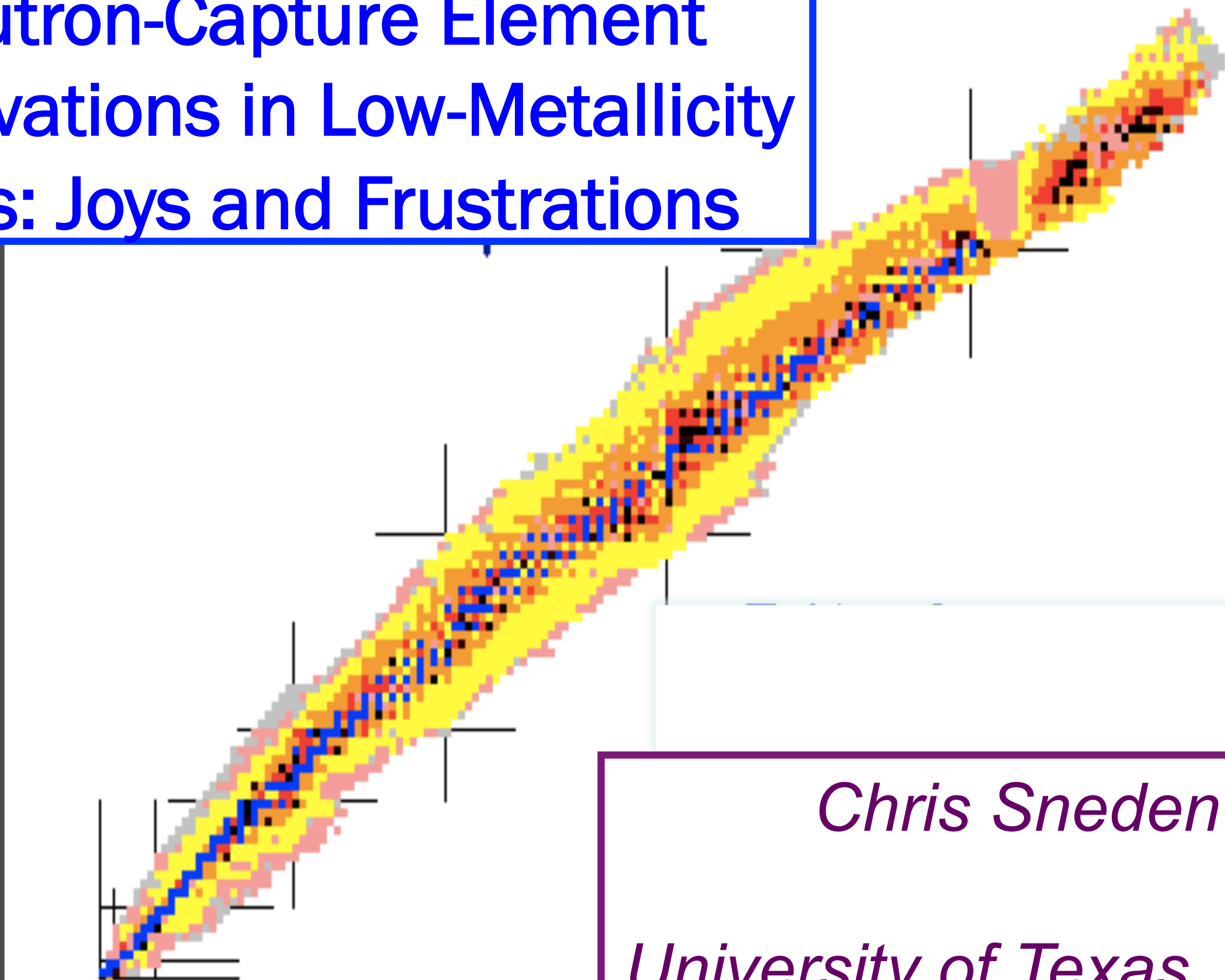
Neutron-Capture Element Observations in Low-Metallicity Stars: Joys and Frustrations



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A Very Collaborative Effort

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Outline

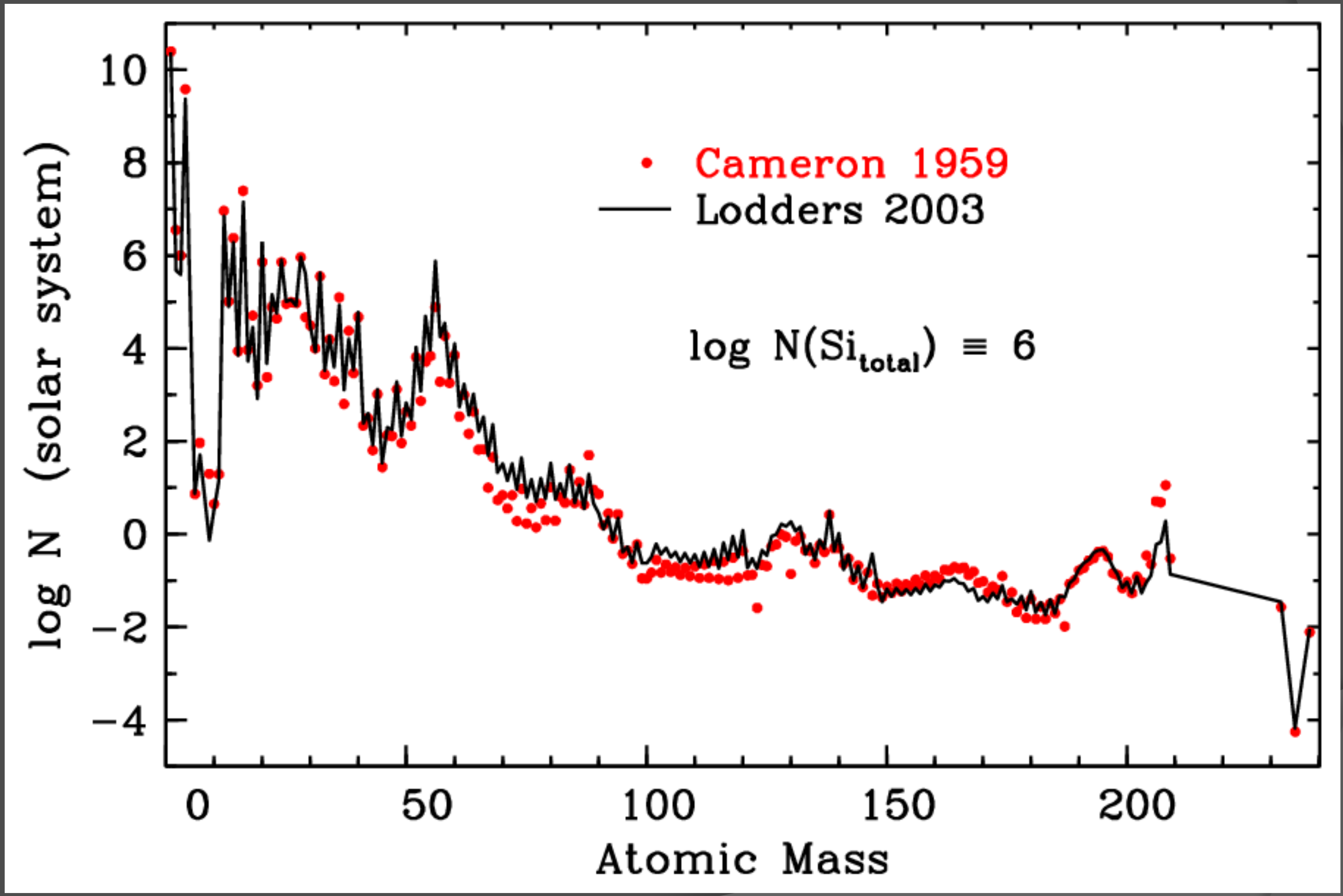
JOYS

- distinct r- and s-process dominance in different stars
- patterns in some element groups known in detail
- discovery of radioactive thorium and uraniun
- deeper exploration of r-process limits

FRUSTRATIONS

- gaps in Periodic Table coverage
- atomic physics limits: transition wavelengths
- spectral line modeling limits: departures from LTE?
- HR diagram limits: reliance mostly on cool giant stars

A basic goal: to understand how our Galaxy produced the solar chemical composition



SCG08 = Sneden, Cowan, & Gallino 2008, ARA&A, 46, 241

The *n*(eutron)-capture elements

Most isotopes of elements with Z>30 are formed by:

$$^{A}Z + n \longrightarrow {}^{A+1}Z$$

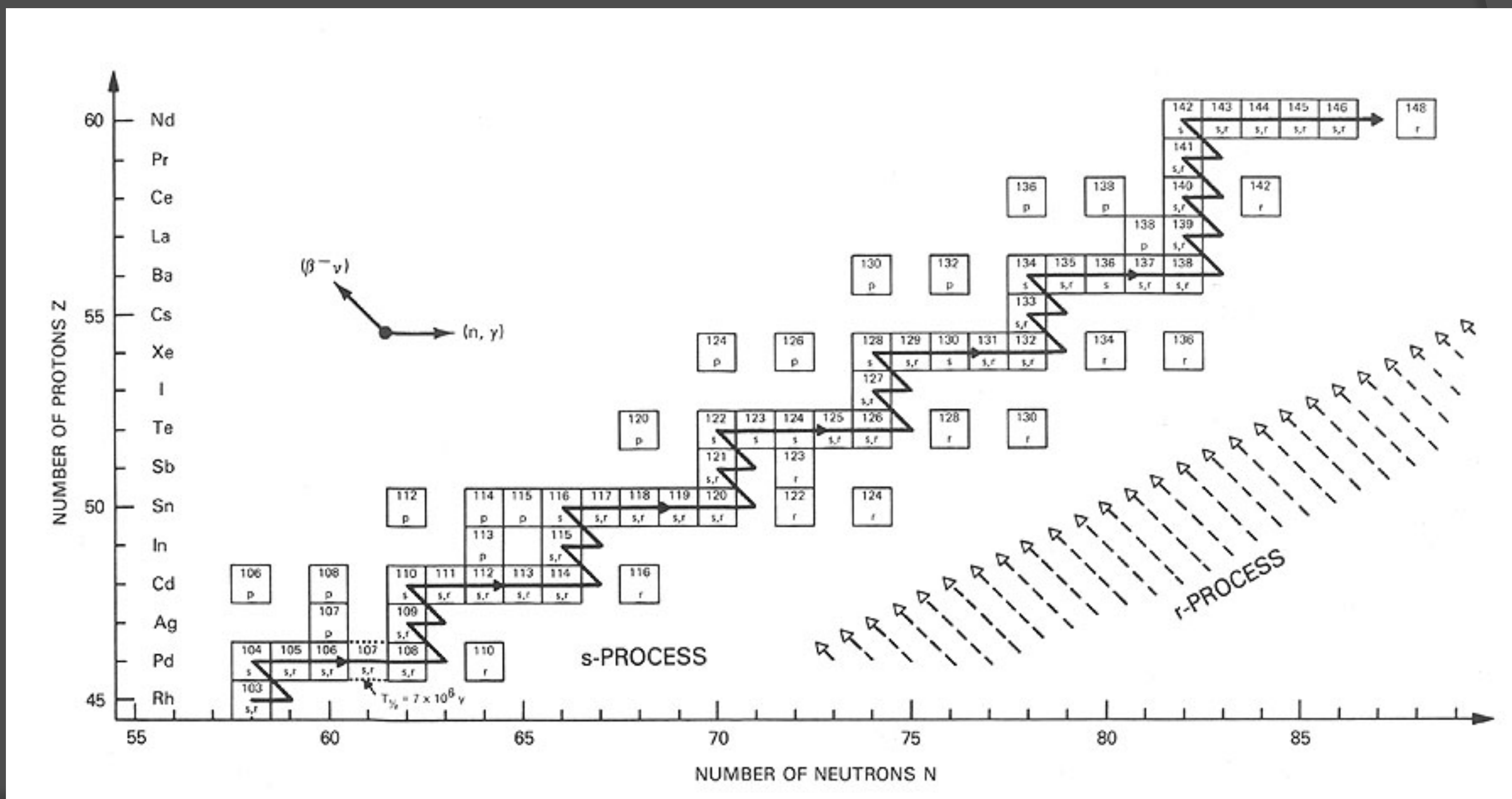
Followed by, for unstable nuclei:

$$^{A+1}Z \longrightarrow {}^{A+1}(Z+1) + \beta^-$$

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						

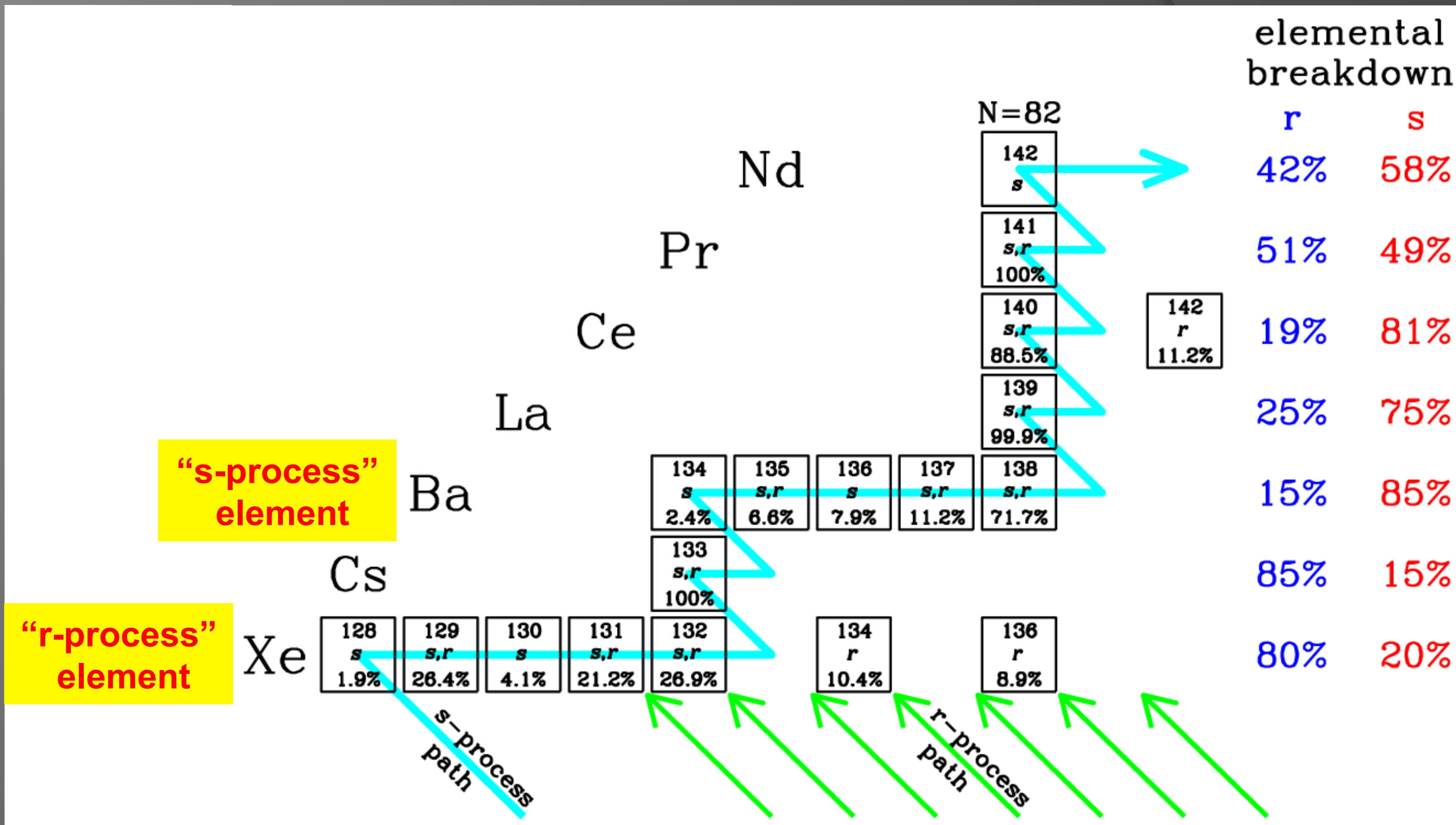
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

