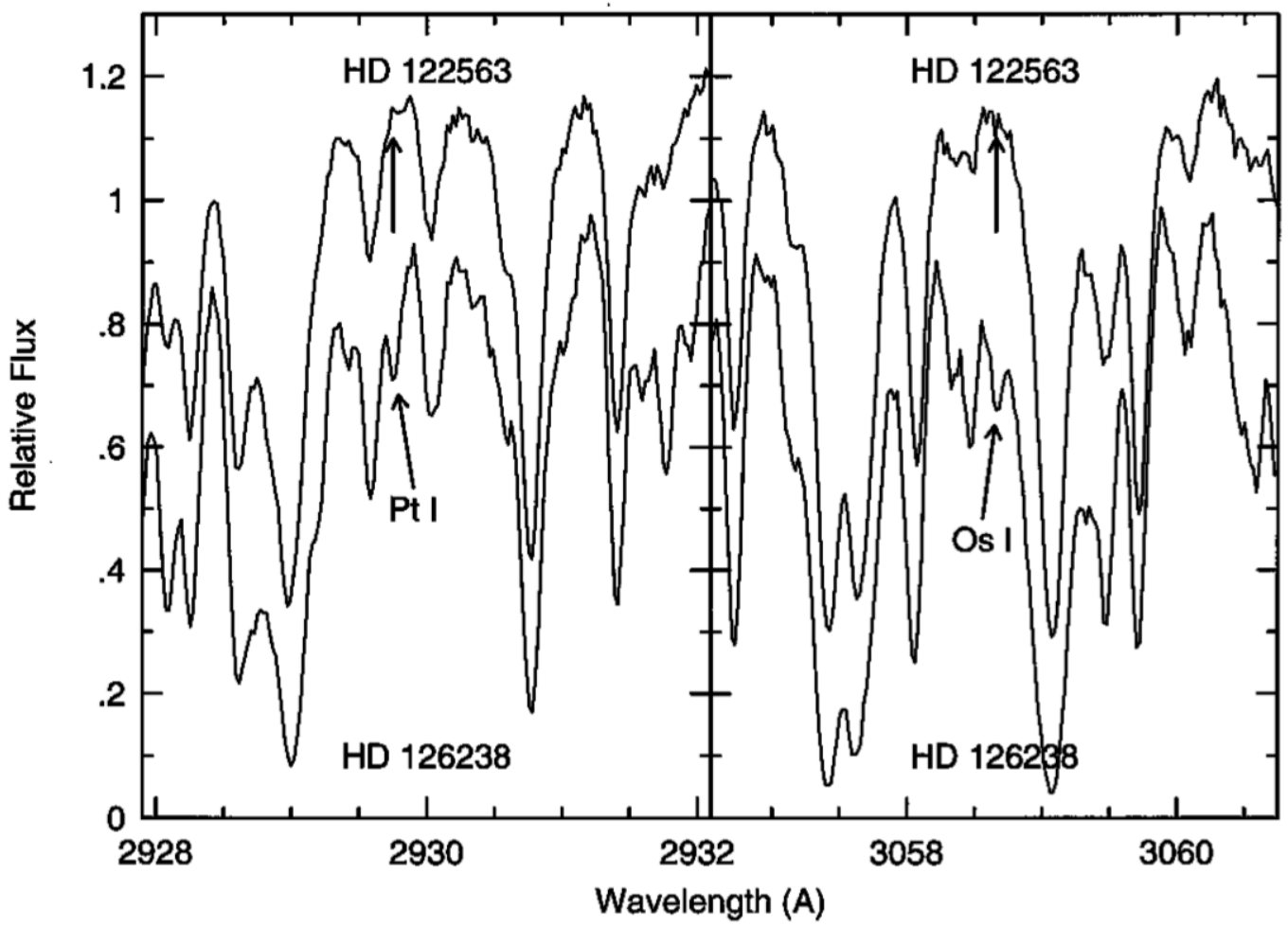


FIG. 2.—(*a*) Theoretical fit to the abundances in CS 22892−052 assuming a relative solar *r*-process distribution for the elements Ba-Er, and the predicted abundances of Sr, Y, and Zr from the weak *s*-process models of Raiteri et al. (1993). (*b*) Same as (*a*) except an additional contribution from the *r*-process is assumed for Zr.

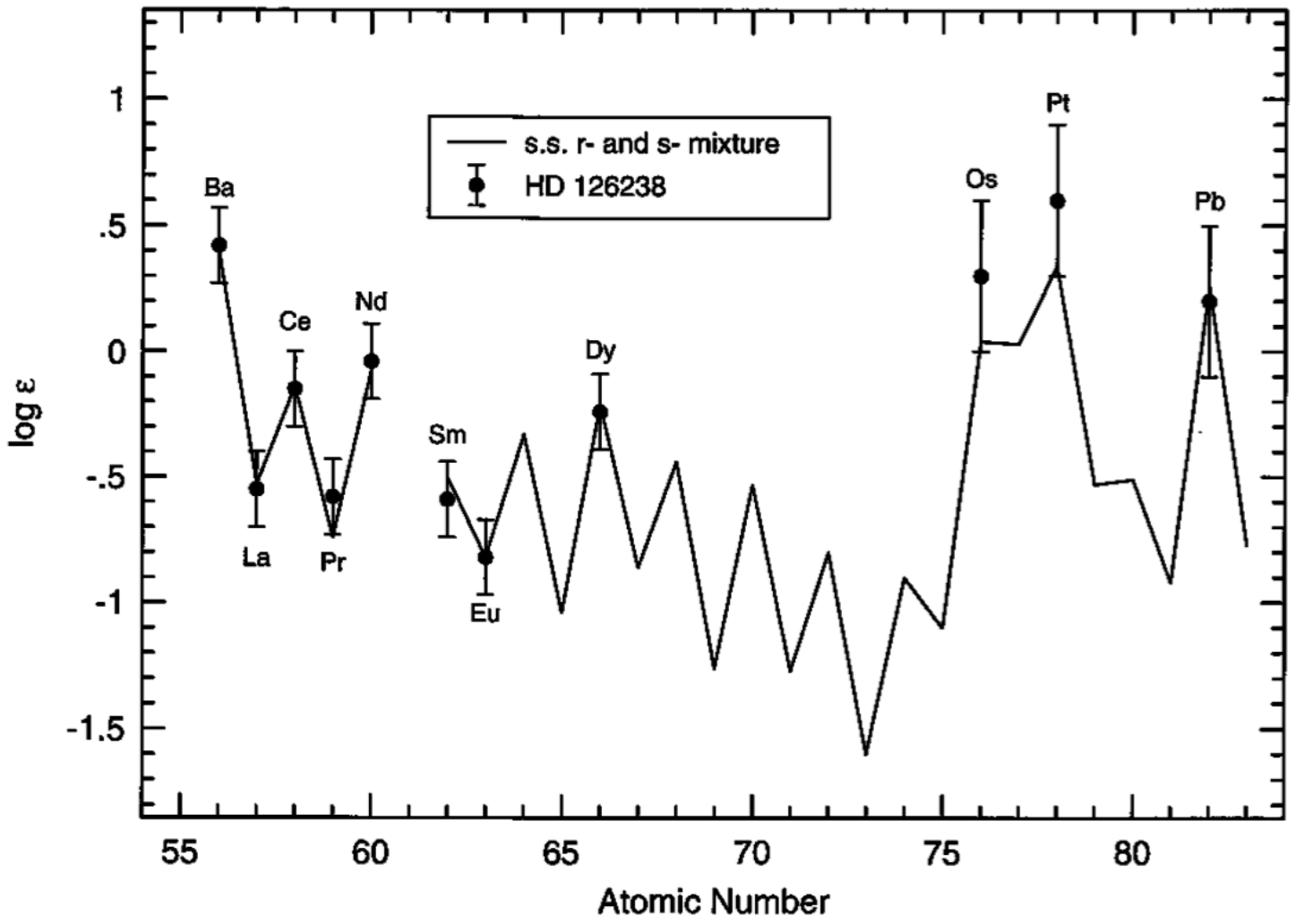
Cowan et al.1995

Into UV fog: first metal-poor star detections of Pt, Os



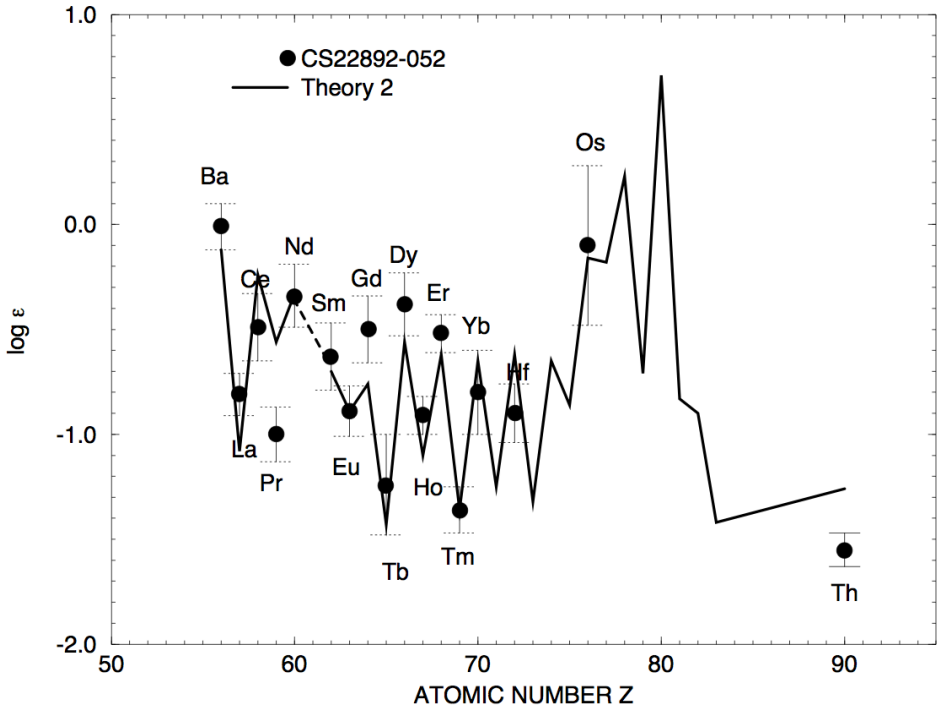
Cowan, Sneden, Truran, Burris 1996

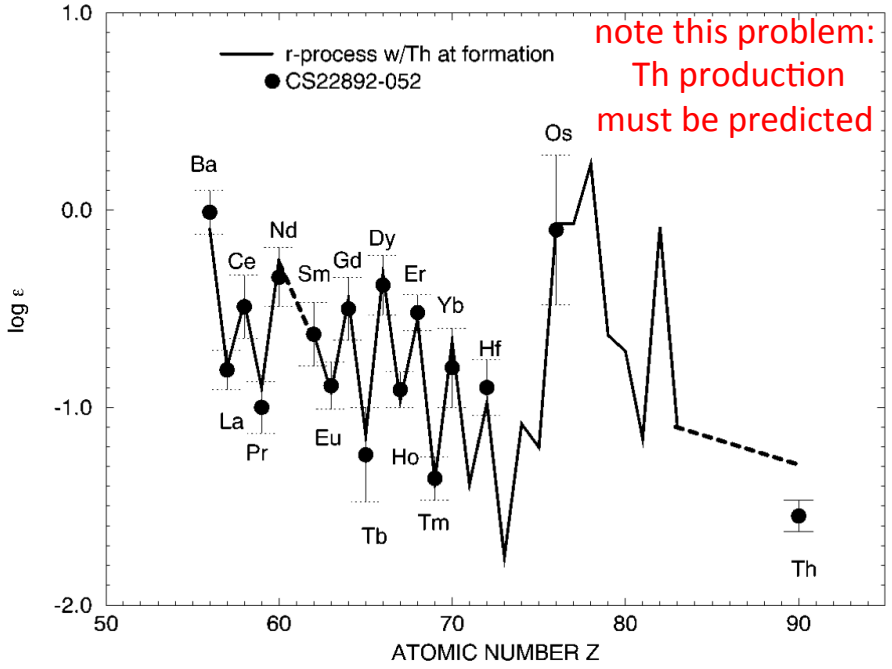
To extend out to the heaviest stable elements