- *s*-process: β-decays occur between successive n-captures
- *r*-process: rapid, short-lived neutron blast
  temporarily overwhelms β-decay rates
- *r*- or *s*-process element: origin in ***solar-system***
  dominated by one or the other process



Rolfs & Rodney (1988)

A detailed look at the r- and s-process paths



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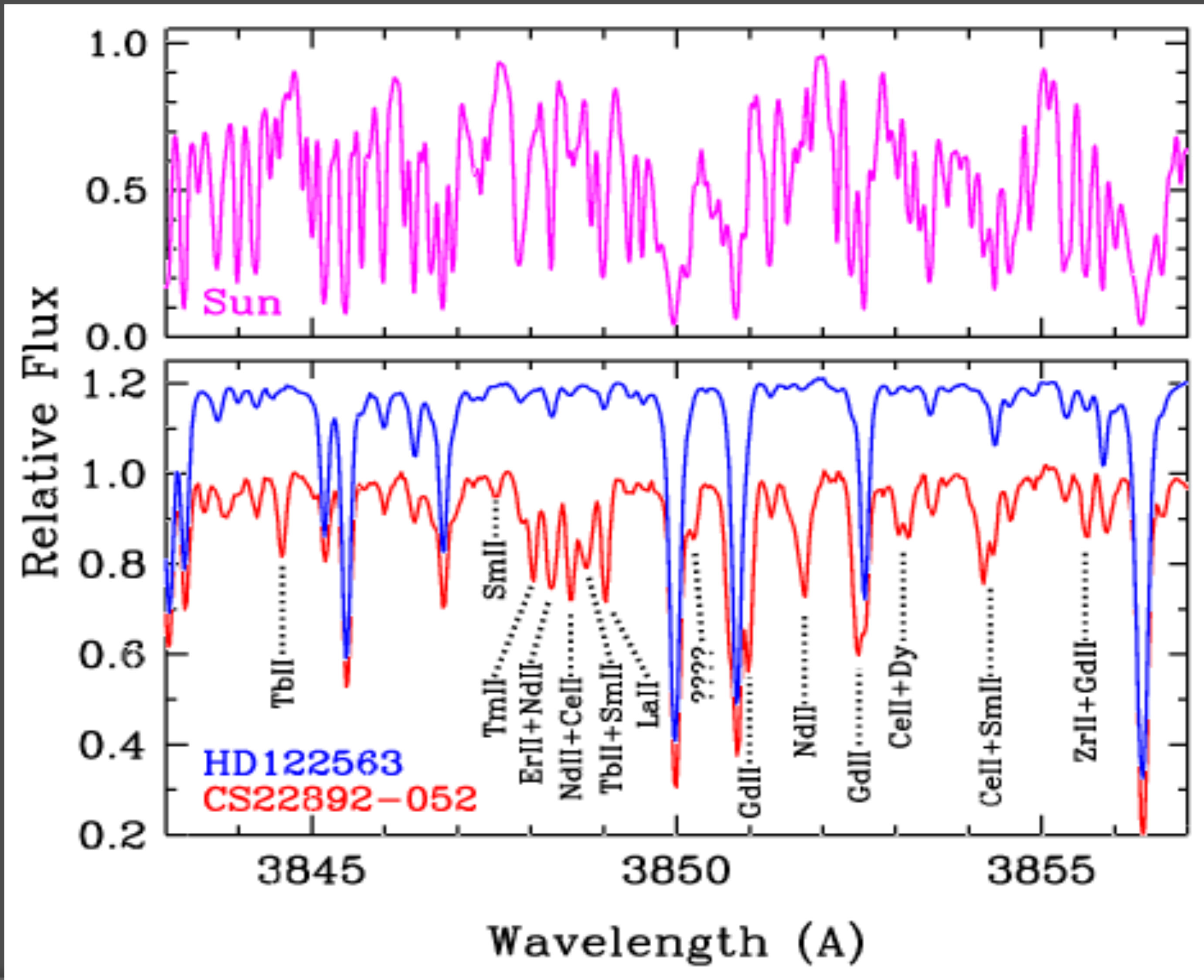
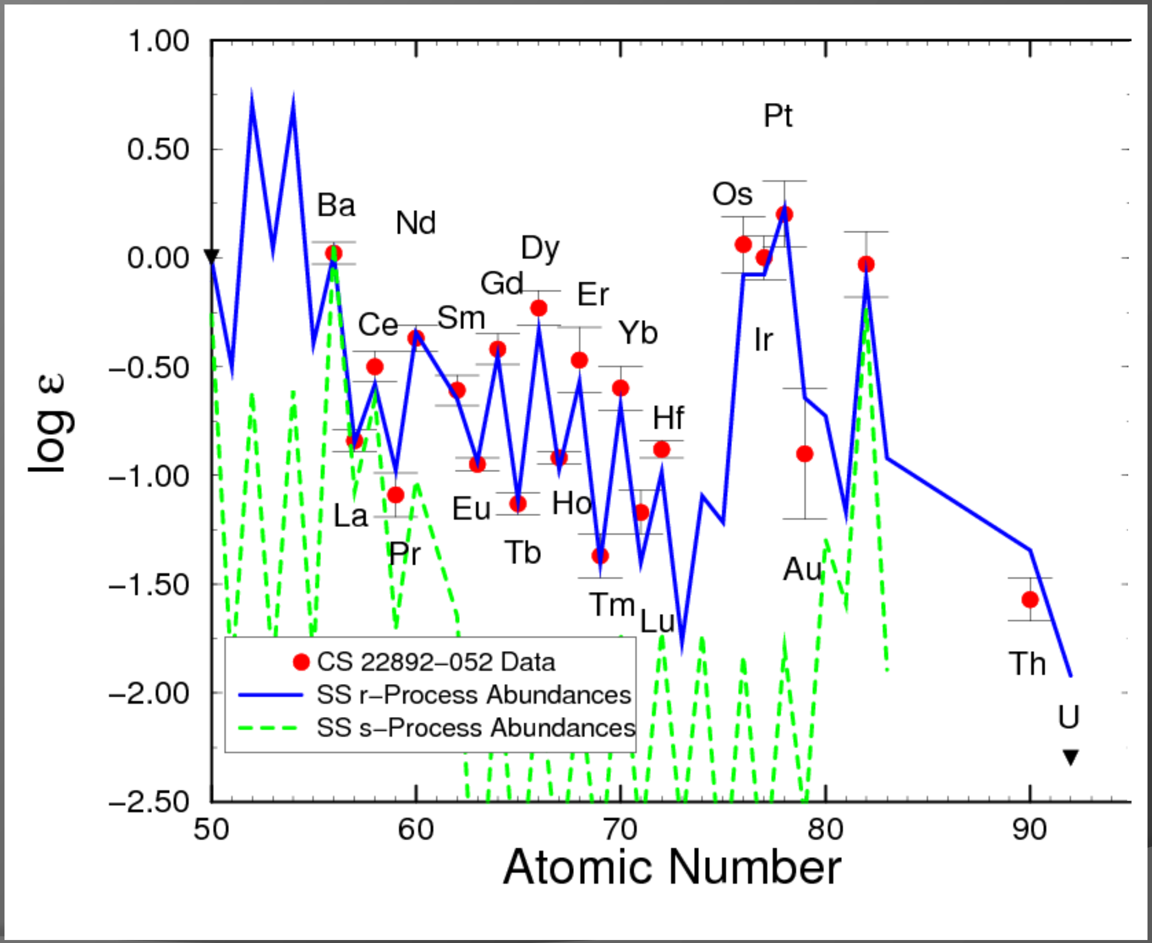
n-capture elements in metal-poor stars



Now a well-known phenomenon: "*r*-process-rich" metal-poor stars

first example, HD 115444, was reported by Griffin et al. 1982



An important abundance ratio:
log ε(La/Eu) = +0.6
(solar total)
= +0.2
(solar r-only)
= +1.5
(solar s-only)ç

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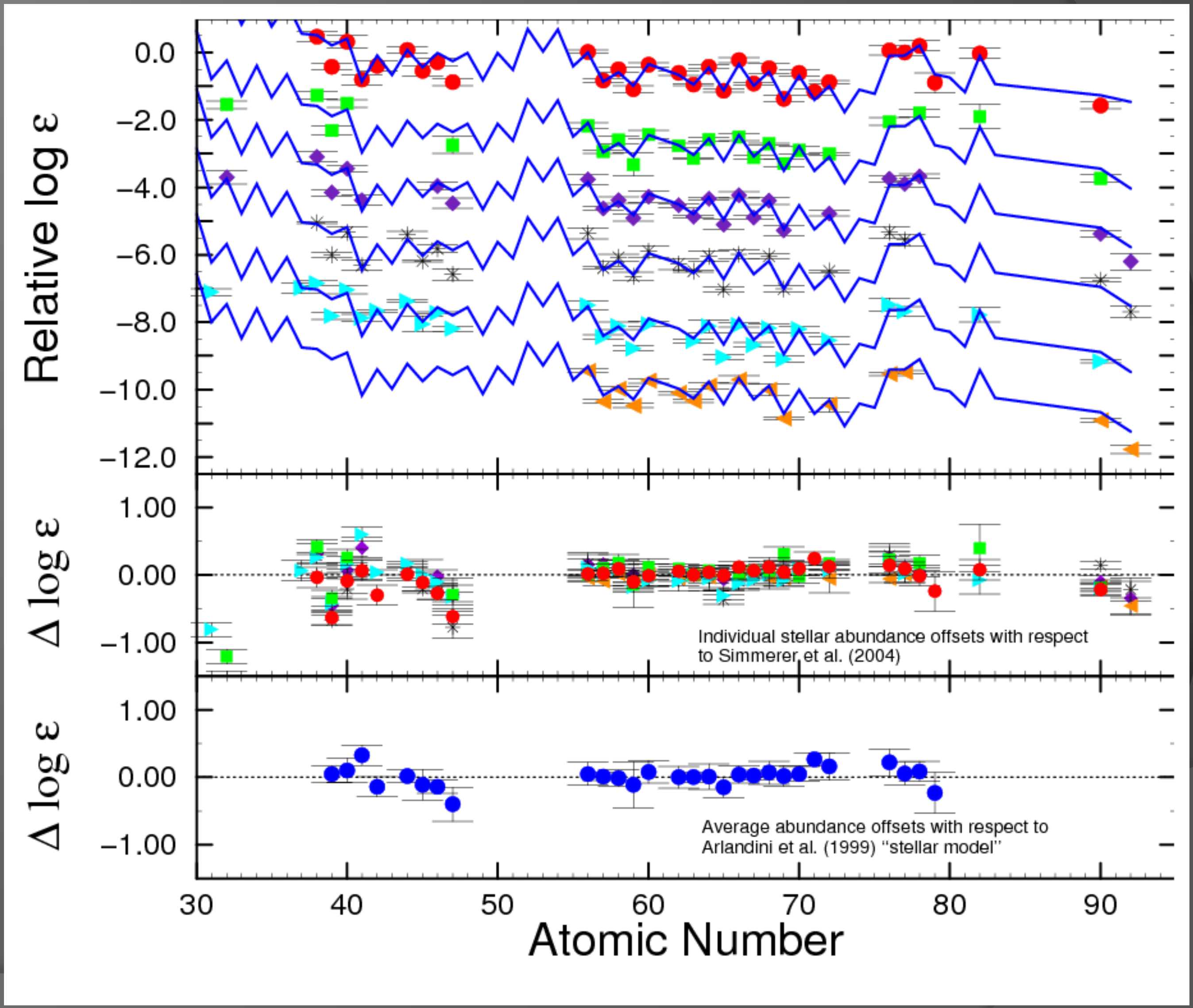
n-capture compositions of well-studied *r*-rich stars: *Così fan tutte??*



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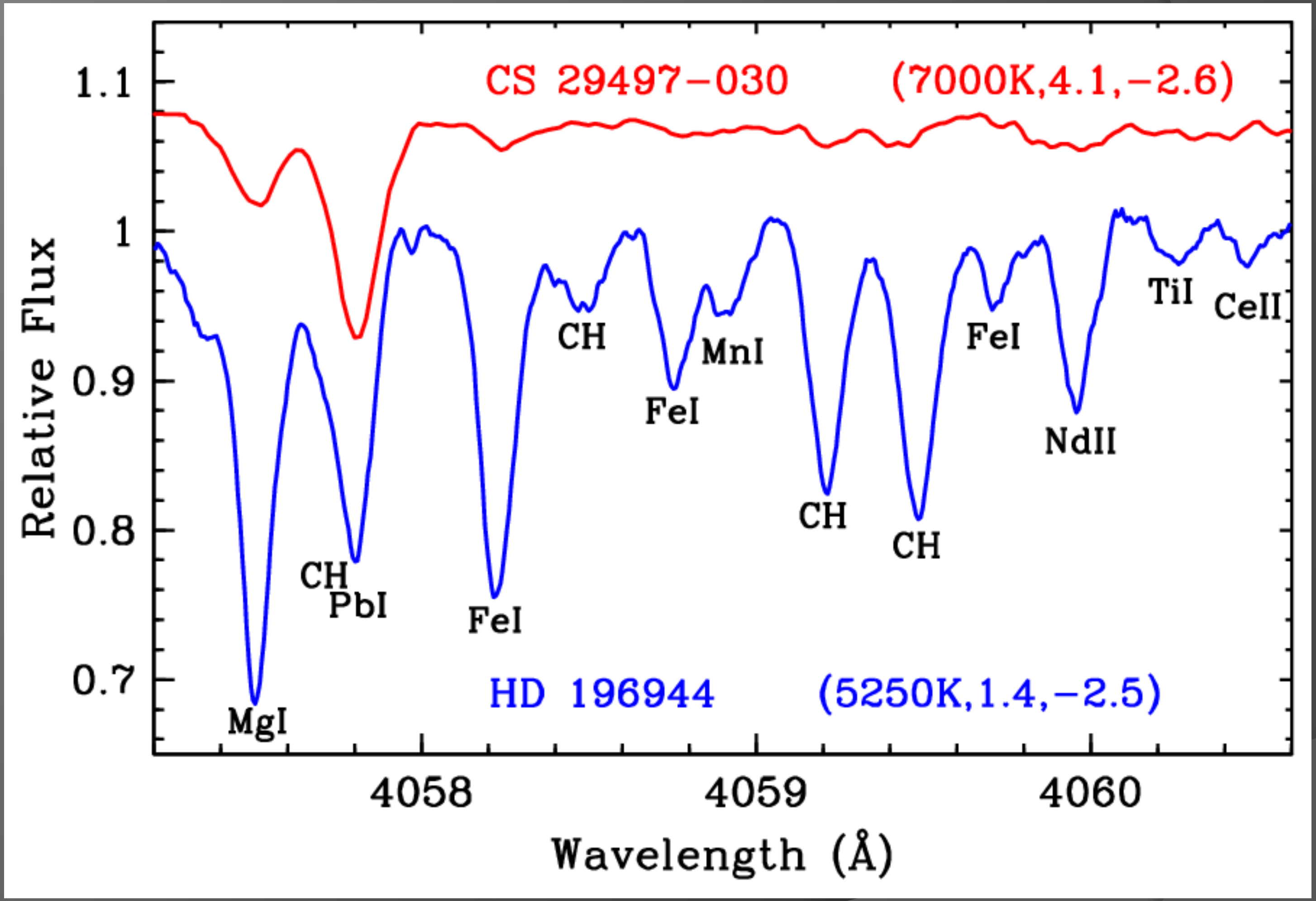
the *other* n-capture-rich stars: s-process “lead stars”



With thanks to Sophie Van Eck

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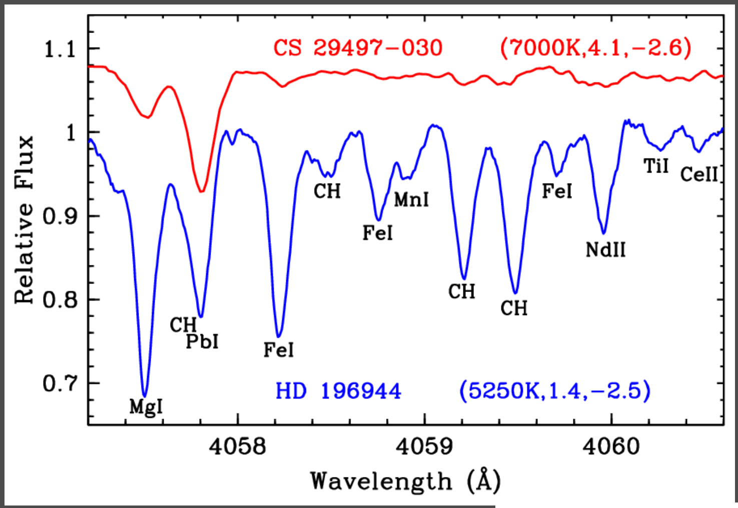
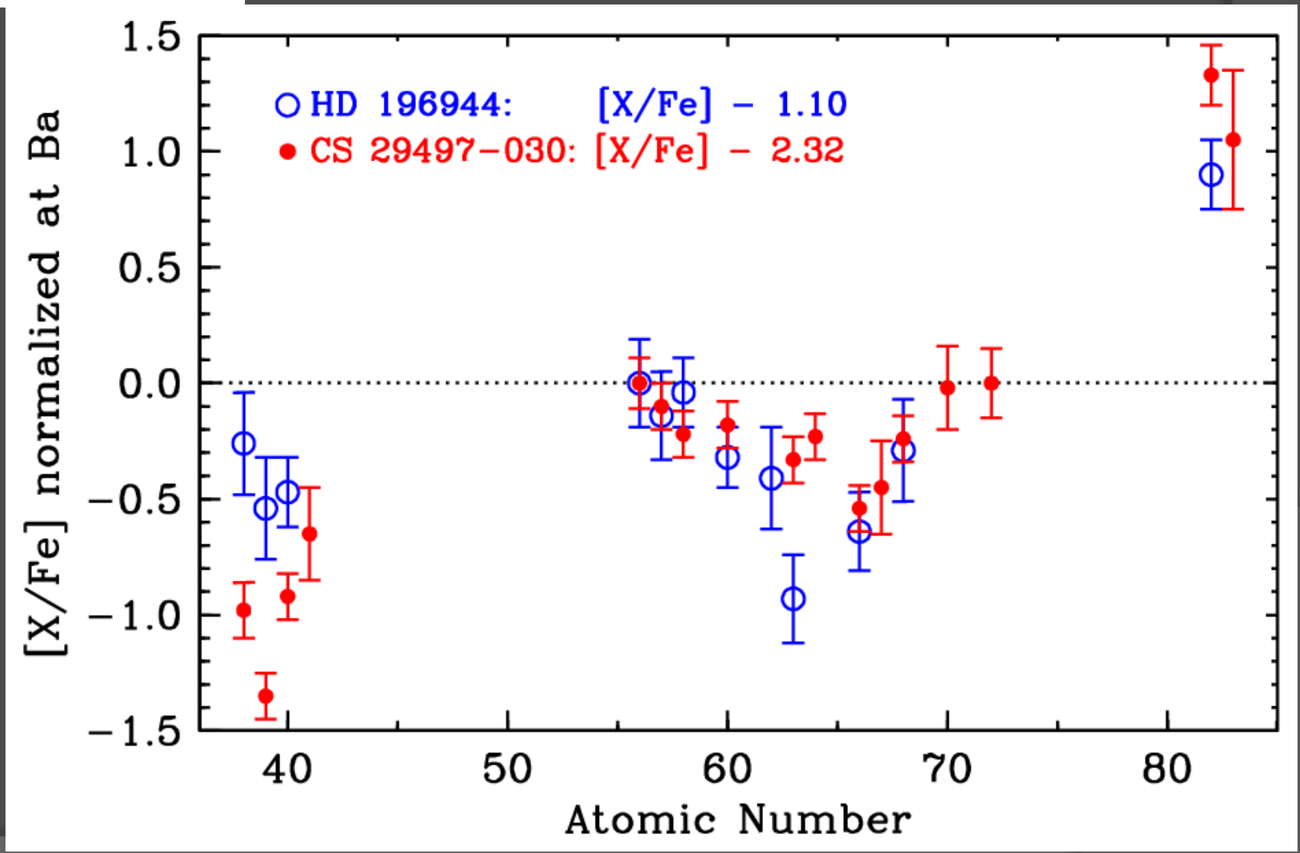


Superficially similar abundance patterns in all low metallicity s-rich stars



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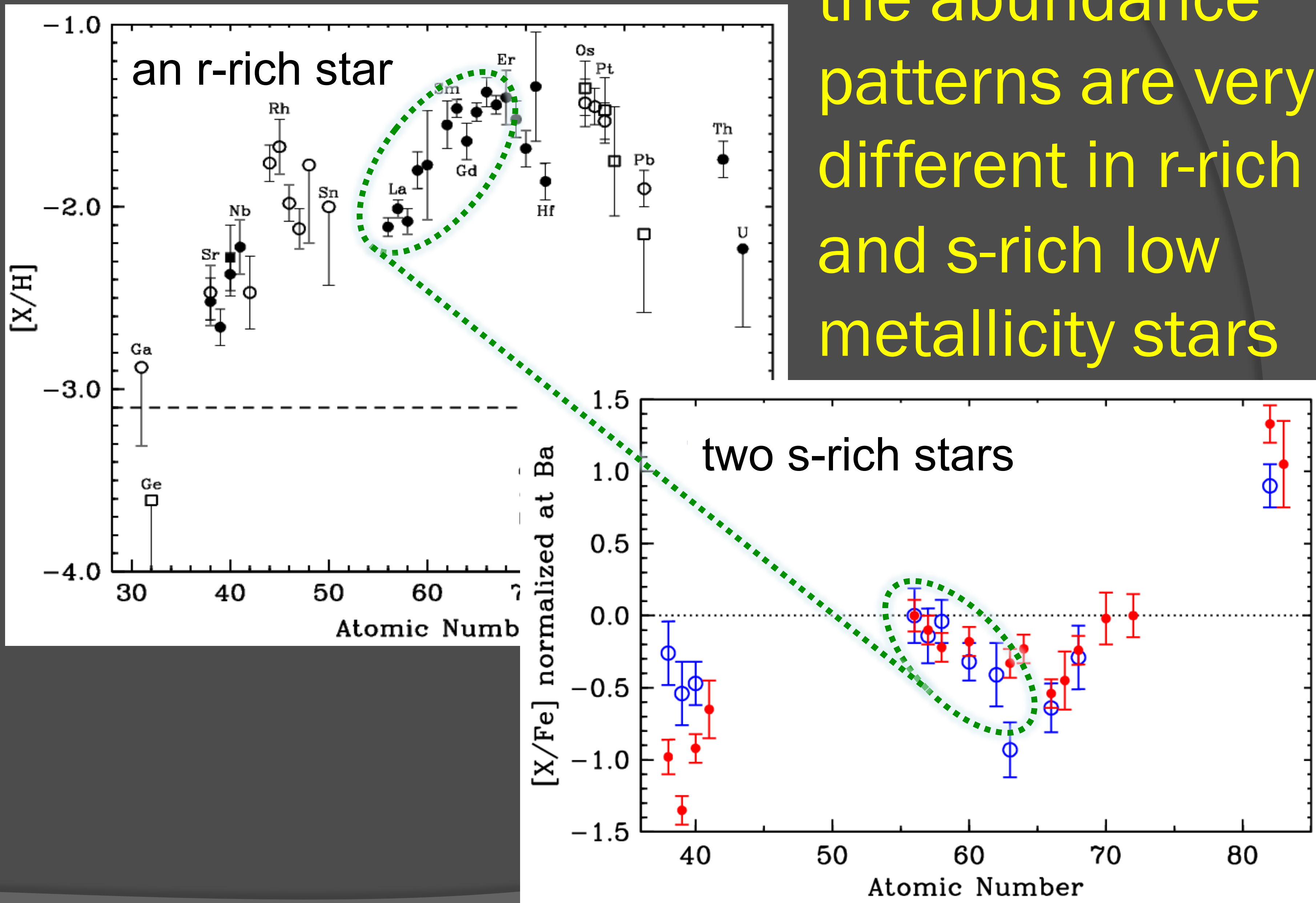
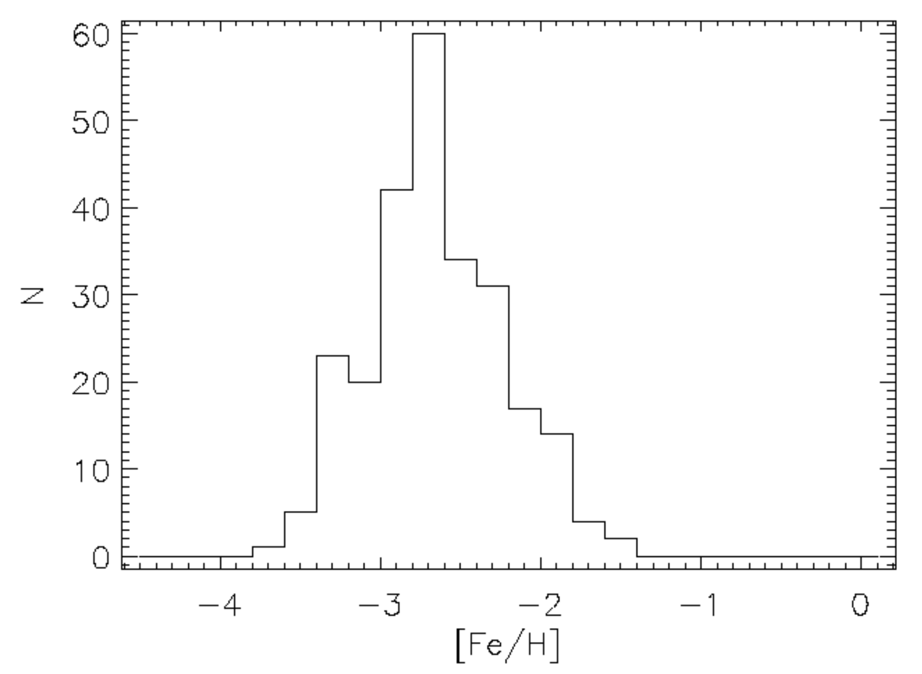
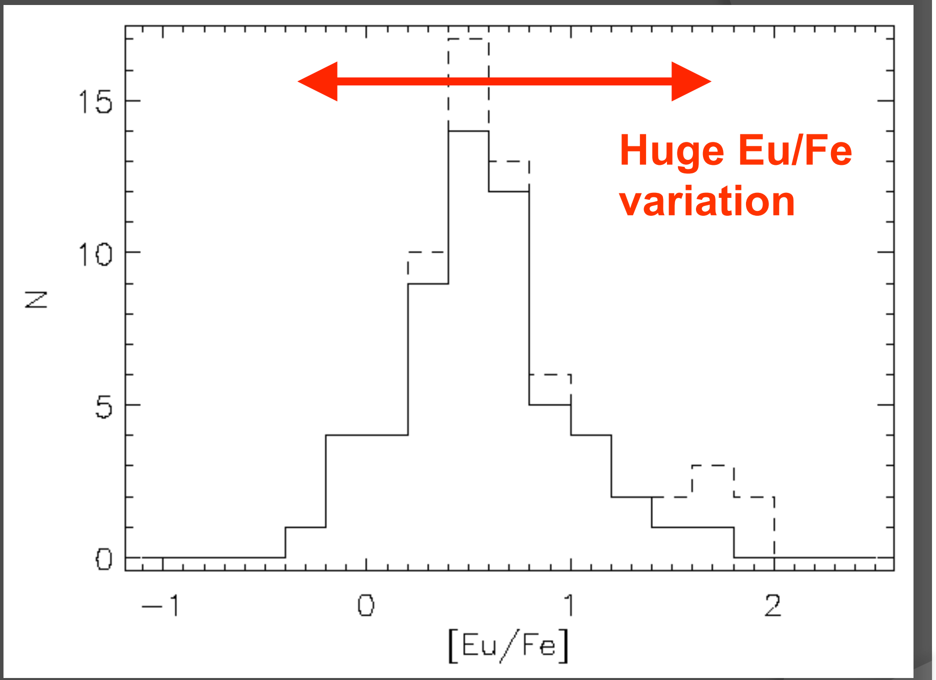
the abundance patterns are very different in r-rich and s-rich low metallicity stars