Cowan et al. 1996

R-process quantitative predictions were advancing

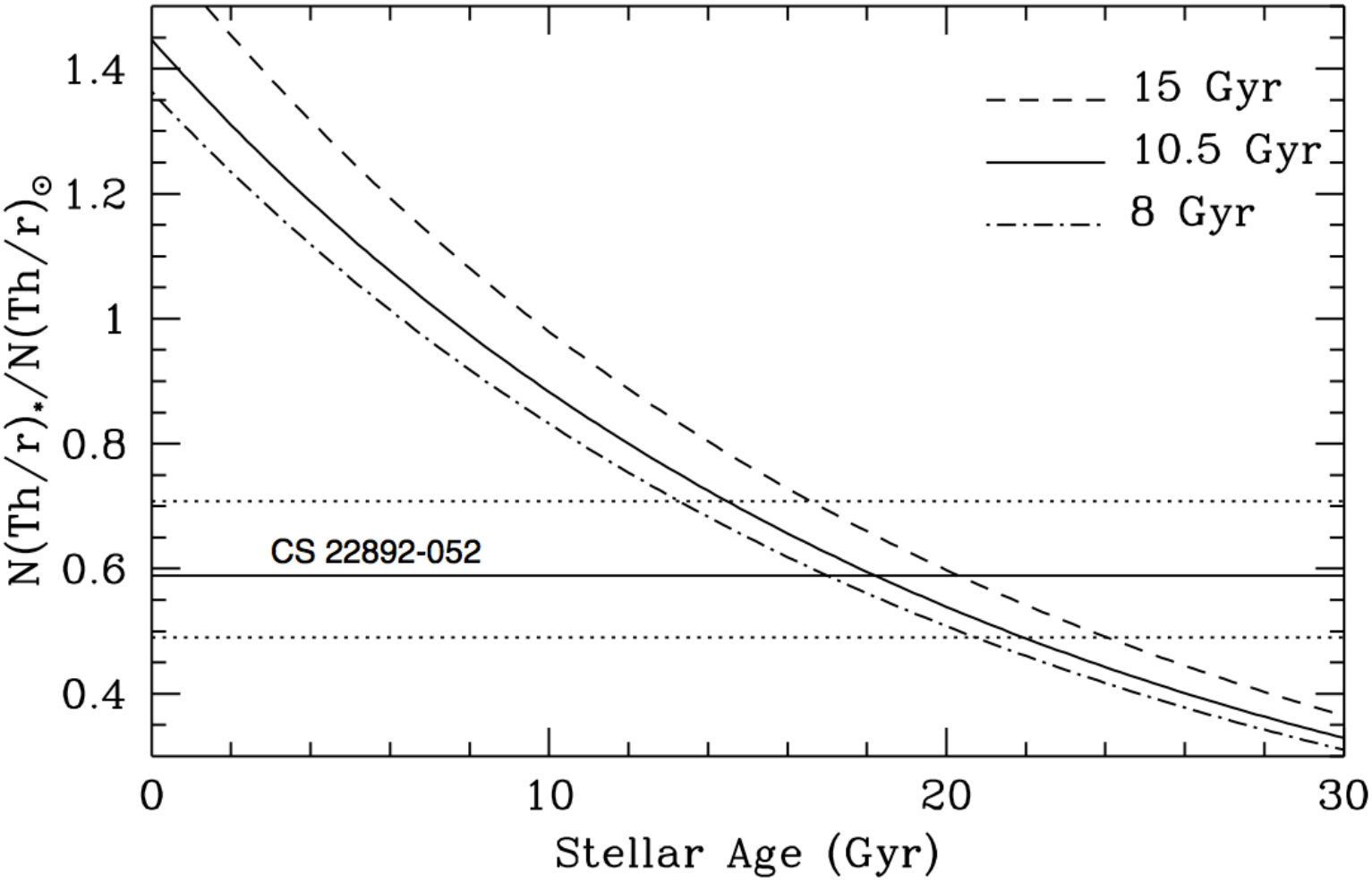




note this problem:
Th production
must be predicted

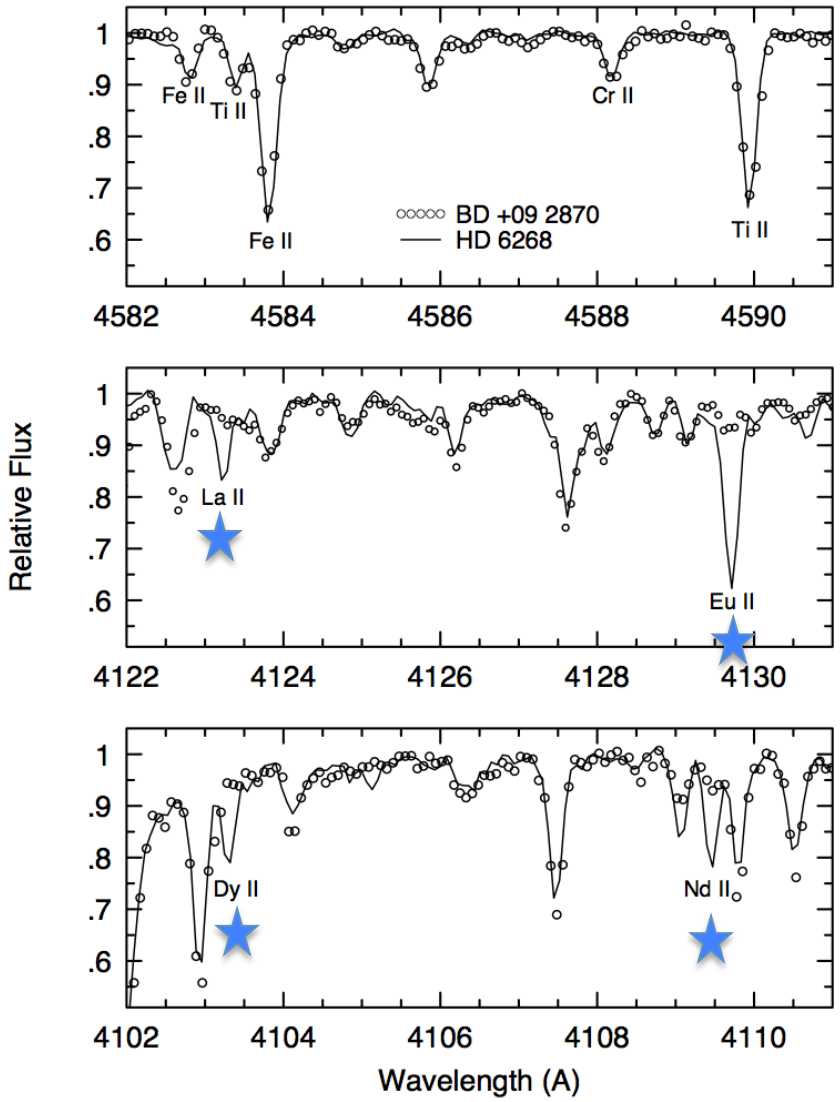
Cowan, McWIlliam, Sneden, Burris 1997

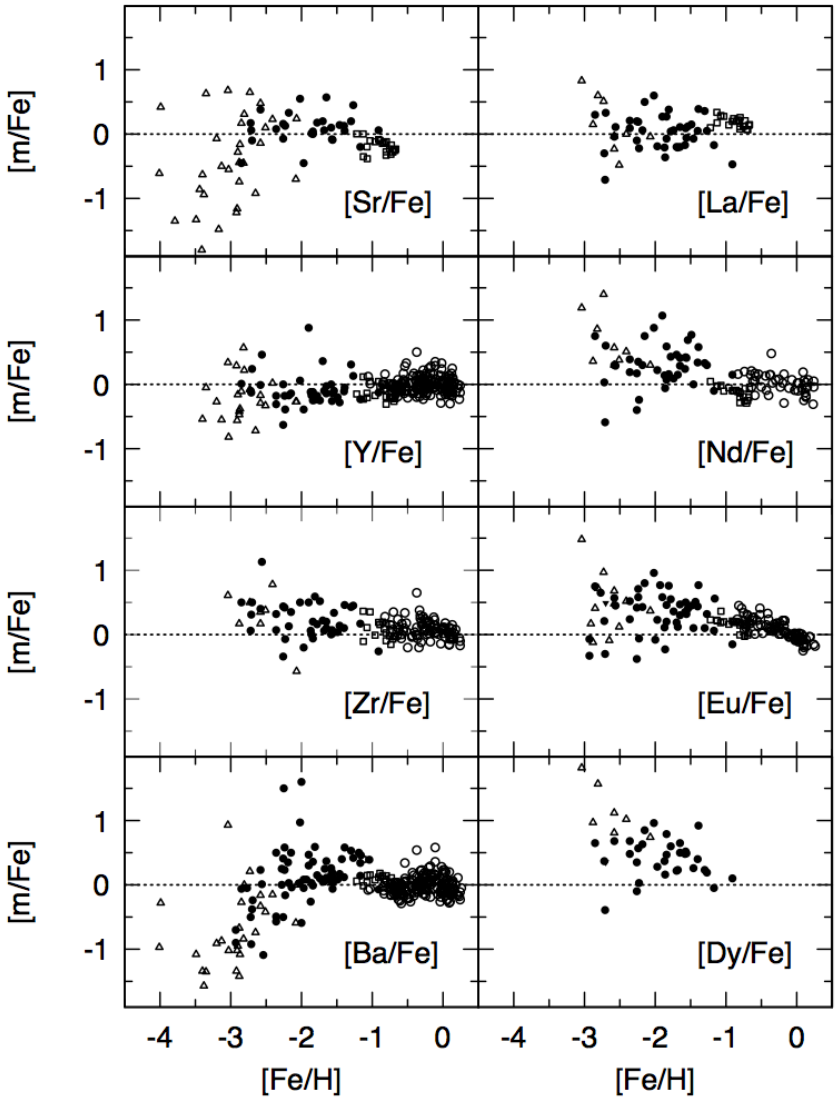
Yielding age estimates with simple Galactic chemical evolution ideas



Cowan, McWIlliam, Sneden, Burris 1997

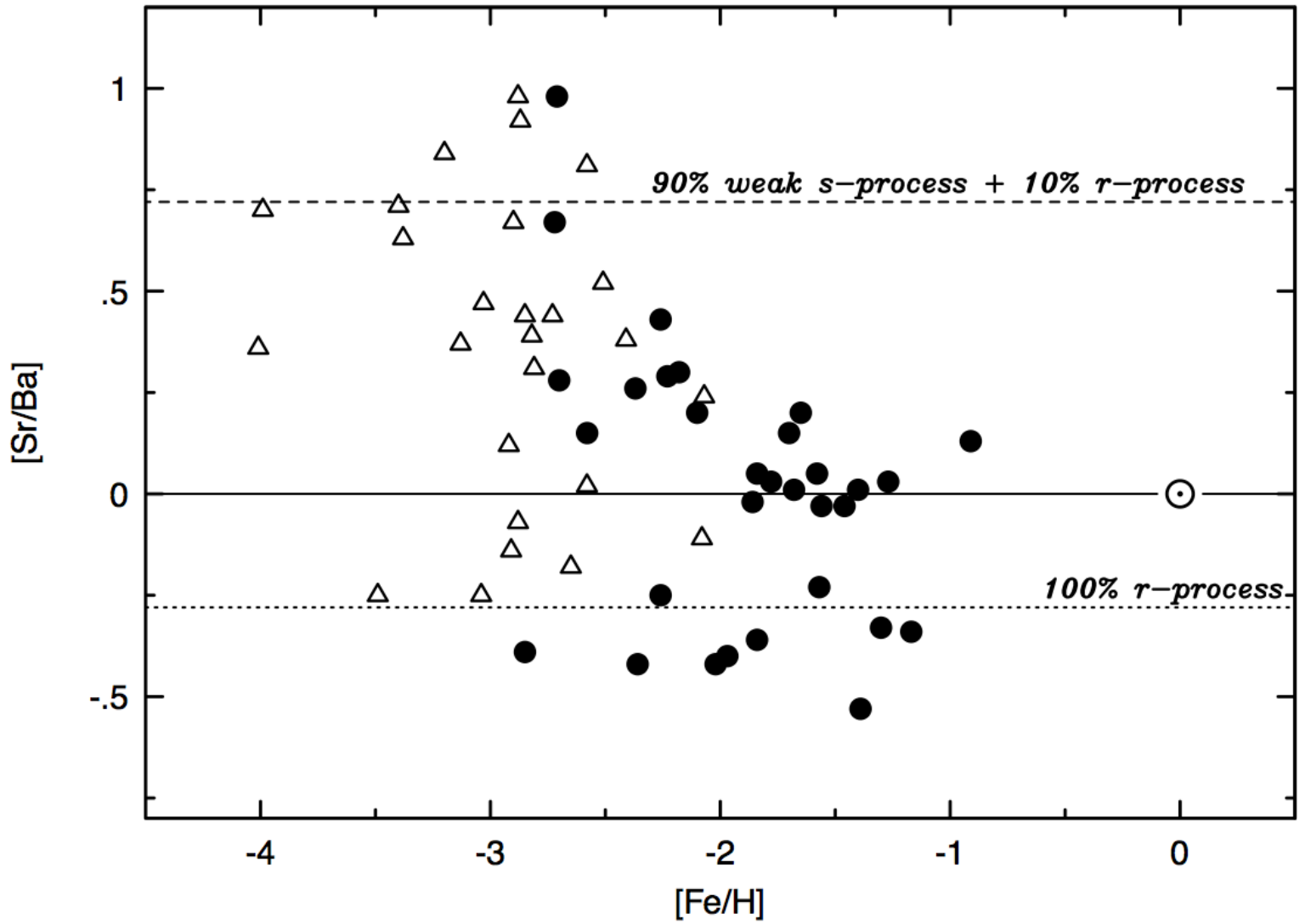
First modern large-sample n-capture survey