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

Here are the distributions

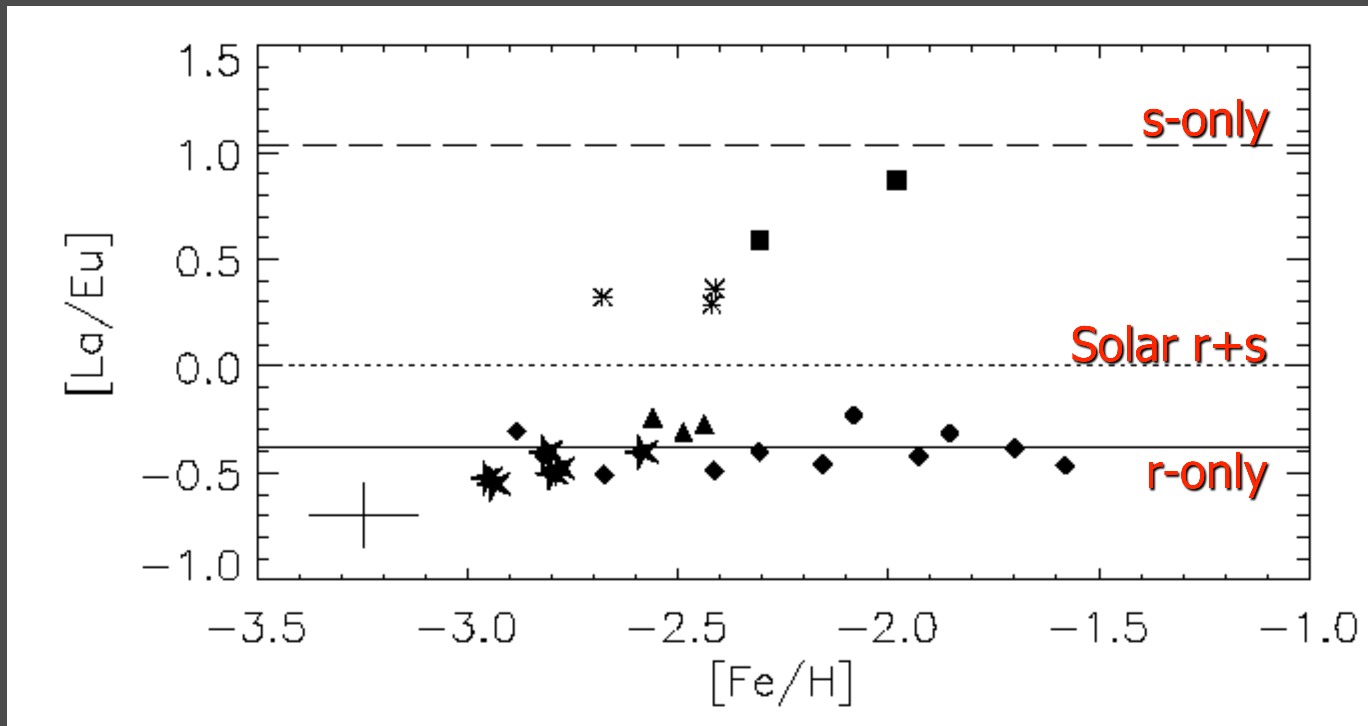


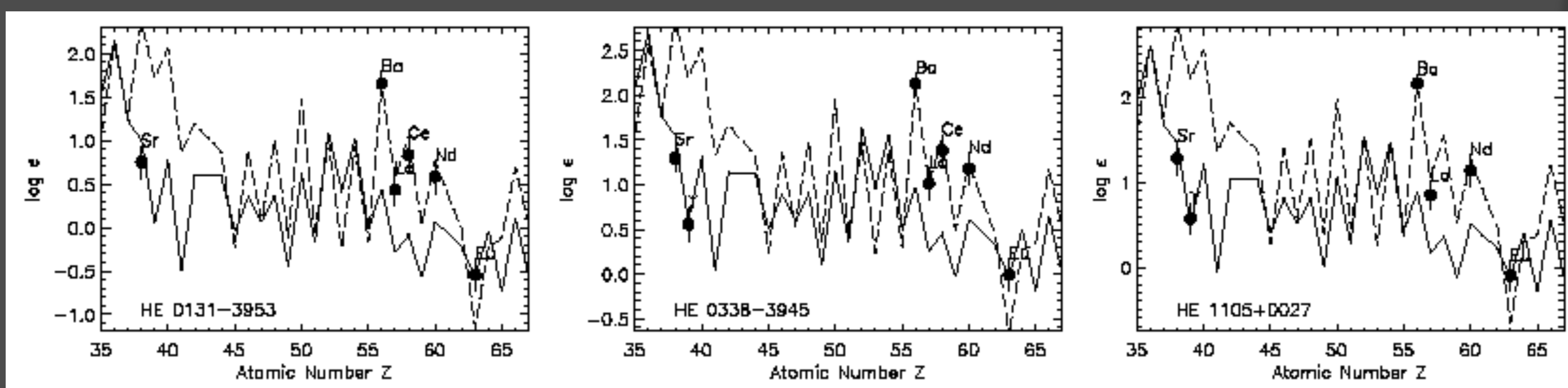


- 253-star "snapshot" detailed survey (R ~ 20,000, S/N ~ 50)
- small number of n-capture elements; approximate abundances
- stars with very strong CH bands discarded from sample (for now)
- 8 new stars with [Eu/Fe]>+1.0 and 35 more with [Eu/Fe]>+0.3

Barklem et al. 2005

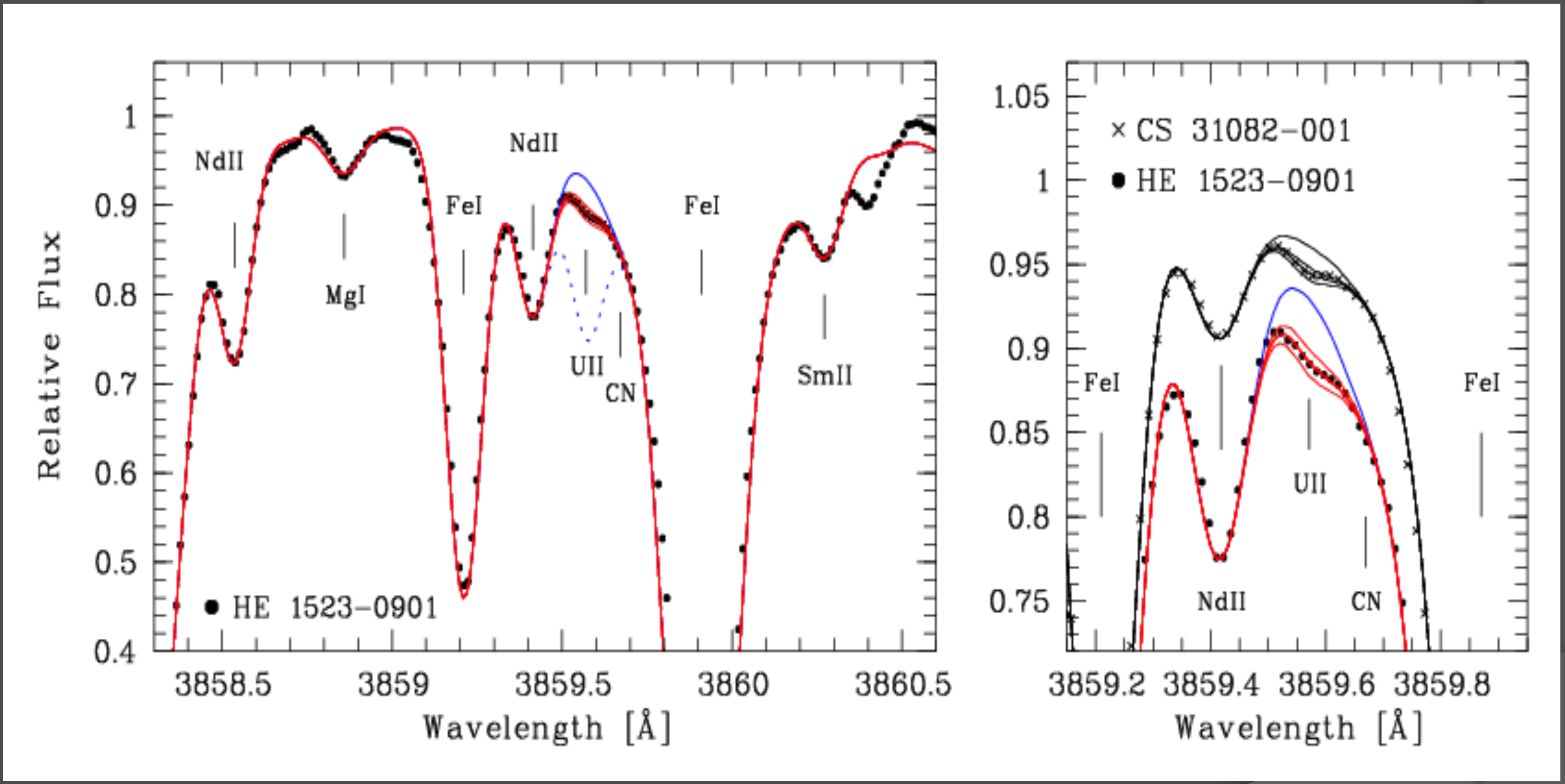
HES: mostly "r-rich" stars; a few "s" ones





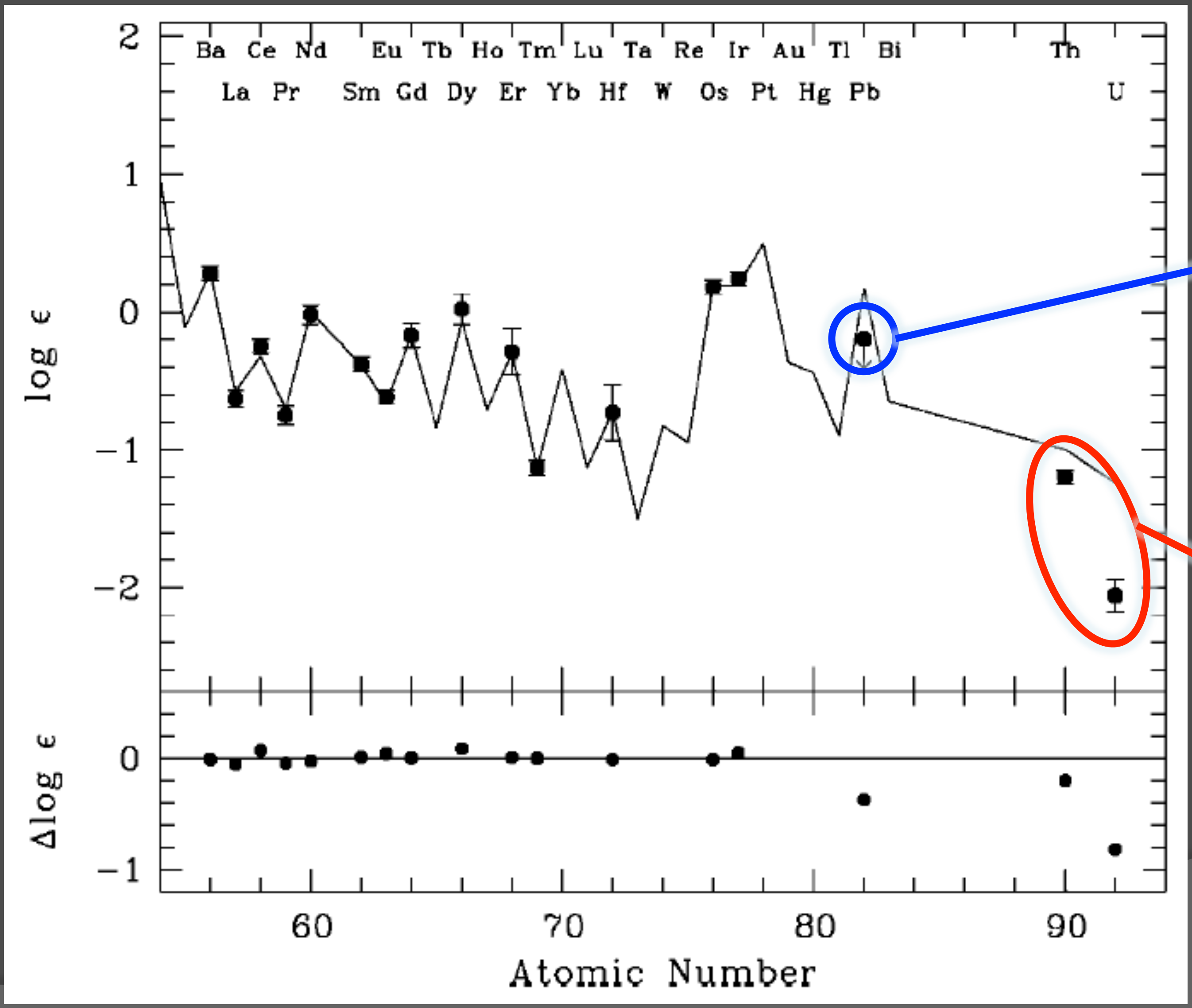
Barklem et al. 2005; dashed lines are scaled solar-system s-only abundances

Thorium/Uranium detections promise alternate Galactic ages



Frebel et al. 2007

leading to possible radioactive decay ages

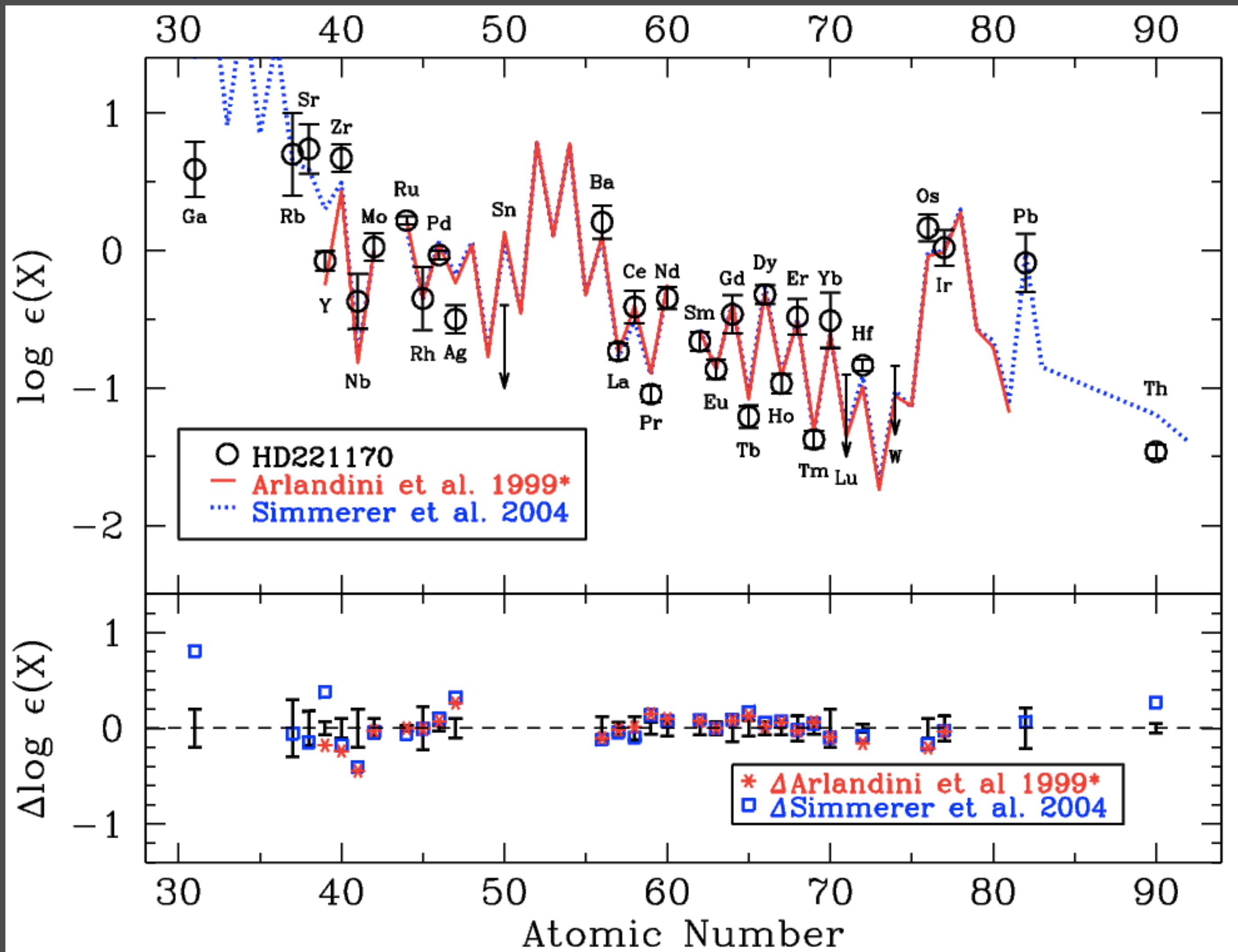


Persistent question: why is Pb usually so low?