Burris, Cowan et al. 2000

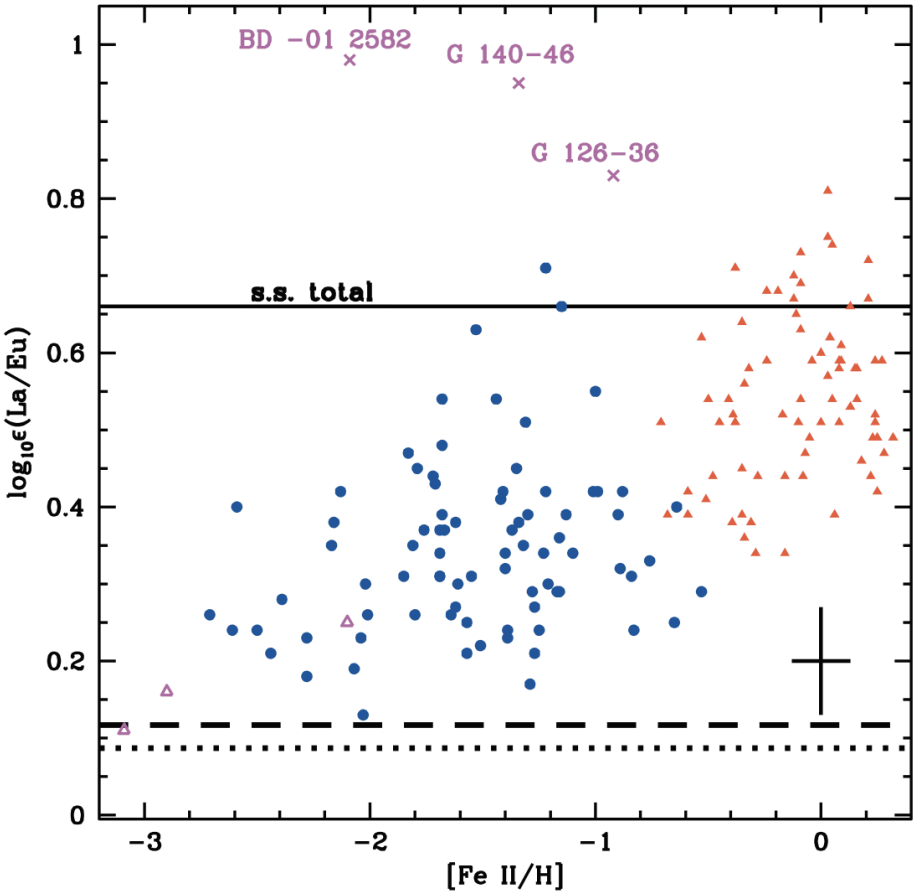
Again, this conference theme is hinted at



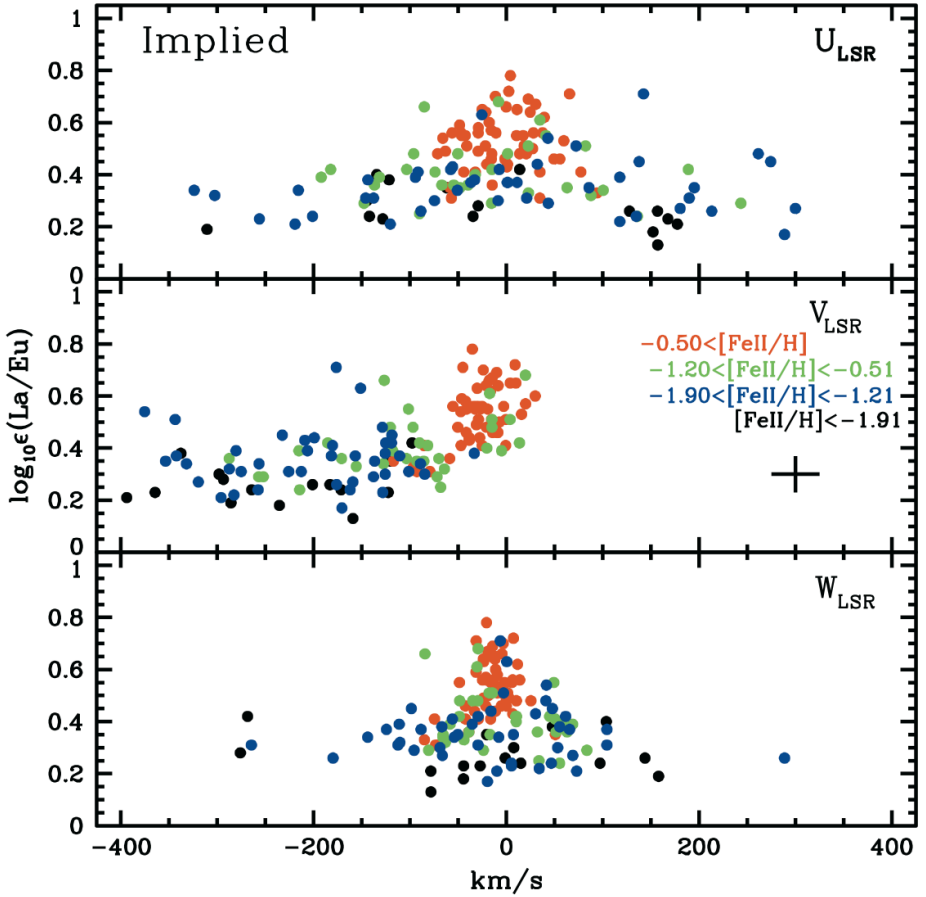
see also Johnson & Bolte 2002

Burris, Cowan et al. 2000

Galactic evolution of rare earths



scatter at a given [Fe/H] is huge;
few stars actually hit pure r-process line



a distinct velocity signature at higher [Fe/H]

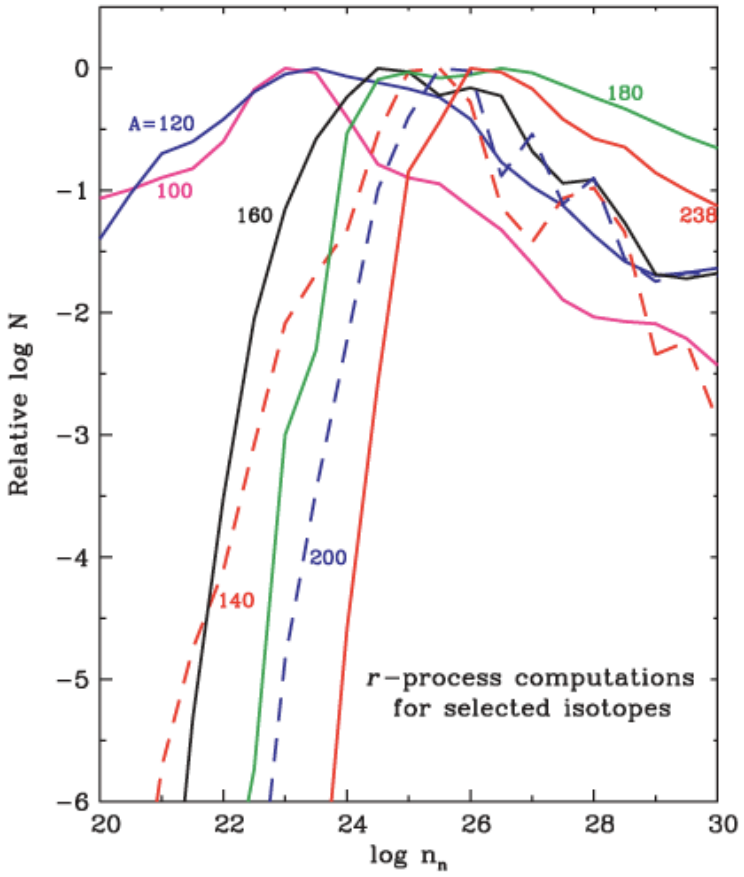
Simmerer, Cowan et al. 2004

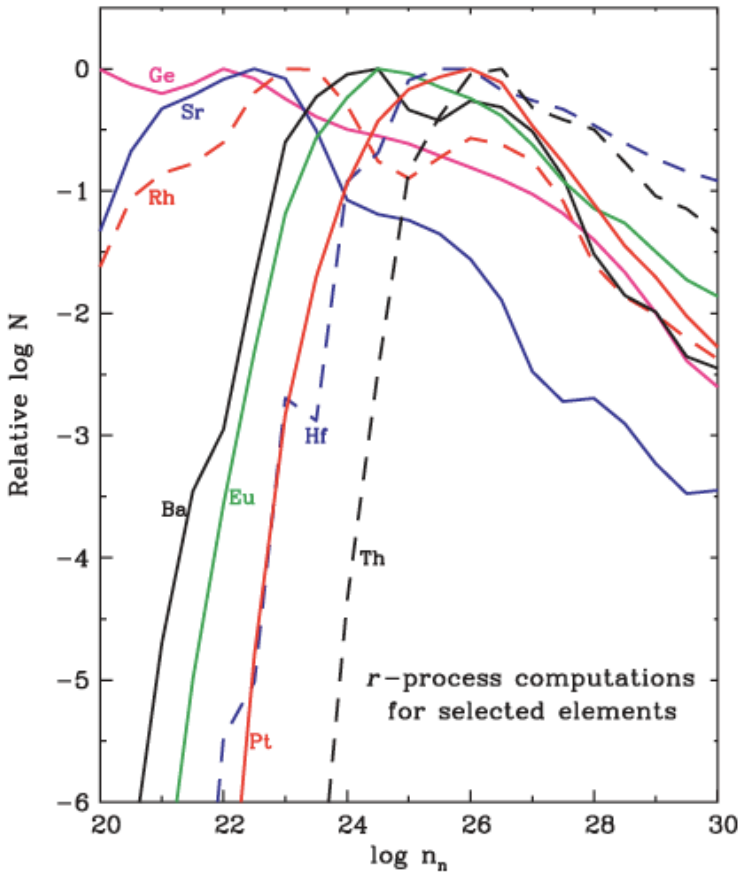
mating modern r-process predictions to observations

EXPLORATIONS OF THE *r*-PROCESSES: COMPARISONS BETWEEN CALCULATIONS AND OBSERVATIONS OF LOW-METALLICITY STARS

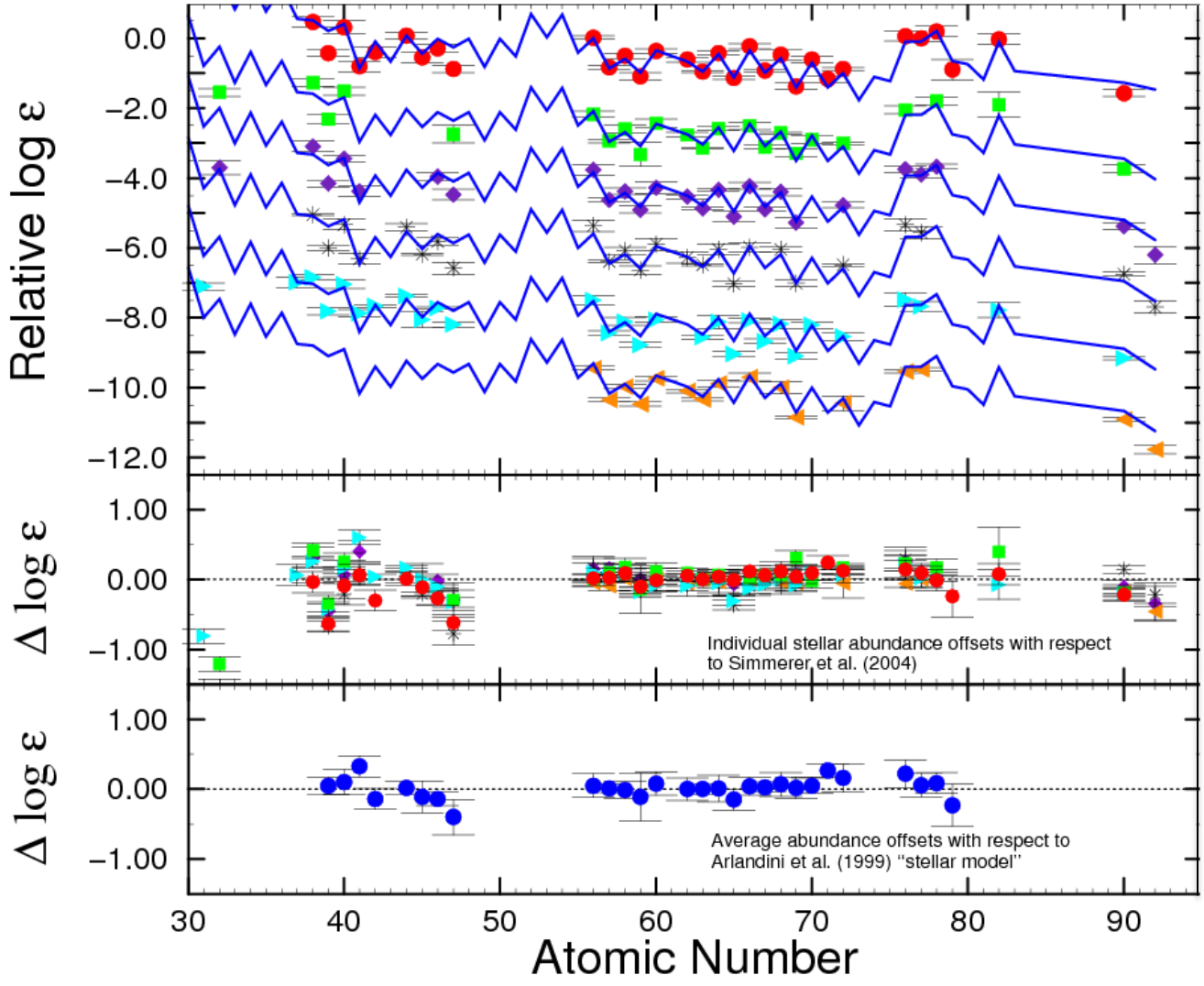
KARL-LUDWIG KRATZ,[1,2] KHALIL FAROUQI,[2] BERND PFEIFFER,[2] JAMES W. TRURAN,[3] CHRISTOPHER SNEDEN,[4] AND JOHN J. COWAN[5]

THE ASTROPHYSICAL JOURNAL, 662:39–52, 2007 June 10





goal: to attack n-capture compositions of well-studied *r*-rich stars (*Così fan tutte??)*



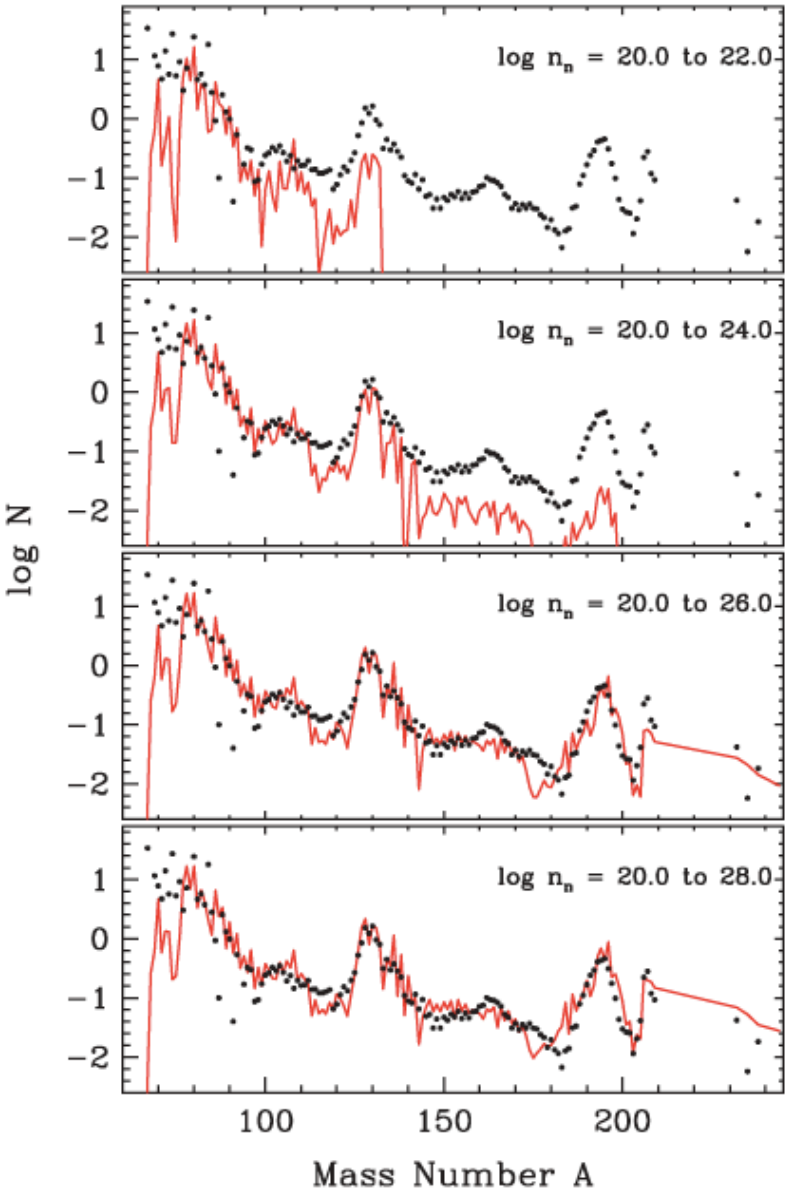
lines are solar-system abundances

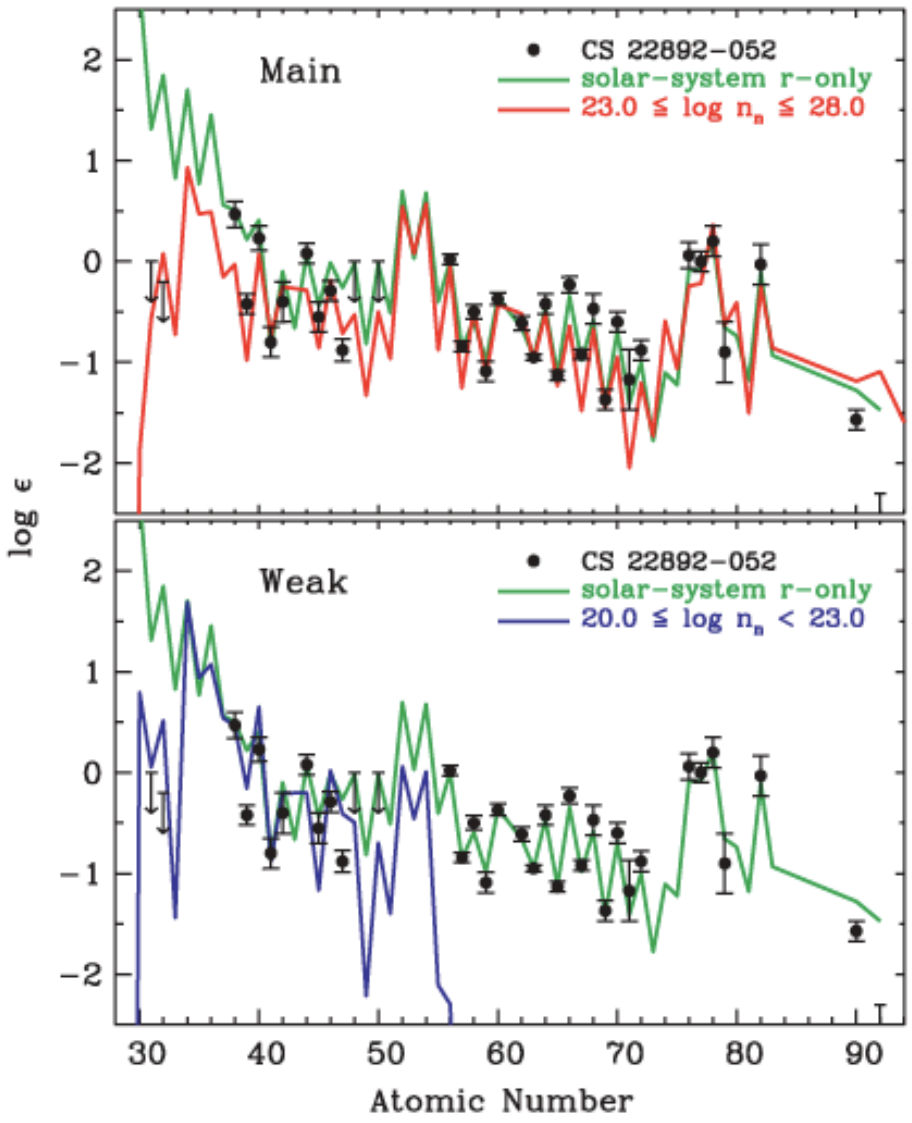
differences from solar-system

means of the differences

Sneden et al. 2008

trying to delimit the density regimes of the r-process





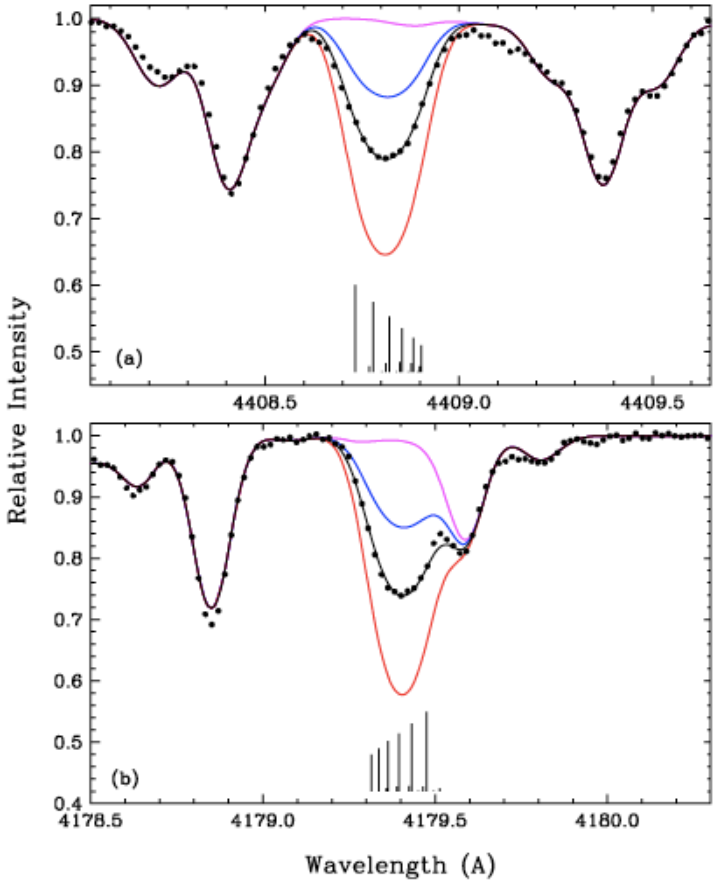
Kratz et al. 2007

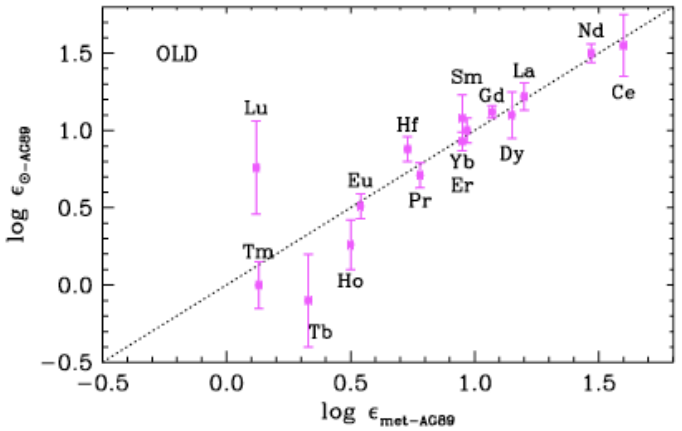
John's role in increasing the abundance rigor

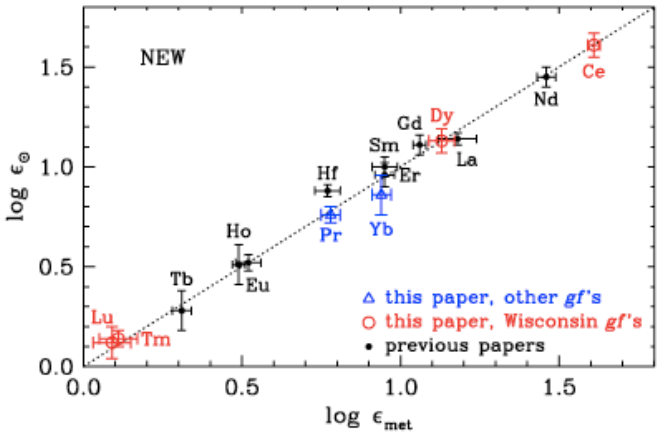
THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 182:80–96, 2009 May
doi:10.1088/0067-0049/182/1/80