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

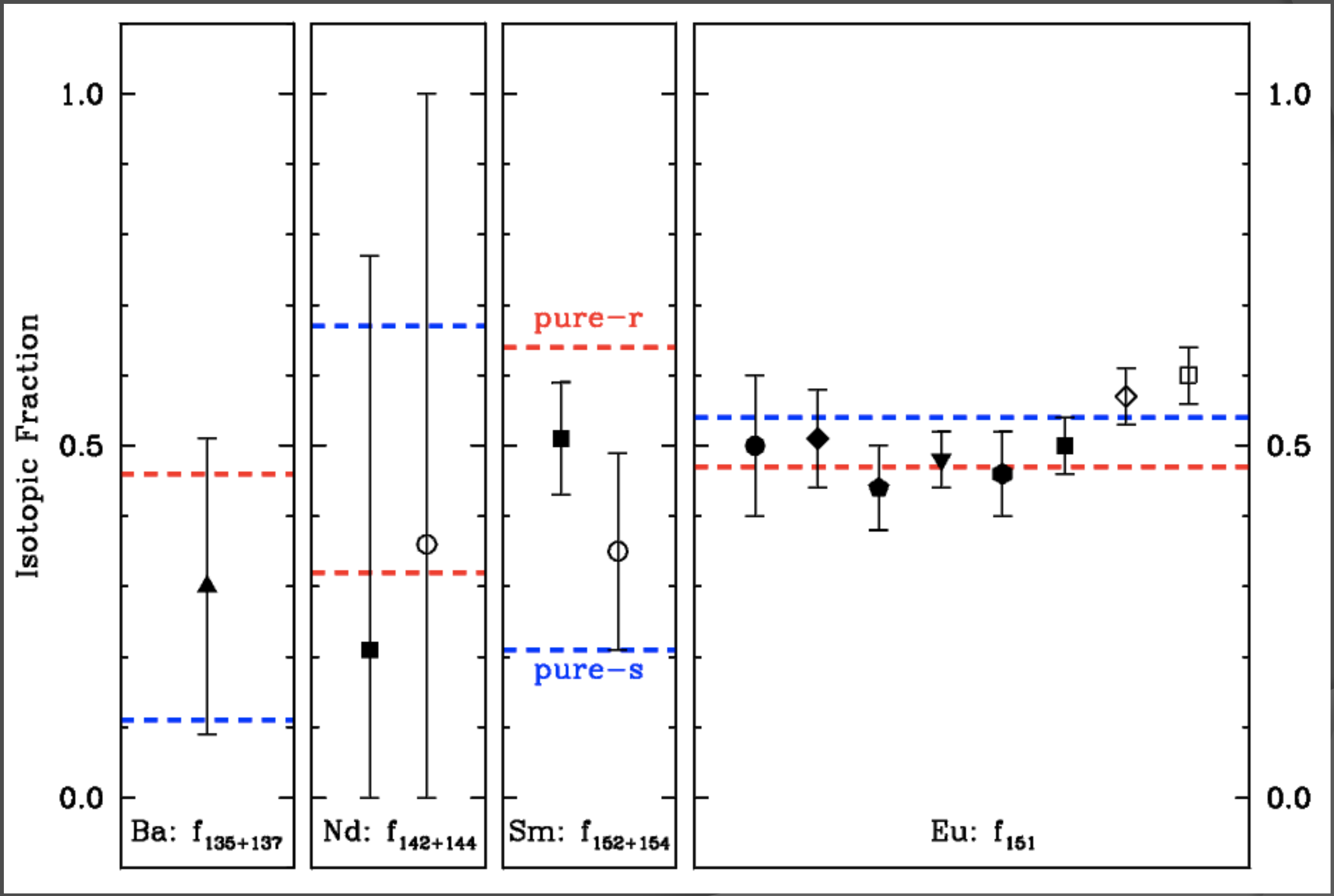
Frebel et al. 2007

with good abundances, predictions of the r-process can be confronted



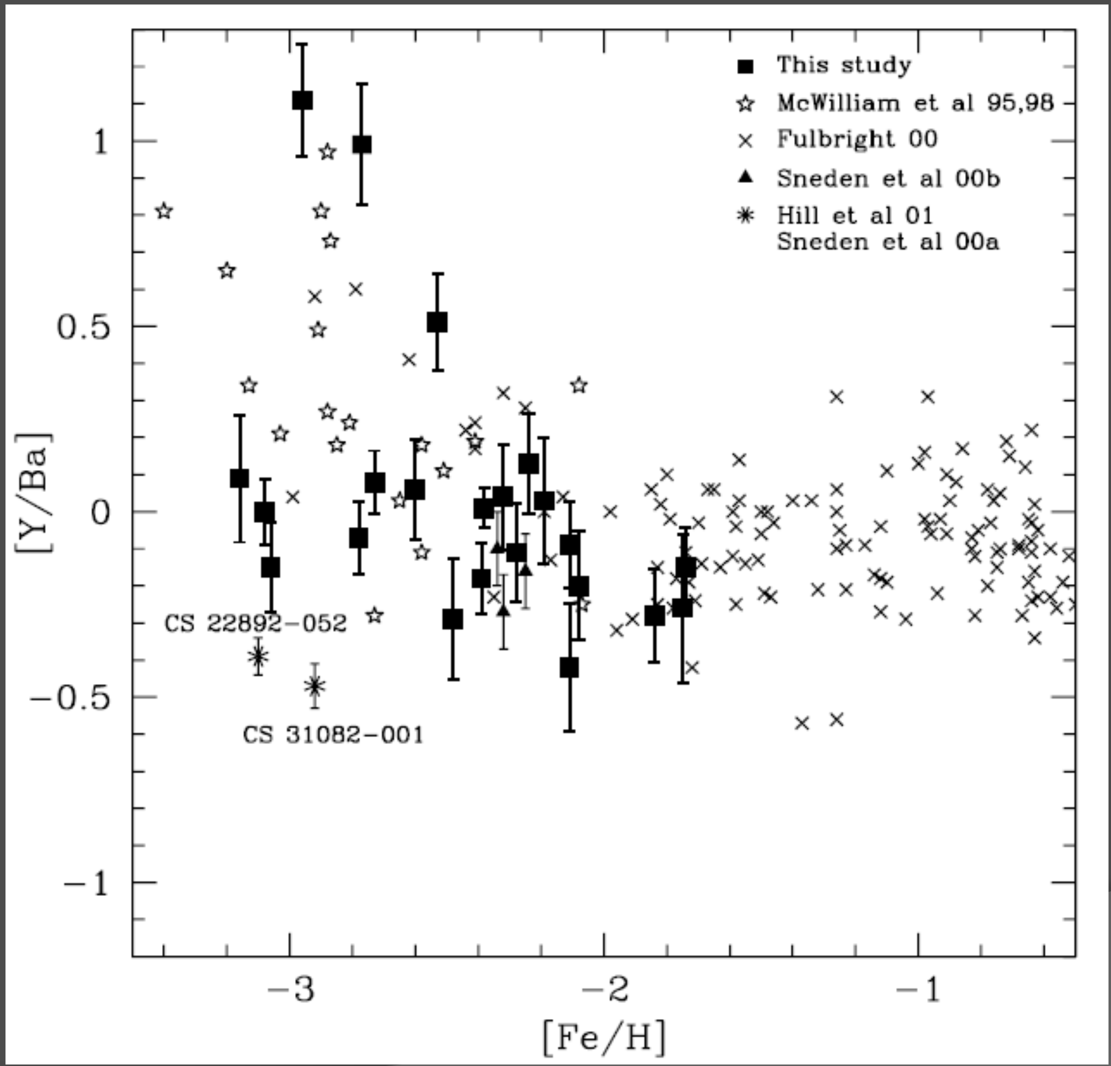
Ivans et al. 2006

can test r/s at the isotopic level (sort-of)



Roederer et al. 2008

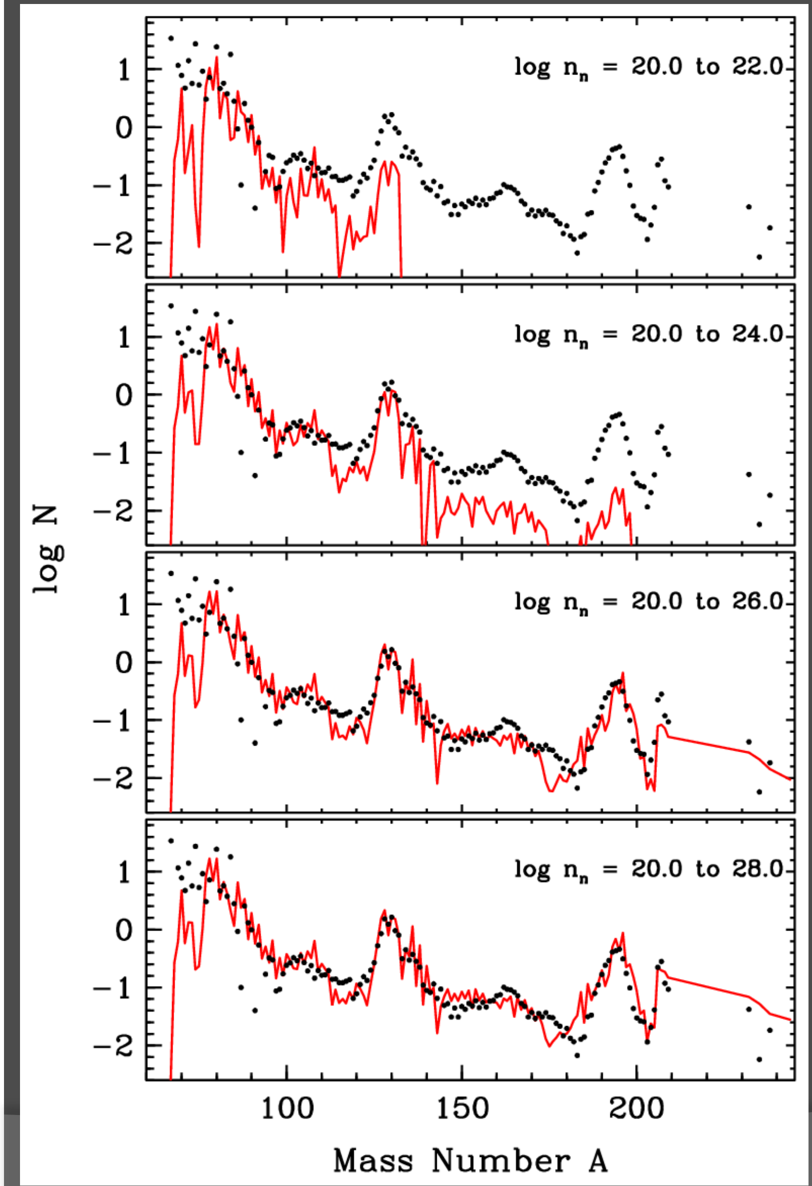
Beyond simplest r-process results: observed de-coupling of the heavy/light r-process elements