NEW RARE EARTH ELEMENT ABUNDANCE DISTRIBUTIONS FOR THE SUN AND FIVE *r*-PROCESS-RICH VERY METAL-POOR STARS

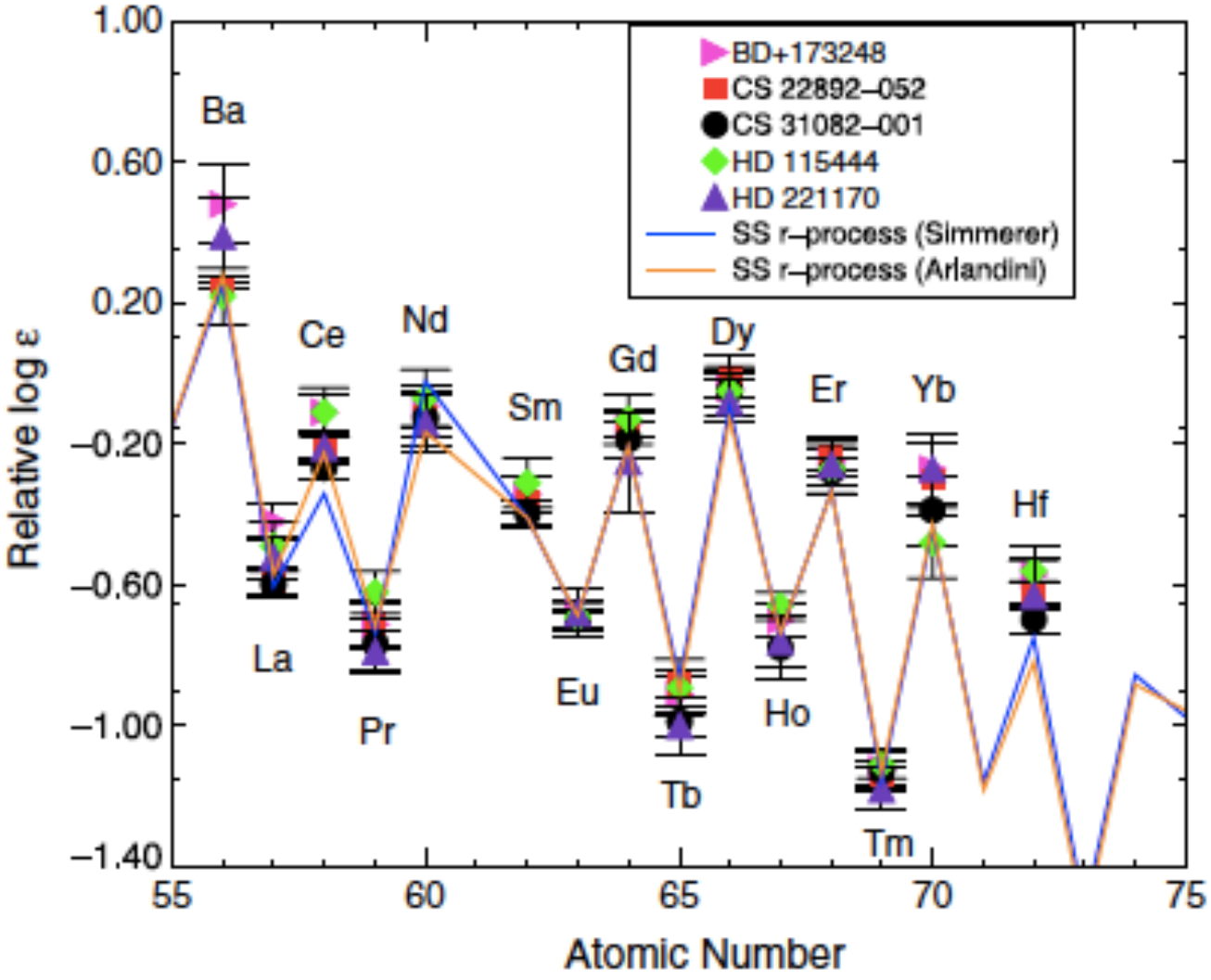
CHRISTOPHER SNEDEN[1,2], JAMES E. LAWLER[3], JOHN J. COWAN[4], INESE I. IVANS[5,6], AND ELIZABETH A. DEN HARTOG[3]





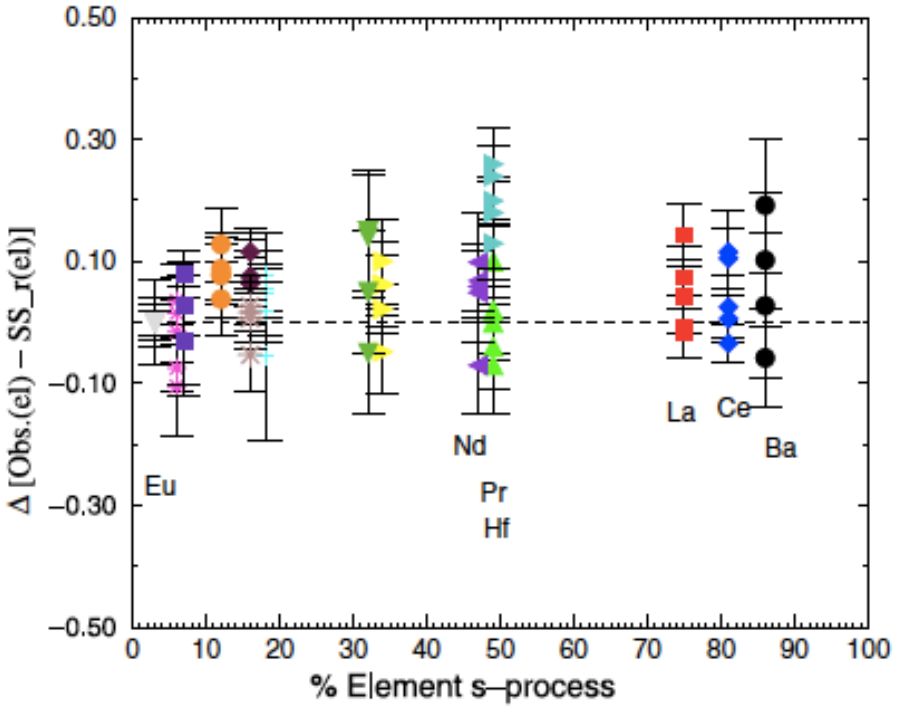


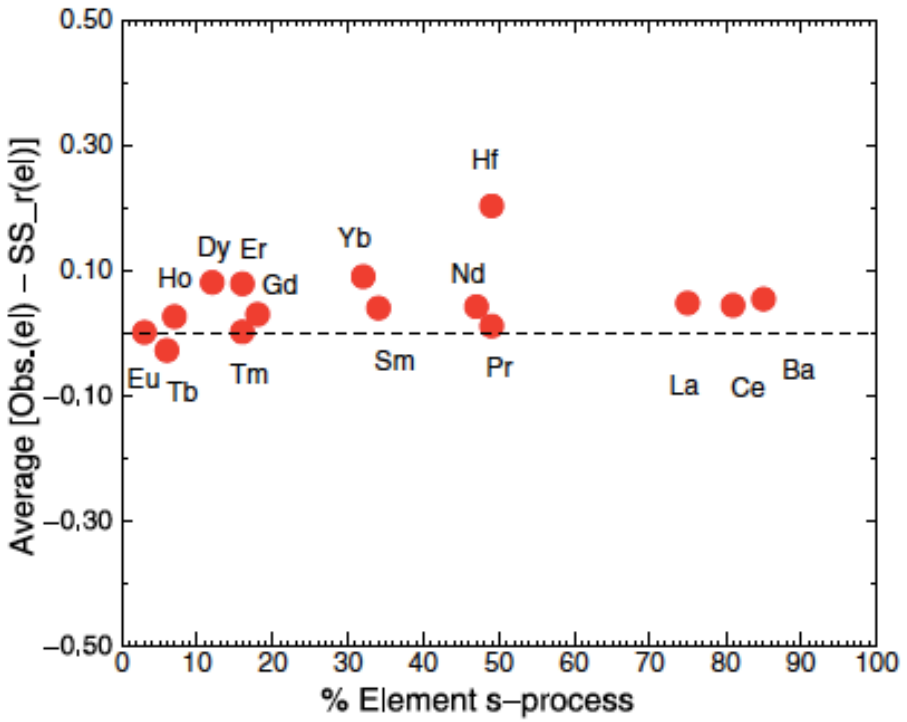
the real purpose: the extreme r-process stars



Sneden, Cowan et al. 2009

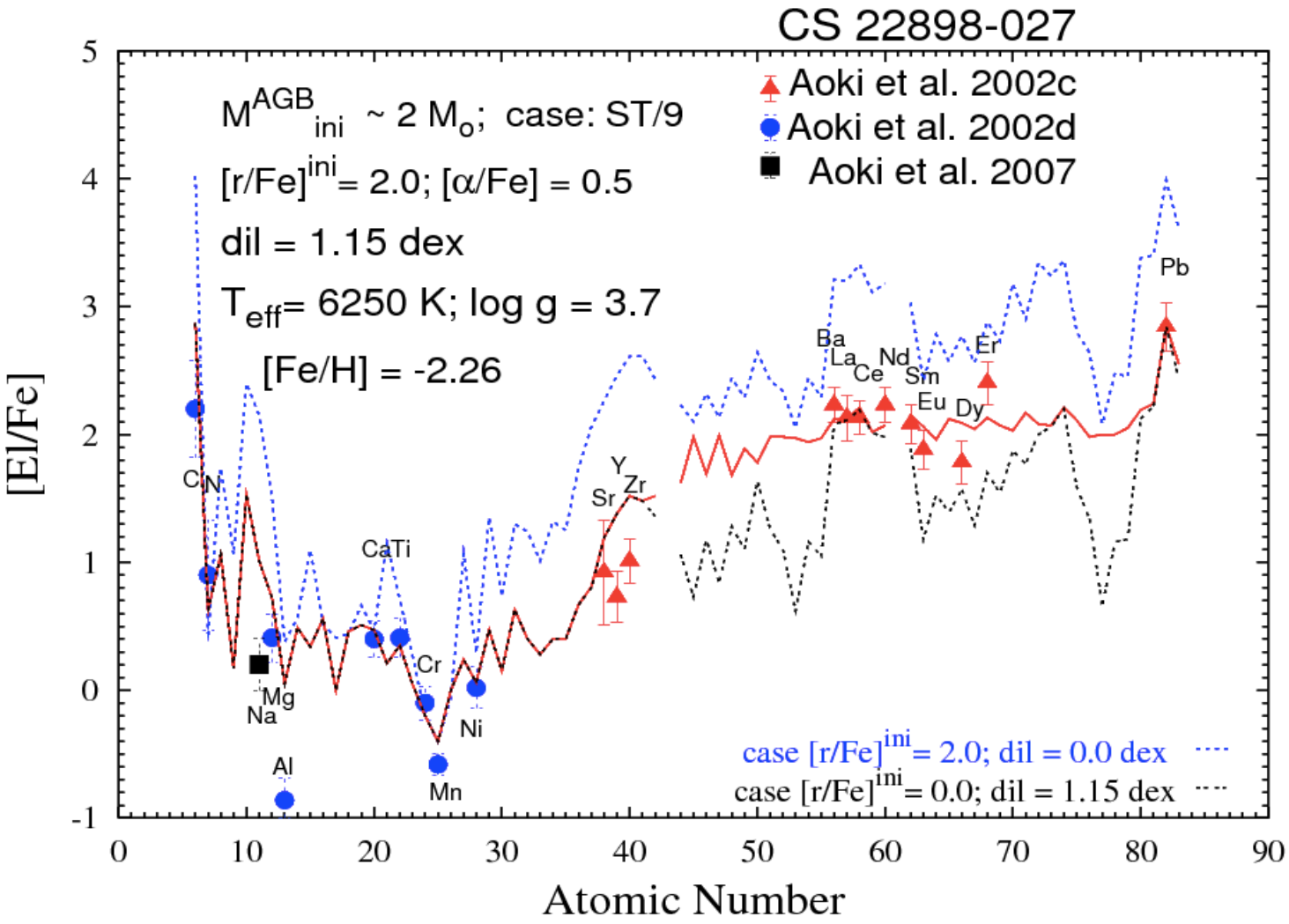
tightening the screws on r-process interpretations





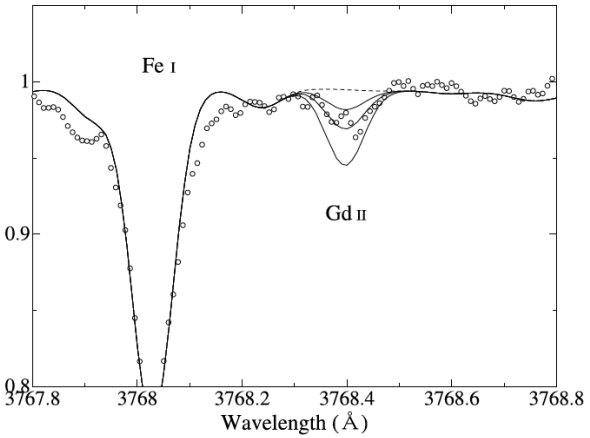
Sneden, Cowan et al. 2009

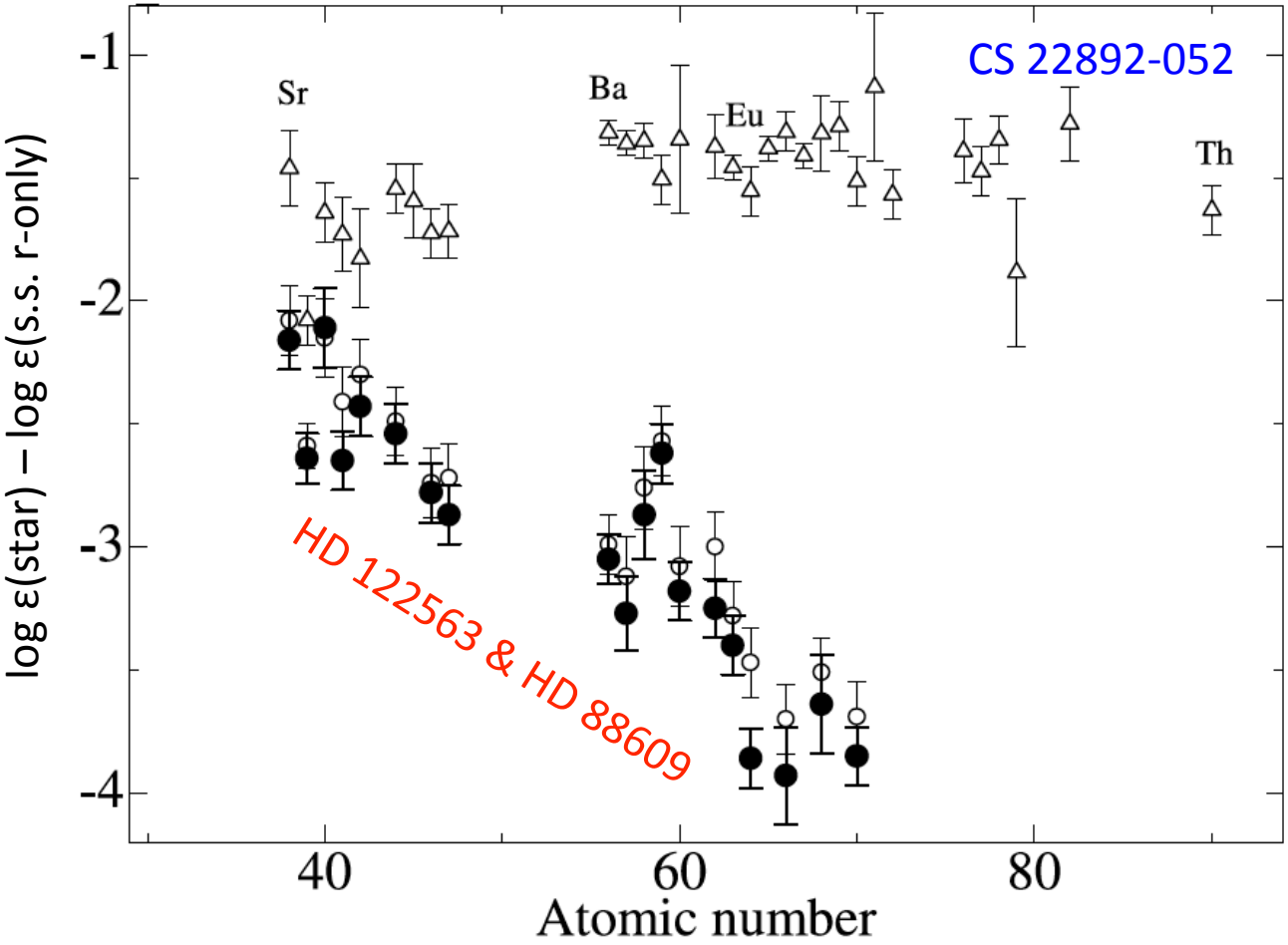
Sort-of digression: interpretation s-process-rich (& r-rich also) abundance patterns is non-trivial



Sneden, Cowan, & Gallino 2008

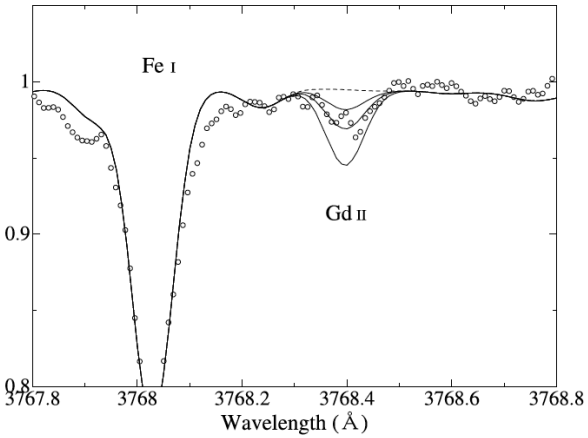
not a digression: n-cap-poor but r-process-rich stars

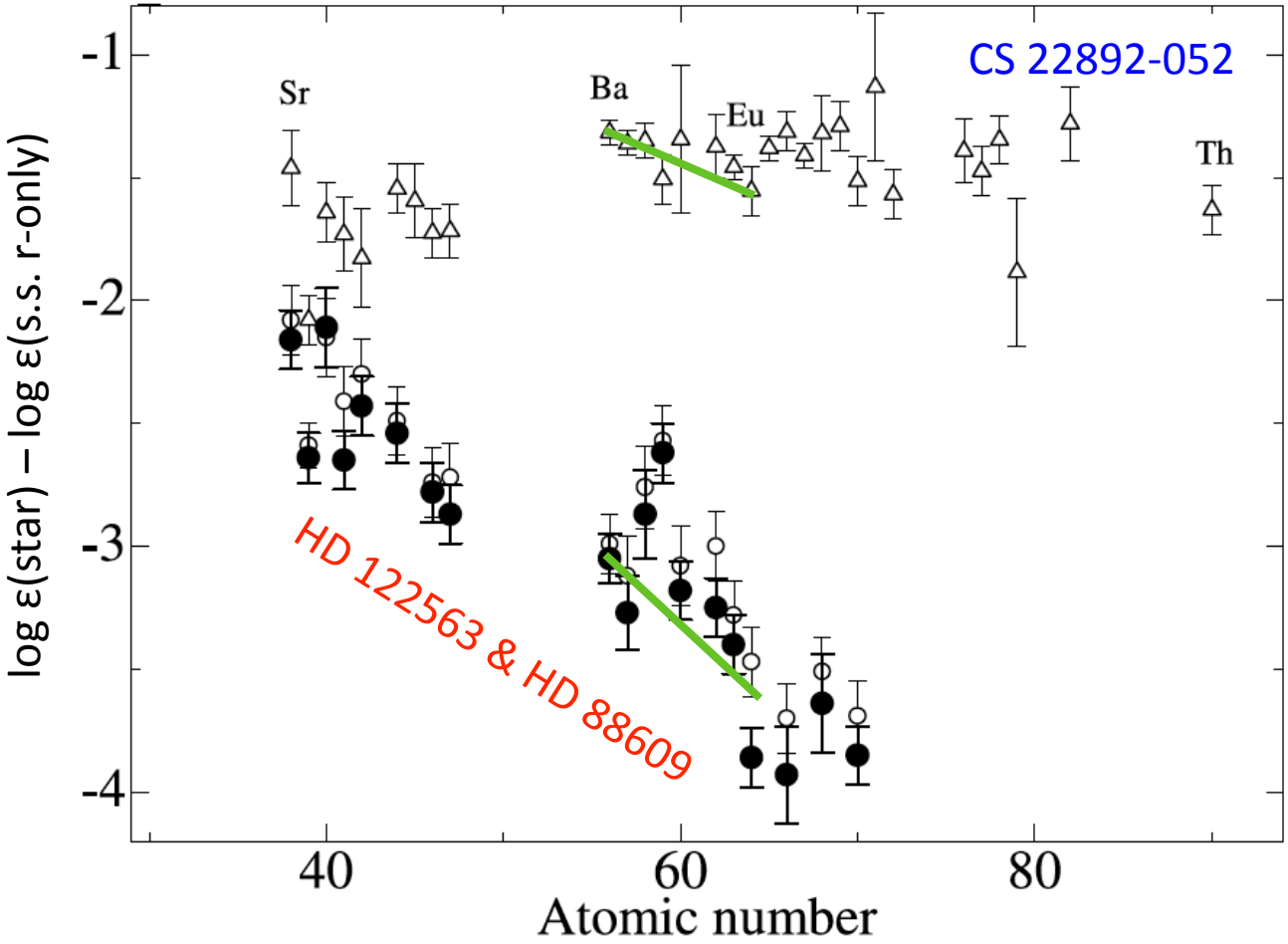




Honda et al. 2007

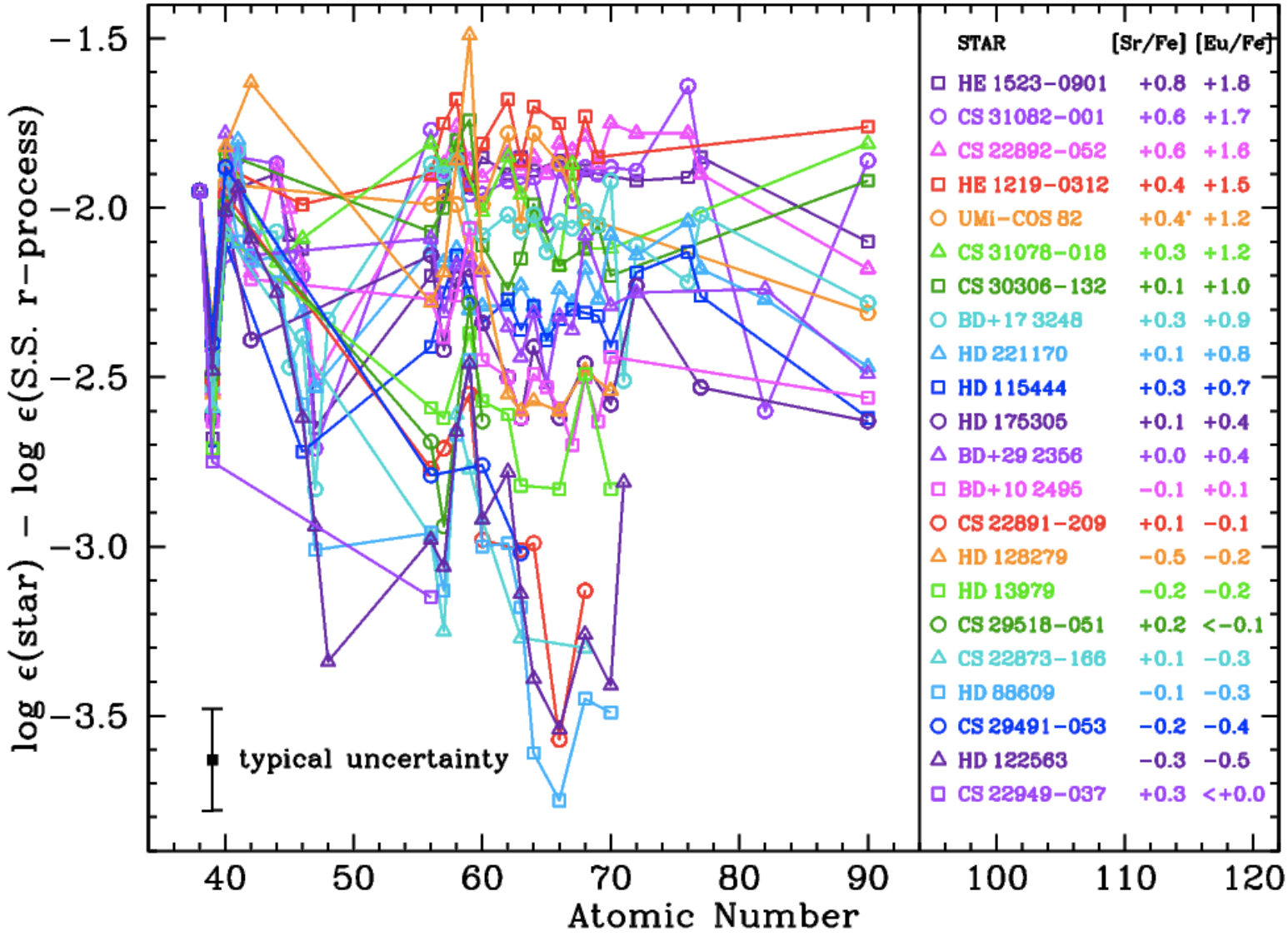
The Ba/Eu ratios are “similar”