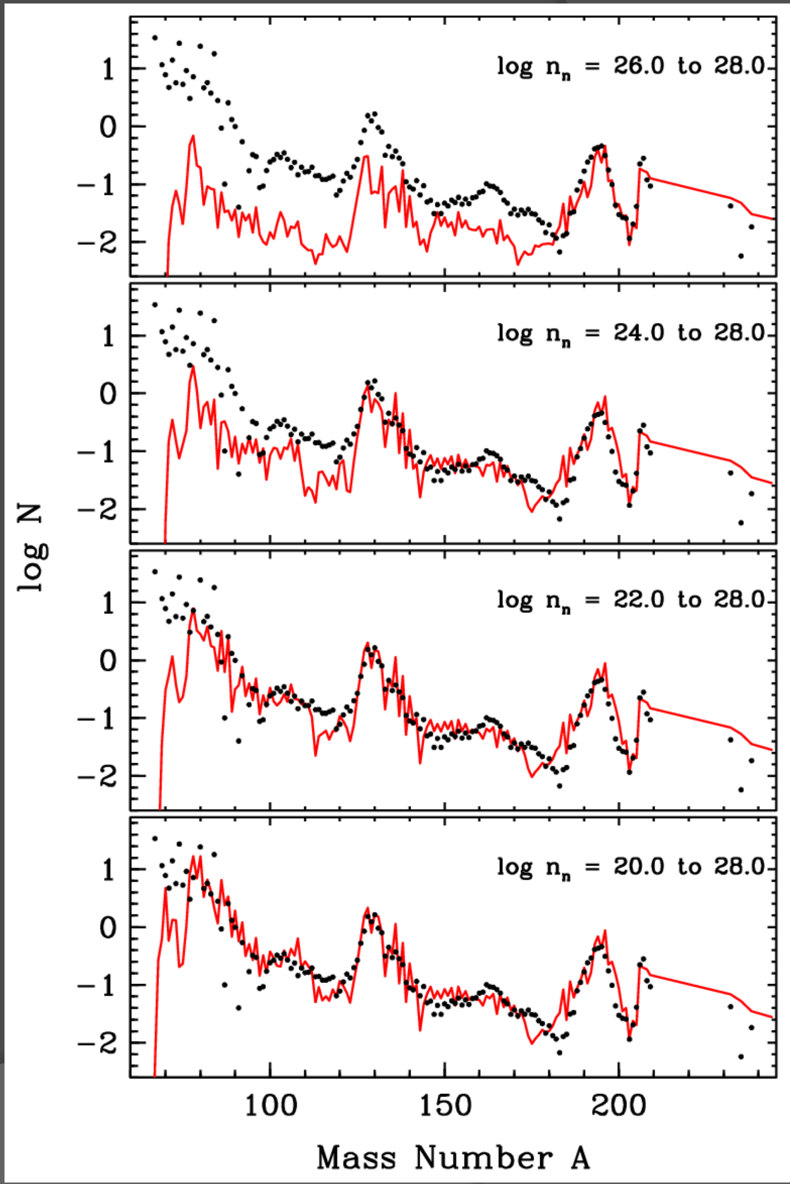
See also Aoki et al. 2005, 2007

Johnson & Bolte 2002

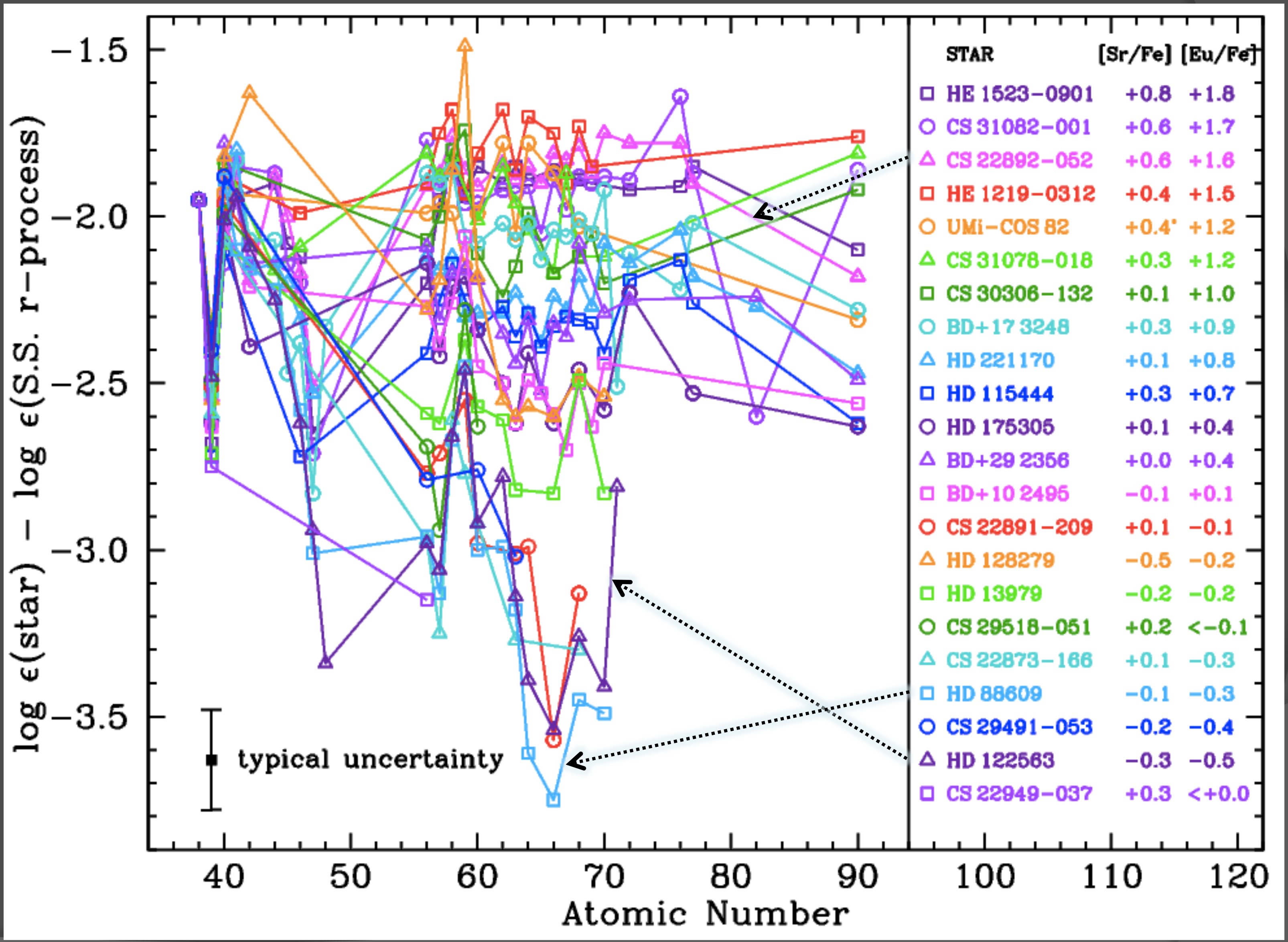
can be understood from various density "needs" for the r-process to match solar abundances



Kratz et al. 2007



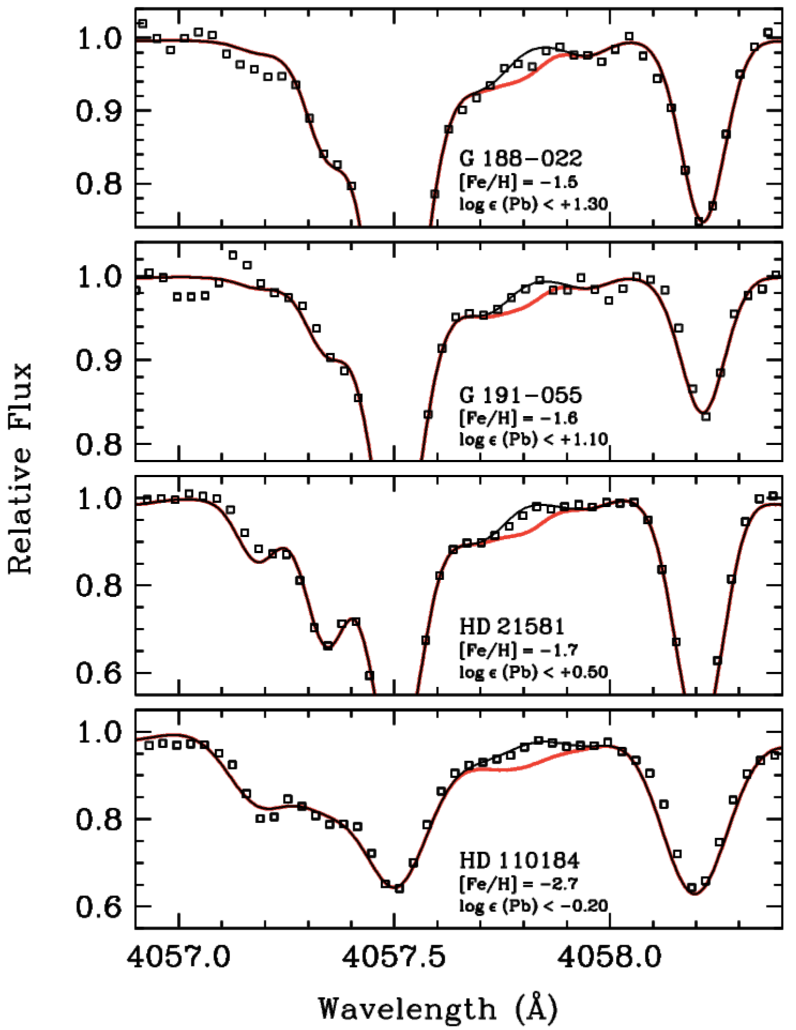
abundance distribution variations are "routine"



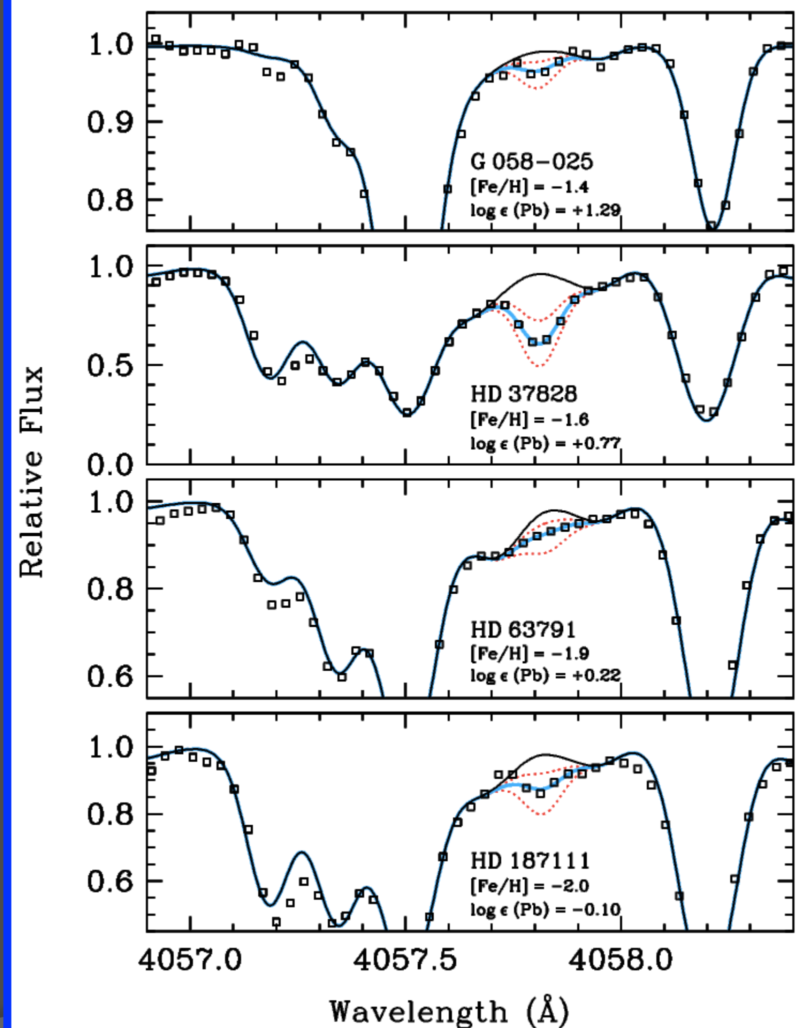
Roederer et al 2010

Is lead the key?

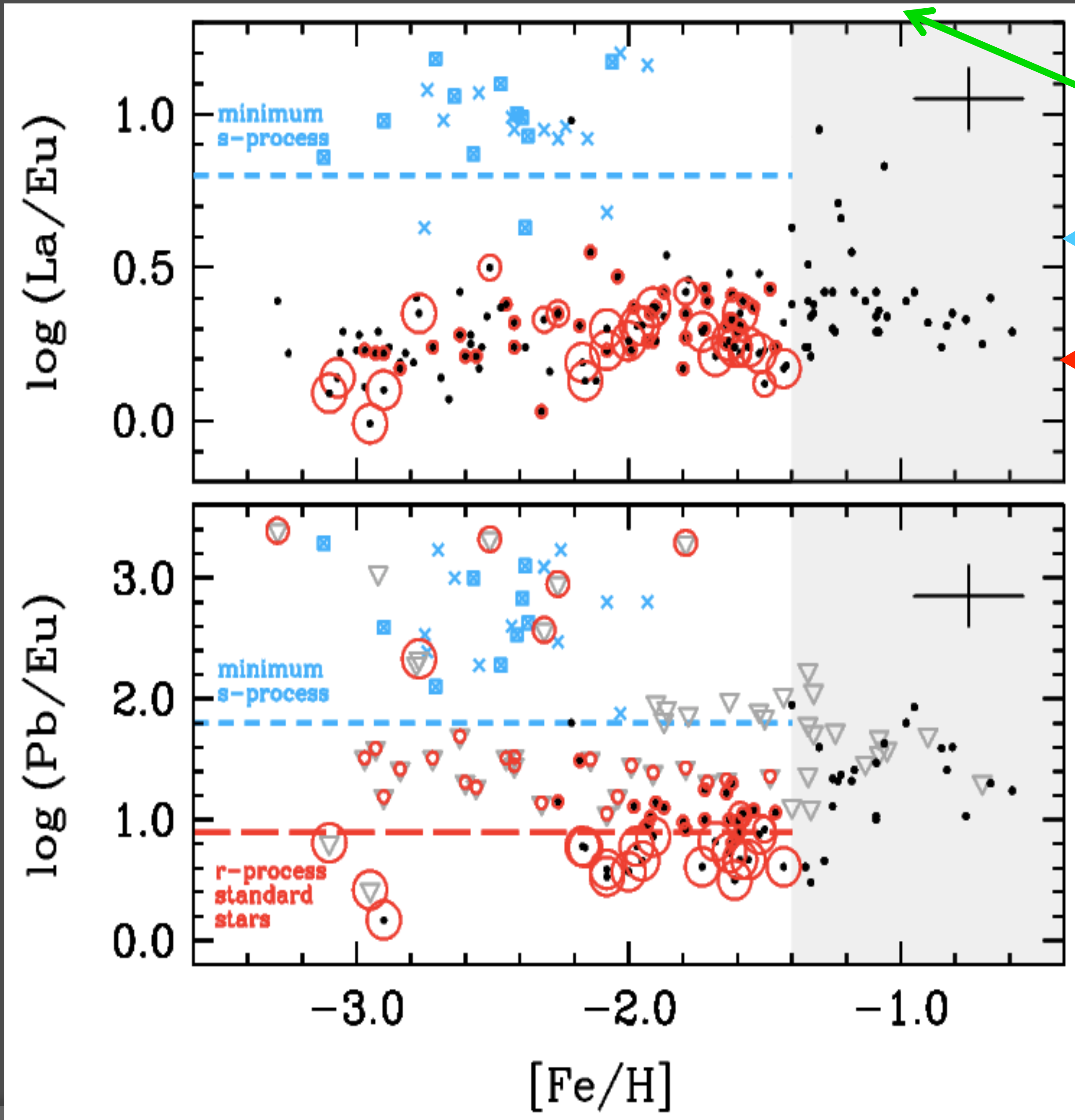
no Pb ➔ r-rich?



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 = r-rich

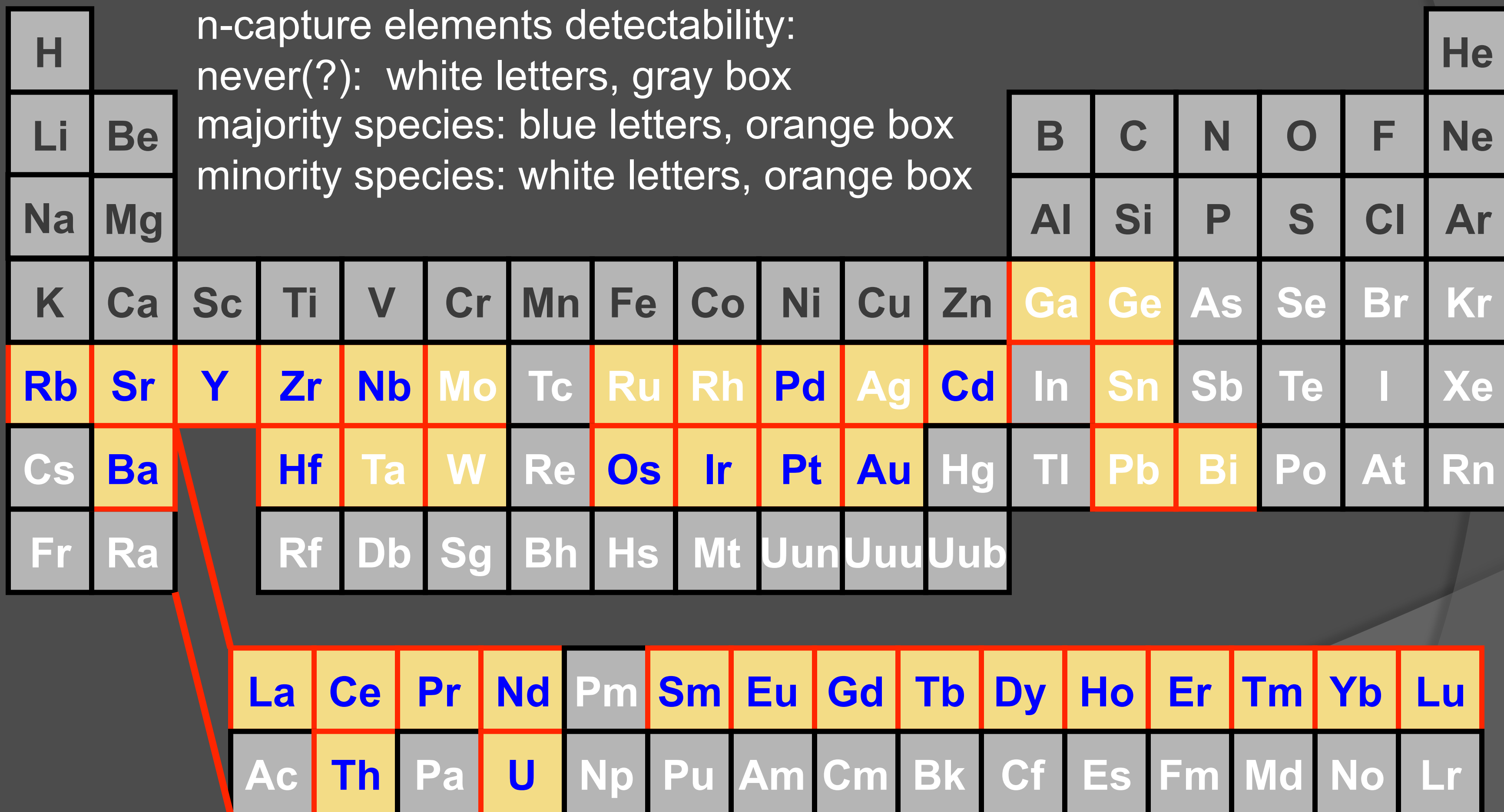
Roederer et al 2010

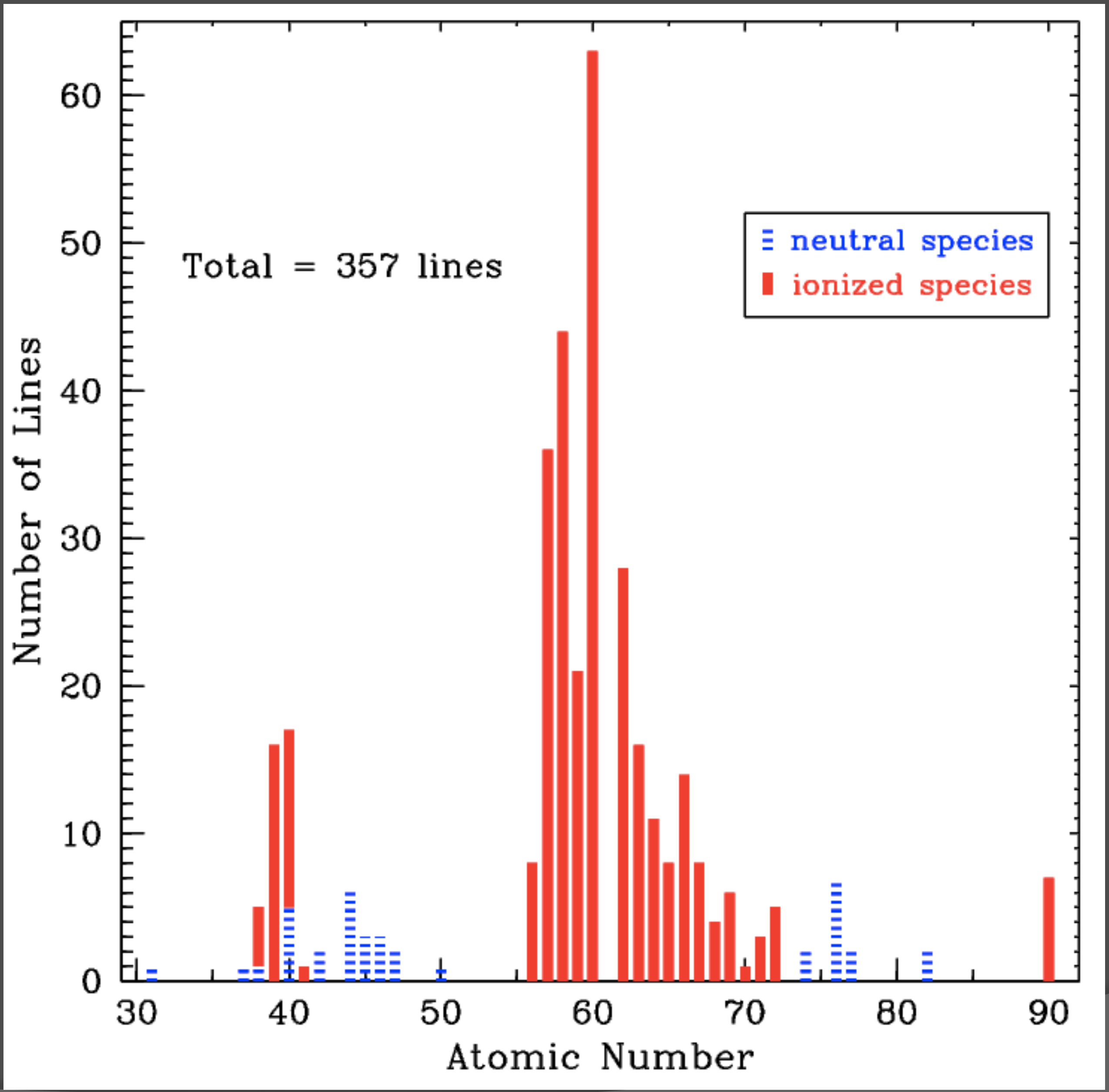
Of course, not all n-capture elements are detectable; basic atomic structure issues

majority species is usually the first ion

light element: black letters, gray box

n-capture elements detectability:
never(?): white letters, gray box
majority species: blue letters, orange box
minority species: white letters, orange box





what elements are we *REALLY* observing in r-rich stars?

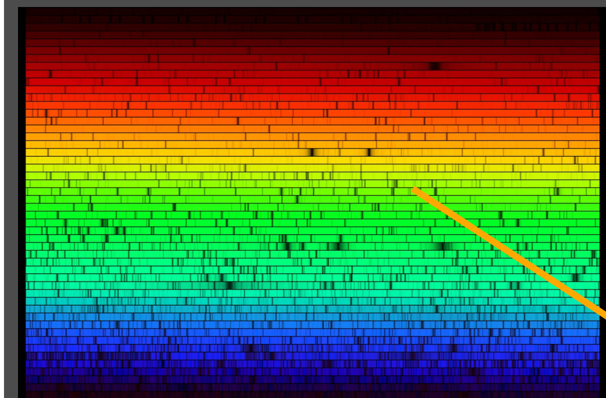
Ivans et al. 2006

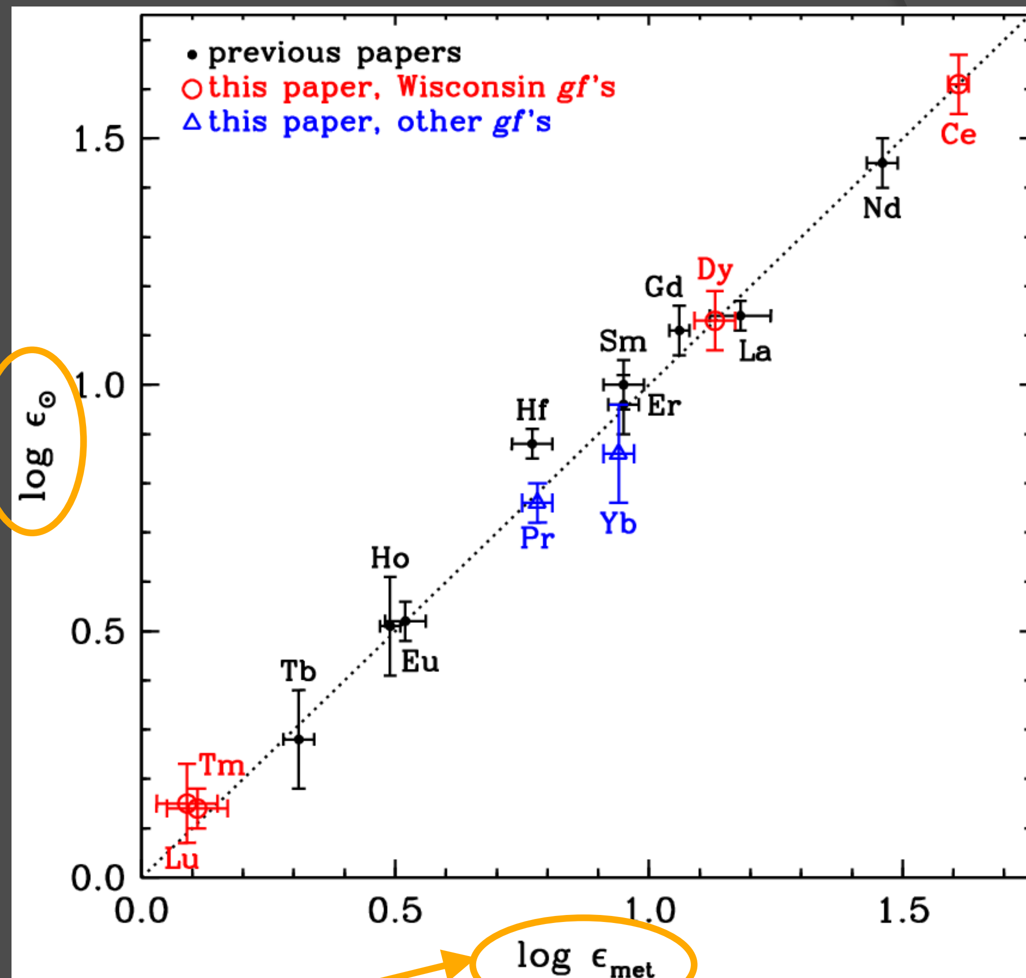
why do we know the rare earths so well?

Wisconsin lab studies of rare-earth ionized-species transitions: log *gf* and hyperfine/isotopic structure

		Sun: # transitions used in analysis	CS 22892-052 : # transitions used in analysis
Ba	(well studied in literature)		4
La	Lawler et al. 2000a	14	15
Ce	Lawler et al. 2009	45	32
Pr	Sneden et al. 2009	5	15
Nd	Den Hartog et al. 2003	46	37
~~Pm~~	(unstable element)		
Sm	Lawler et al. 2006	36	55
Eu	Lawler et al. 2001	14	9
Gd	Den Hartog et al. 2003	20	32
Tb	Lawler et al. 2000b	2	7
Dy	Sneden et al. 2009	13	29
Ho	Lawler et al. 2004	3	13
Er	Lawler et al. 2008	8	21
Tm	Sneden et al. 2009	3	6
Yb	Sneden et al. 2009	1	1
Lu	Sneden et al. 2009	1	
Hf	Lawler et al. 2007	4	8