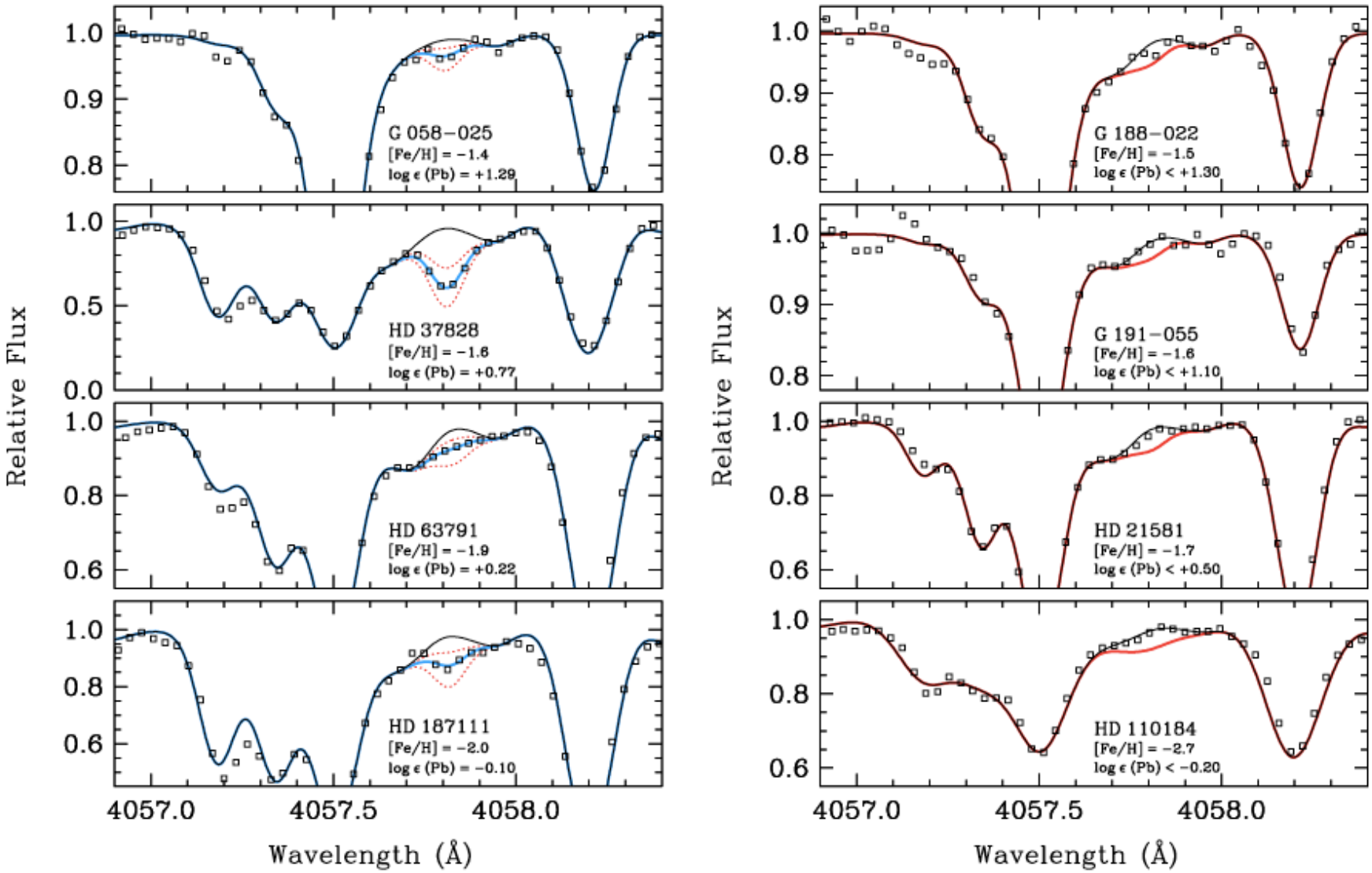
Honda et al. 2007

Leading to this assertion: these are ALL r-rich stars



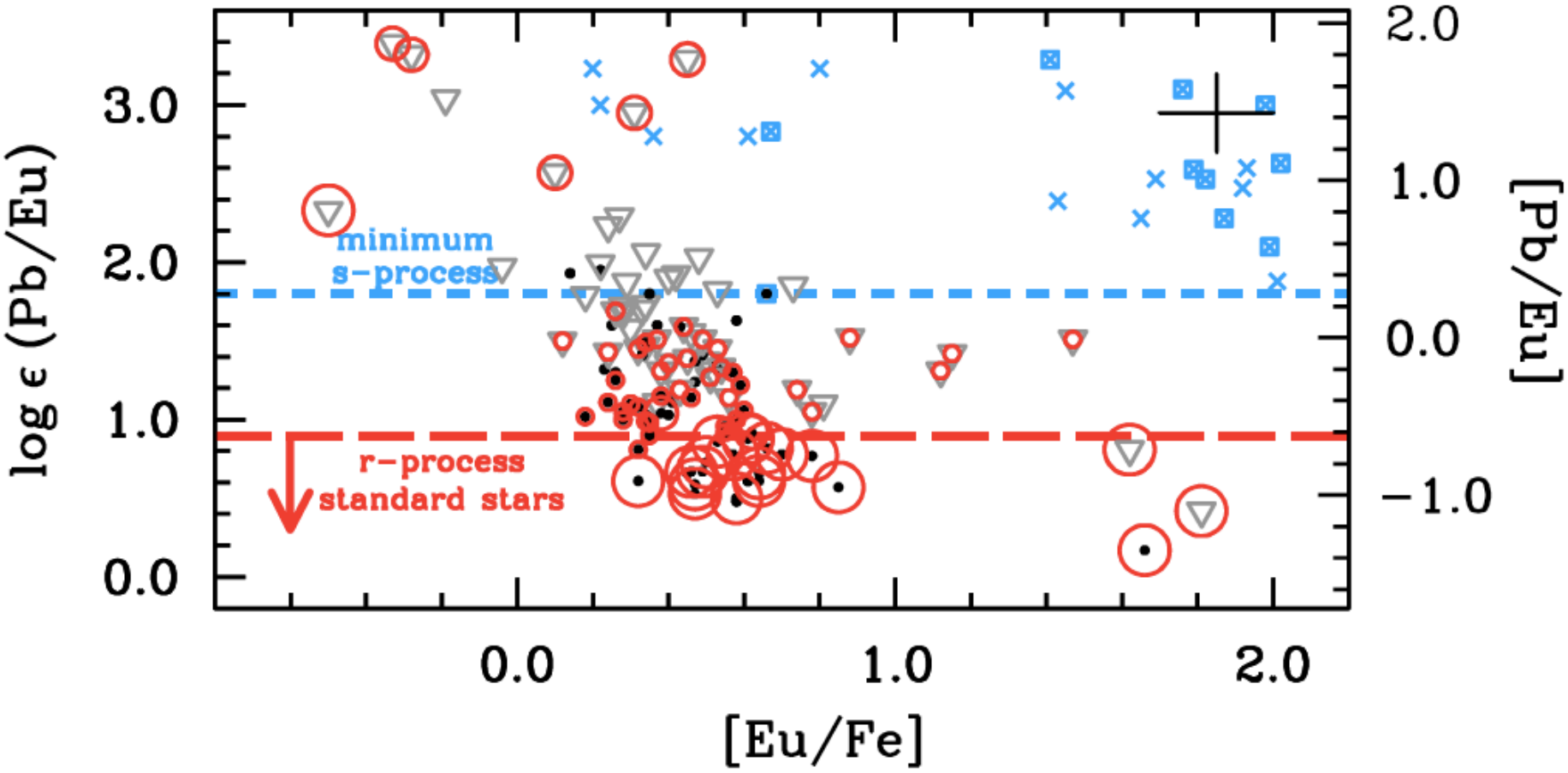
Roederer, Cowan, et al. 2010

How did we know? Pb as s-rich warning



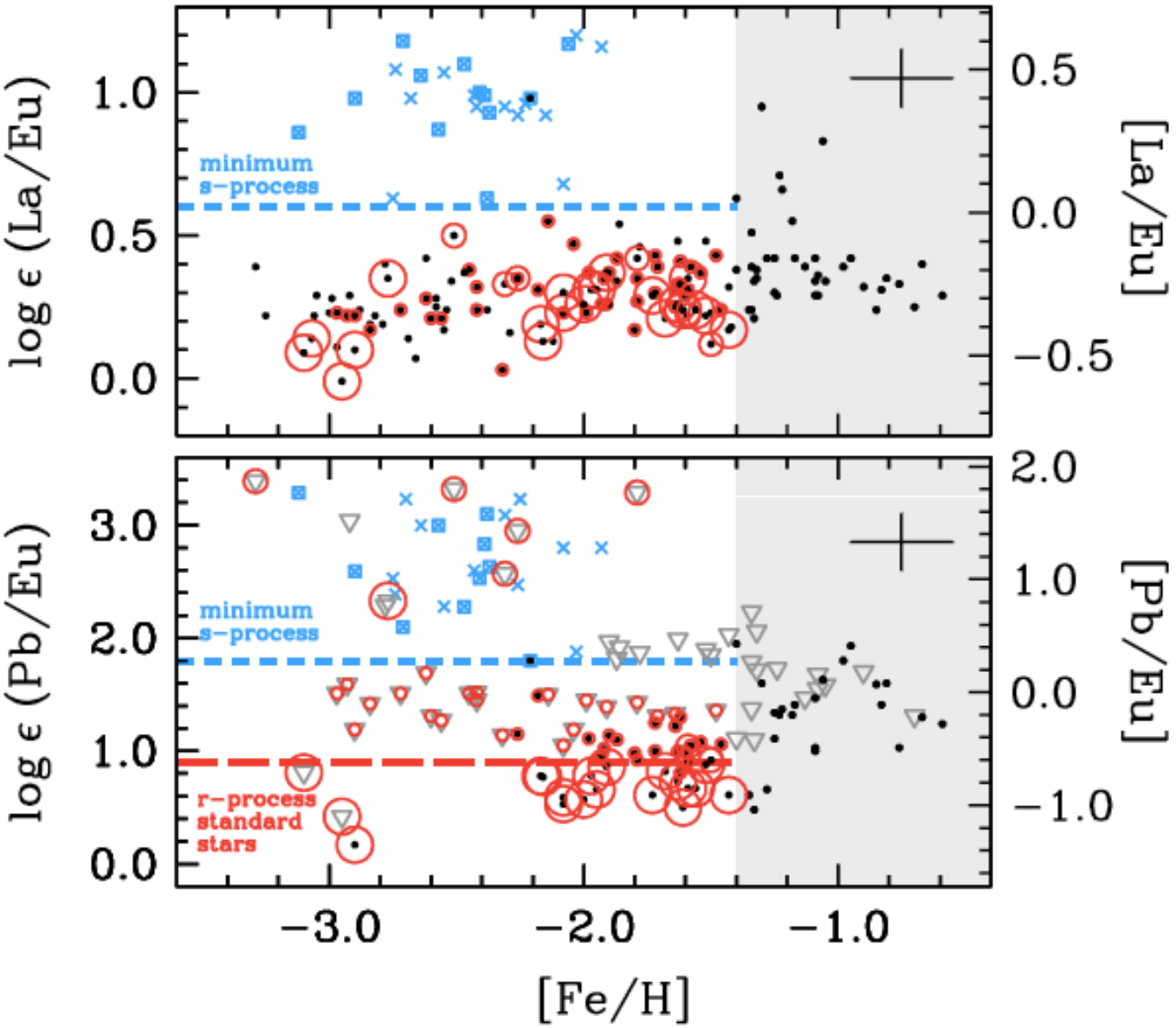
Roederer, Cowan et al. 2010

leading to a cut-off for r-rich stars



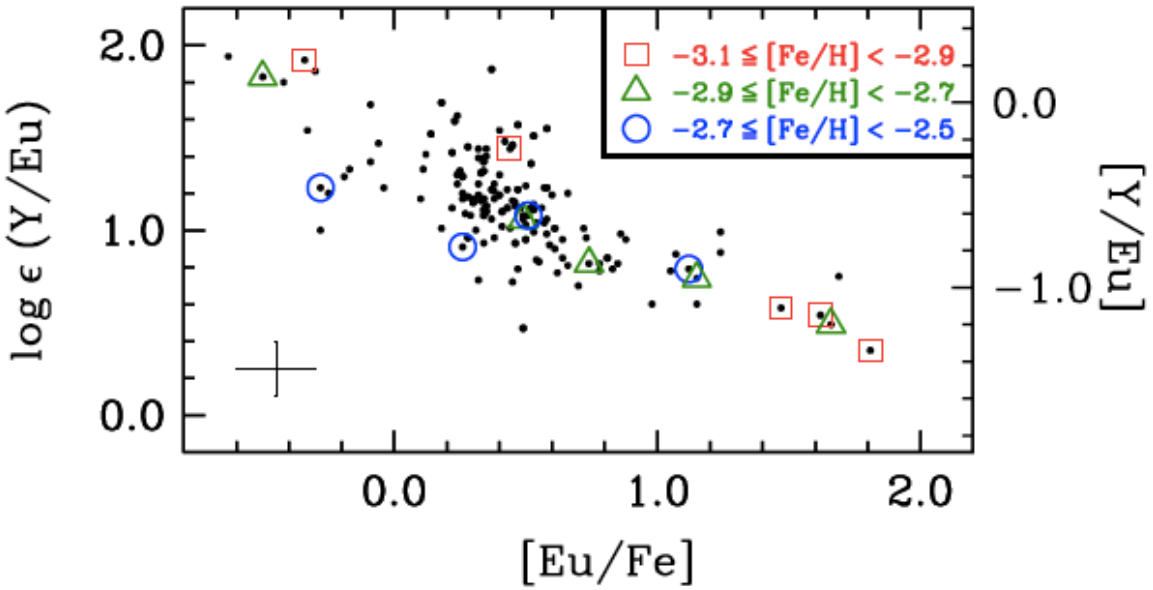
Roederer,, Cowan et al. 2010

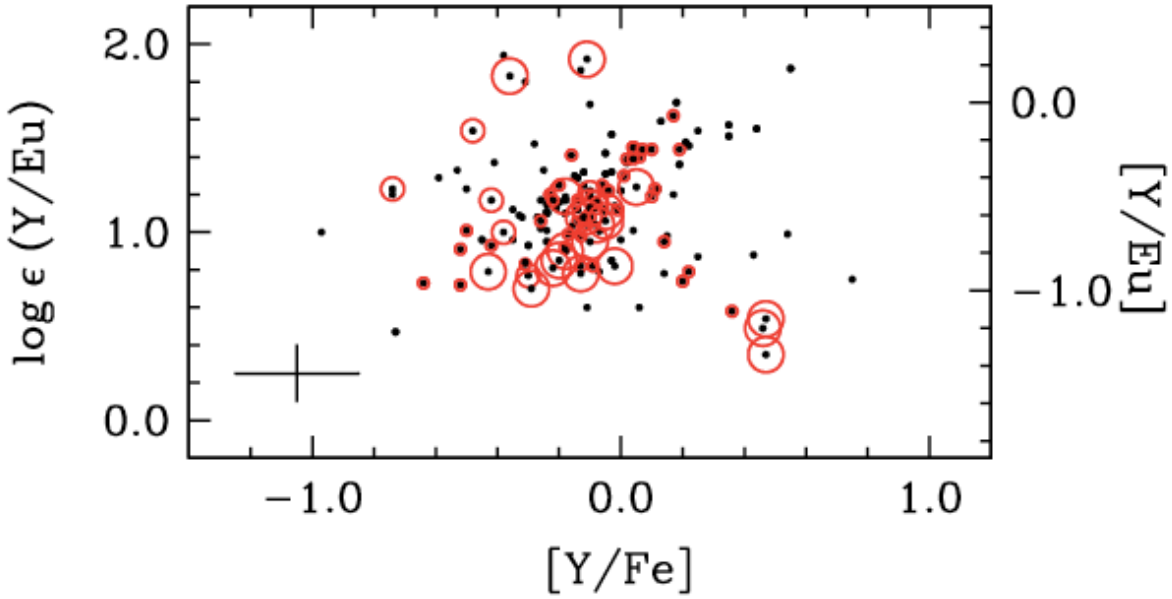
r/s discrimination is important



Roederer, Cowan et al. 2010

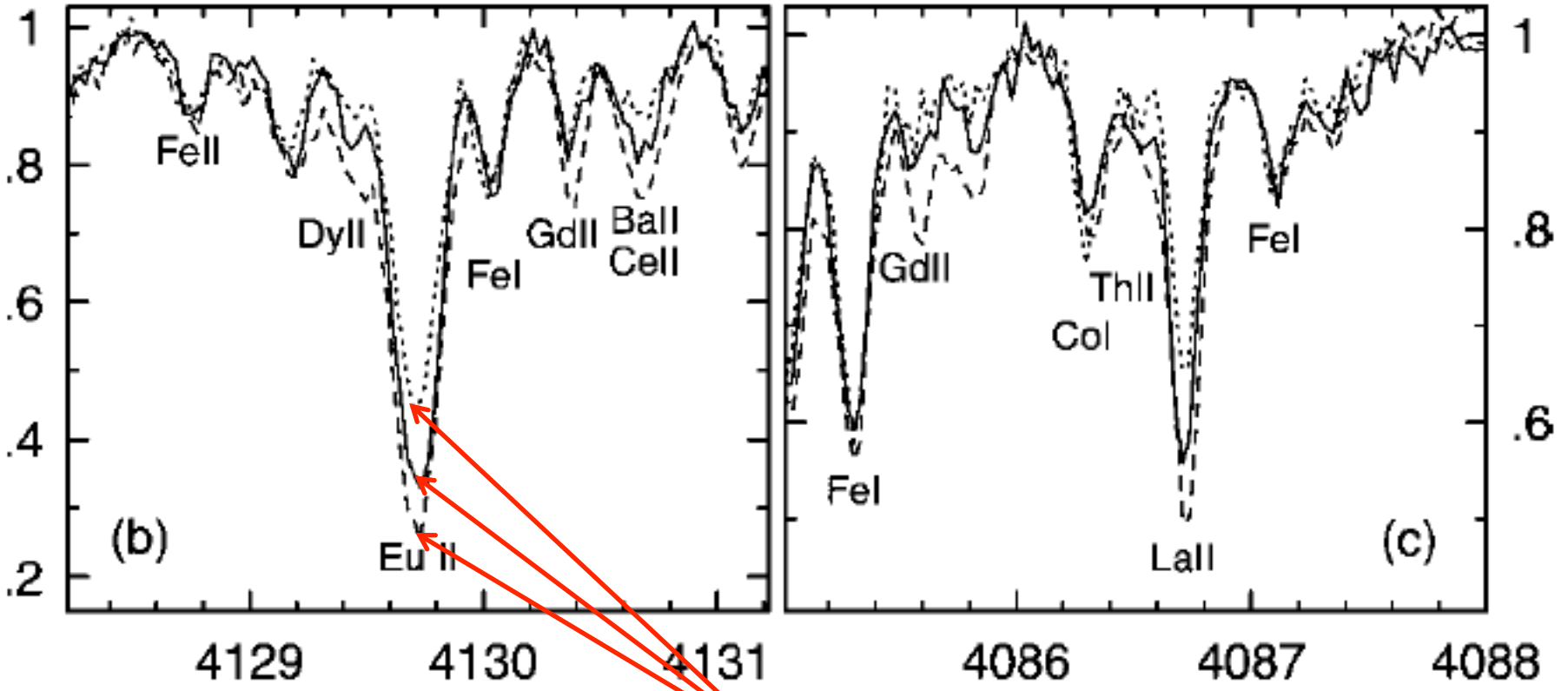
The “action” is mostly happening in the heavier elements





Roederer, Cowan et al. 2010

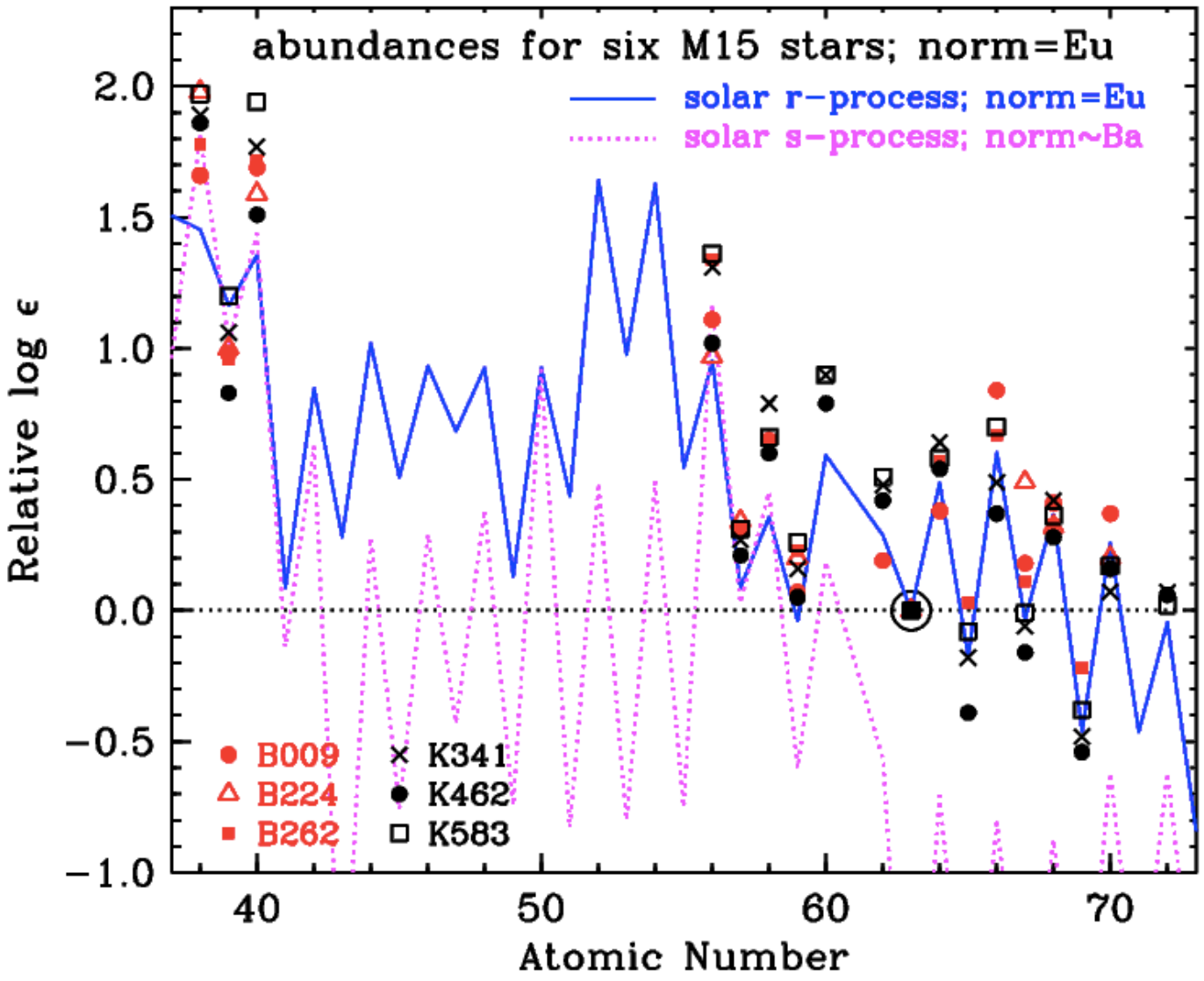
Final thought: WHY is there n-capture star-to-star scatter in M15?



Fe-peak elements are constant, but n-capture elements vary from star to star

Sneden, Cowan, et al. 2000

is normalization at Eu really misleading?



Sobeck, Cowan et al. 2011

This has just been a sample of John's contributions

A one-note astrophysicist? Hardly …

- ✓nuclear physics of the neutron-capture elements
- ✓and (back to the future) iron-peak elements
- ✓stellar evolution theory
- ✓Galactic chemical evolution
- ✓lab atomic physics
- ✓observational stellar spectroscopy
- ✓supernova observations (photometry!)
- ✓supernova remnant imaging
- ✓X-ray point source surveys
- ✓redshift distributions in superclusters: radio obs.
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With many thanks to John for the decades of collaborations

Slide title

add Griffin et al. 115444

add Roederer et al.

citation

n-capture spectra of metal-poor stars

HD 122563:
- [Fe/H] = -2.7
- T_{eff} ~ 4750
- LOW n-capture

CS 22892-052:
- [Fe/H] = -3.1
- T_{eff} ~ 4750
- HIGH n-capture