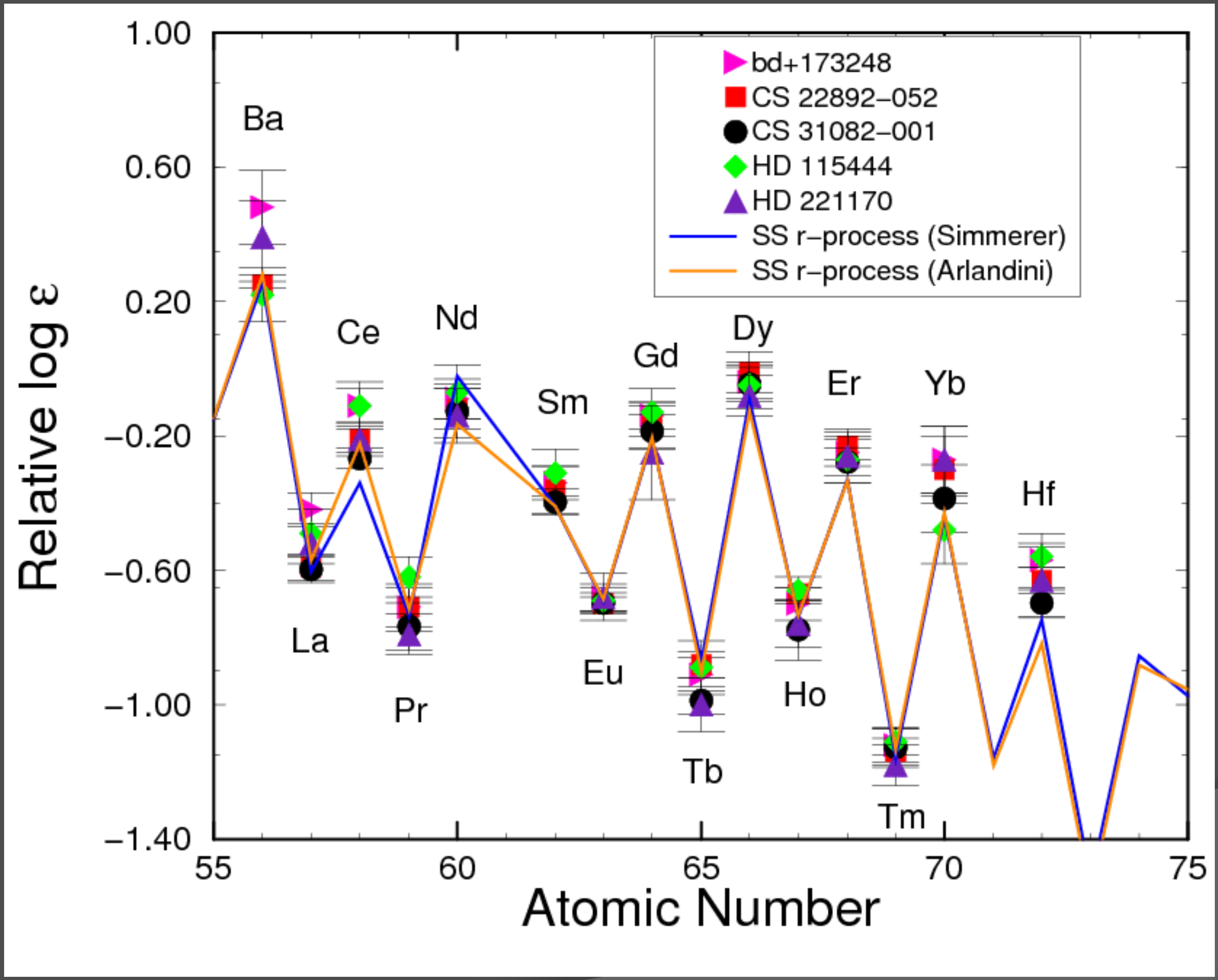
Application to solar abundances





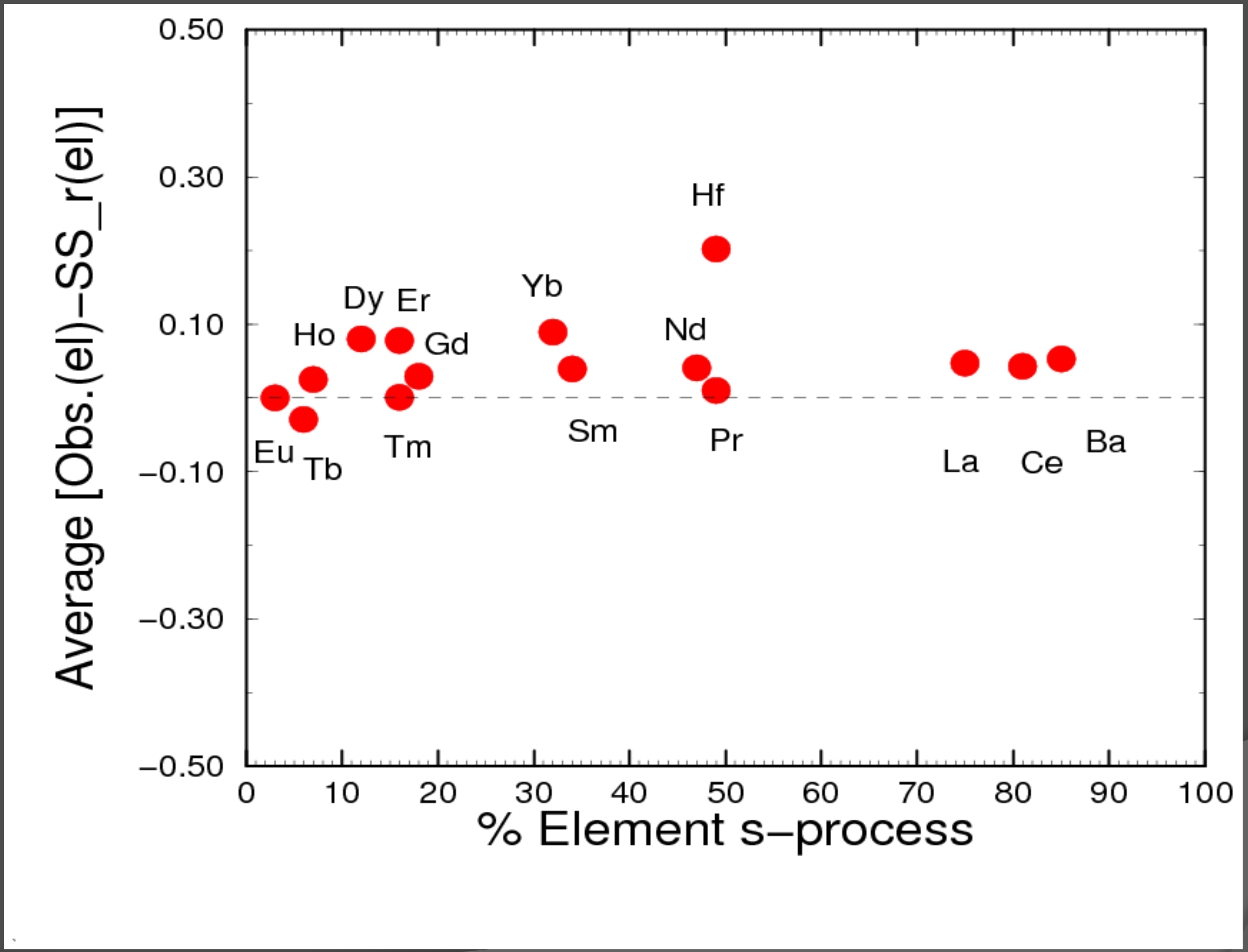
Sneden et al. 2009

Application of good lab data to good observations of r-process-rich metal-poor stars



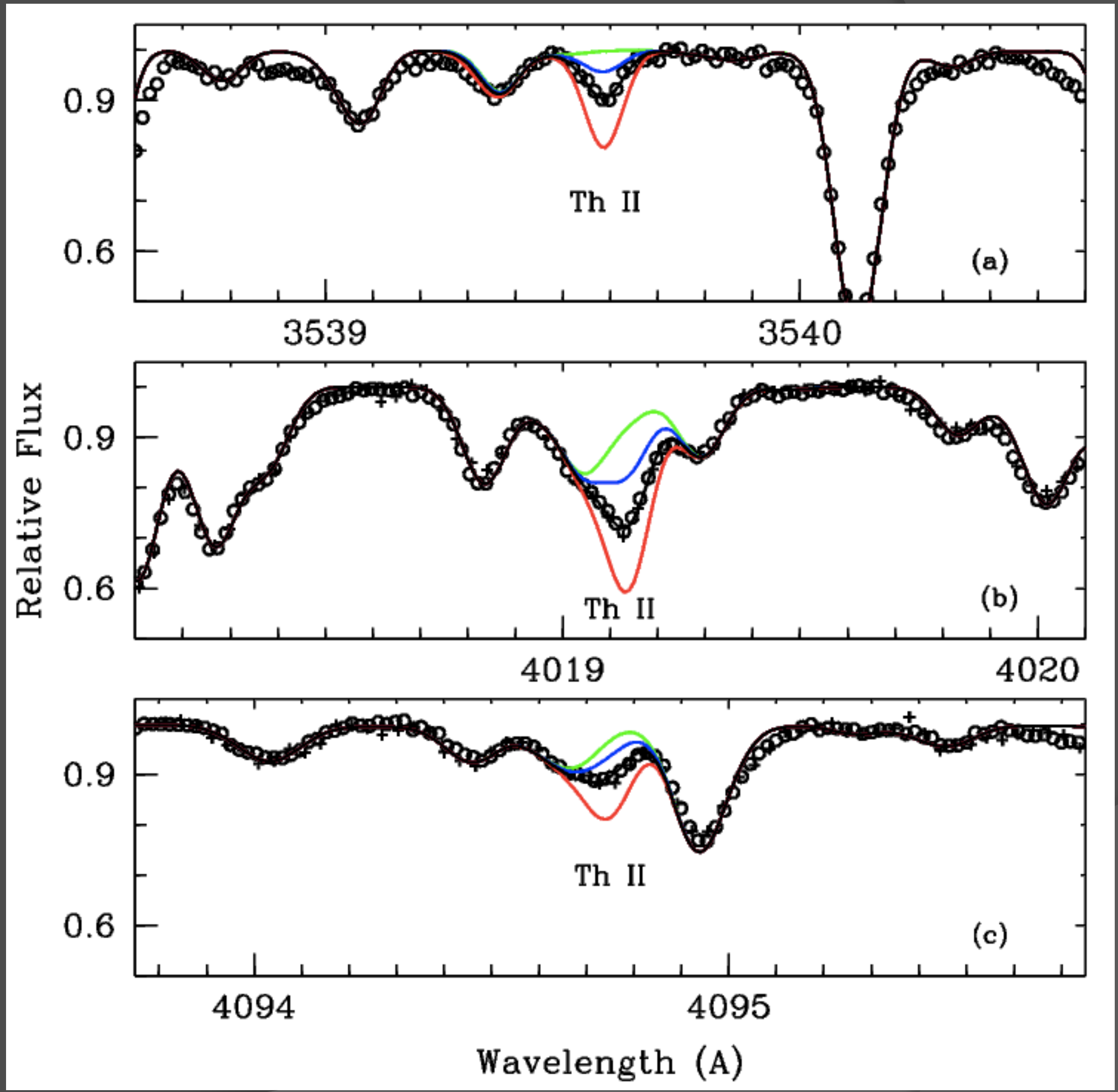
Sneden et al 2009

Only hafnium sticks out; problem with r/s solar fraction?



Sneden et al 2009

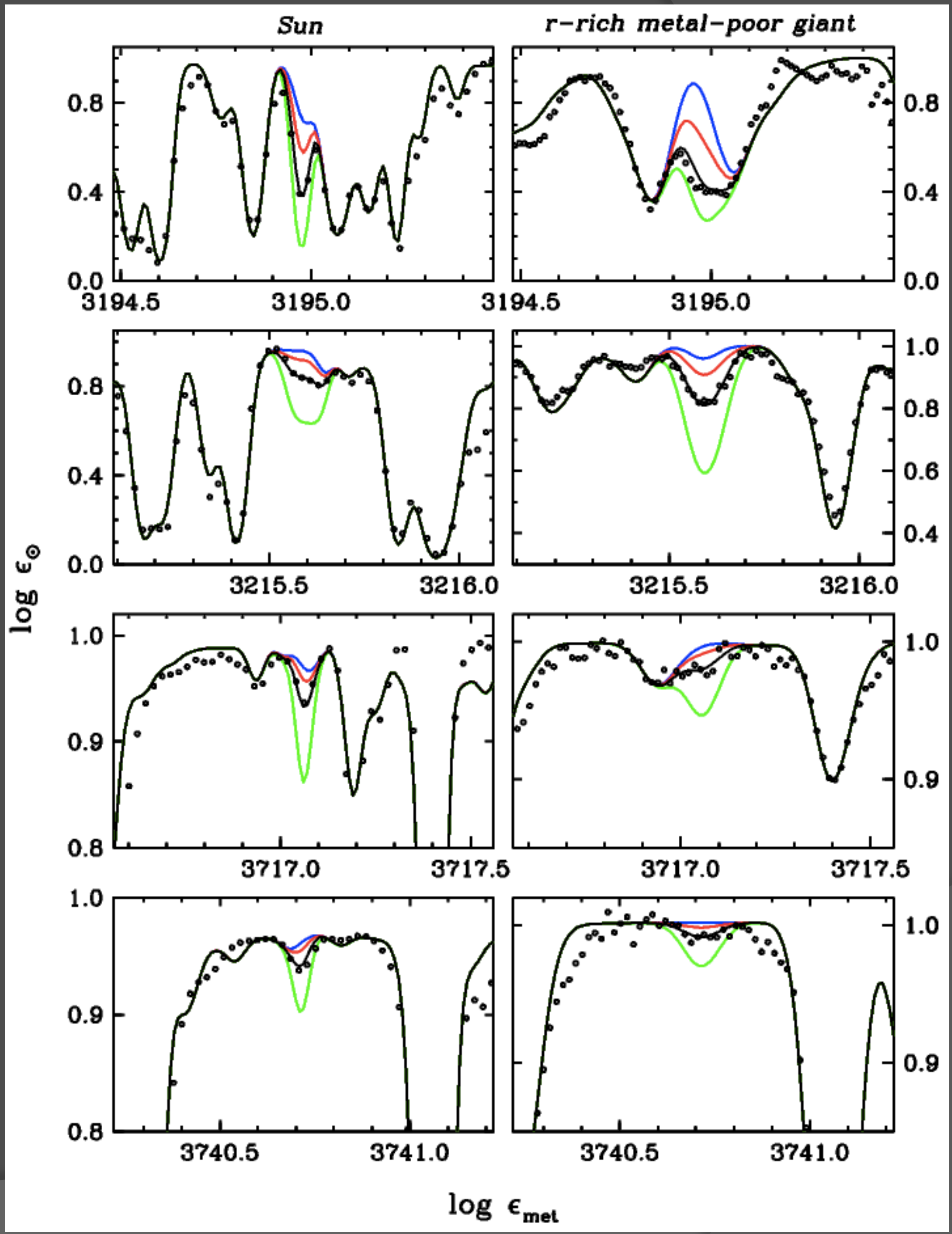
Critical element thorium is a struggle even in the best cases



Ivans et al. 2006

Niobium (Z=41): Good luck!

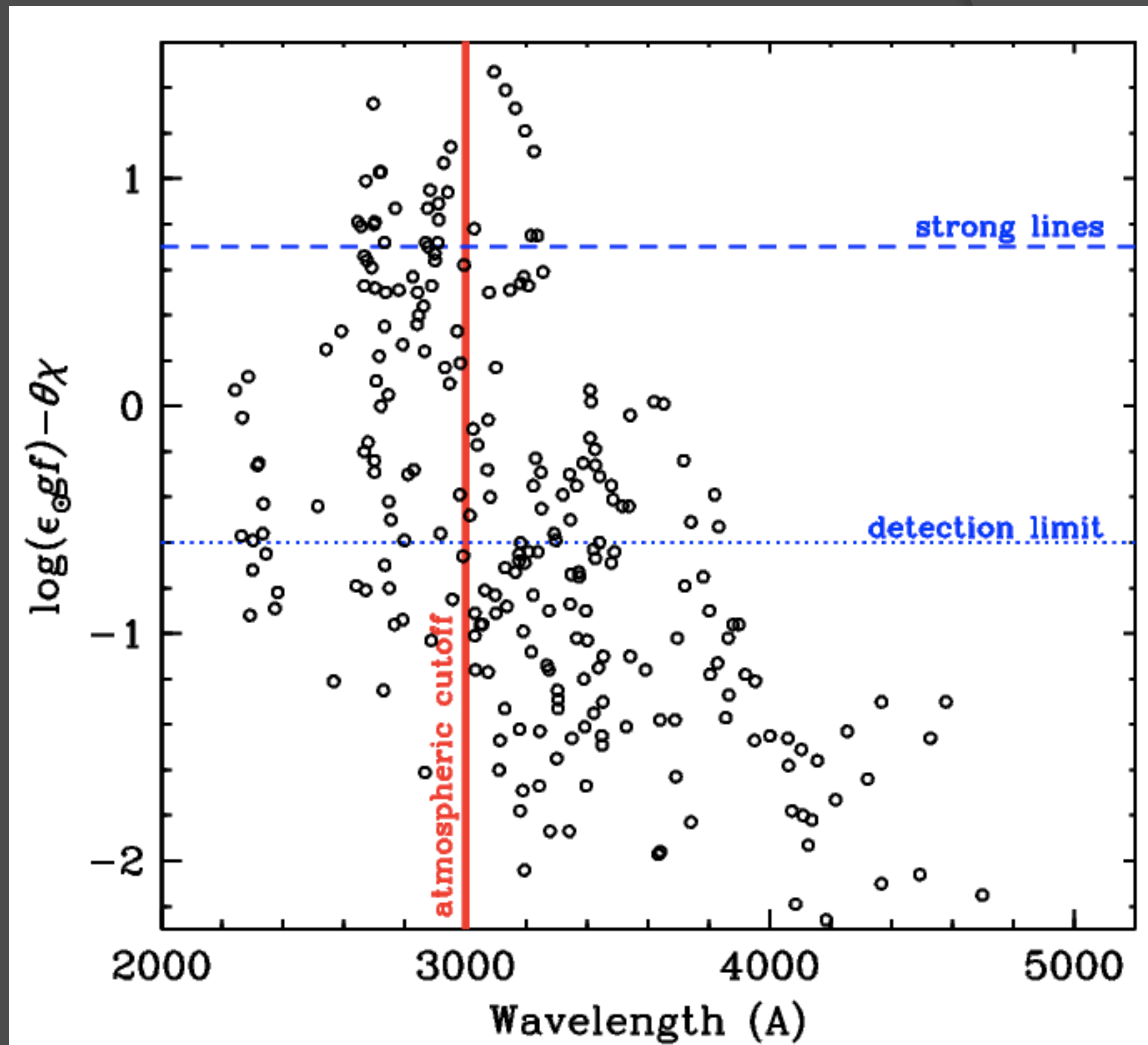
these are the best transitions in the most favorable detection cases



Nilsson et al. 2010

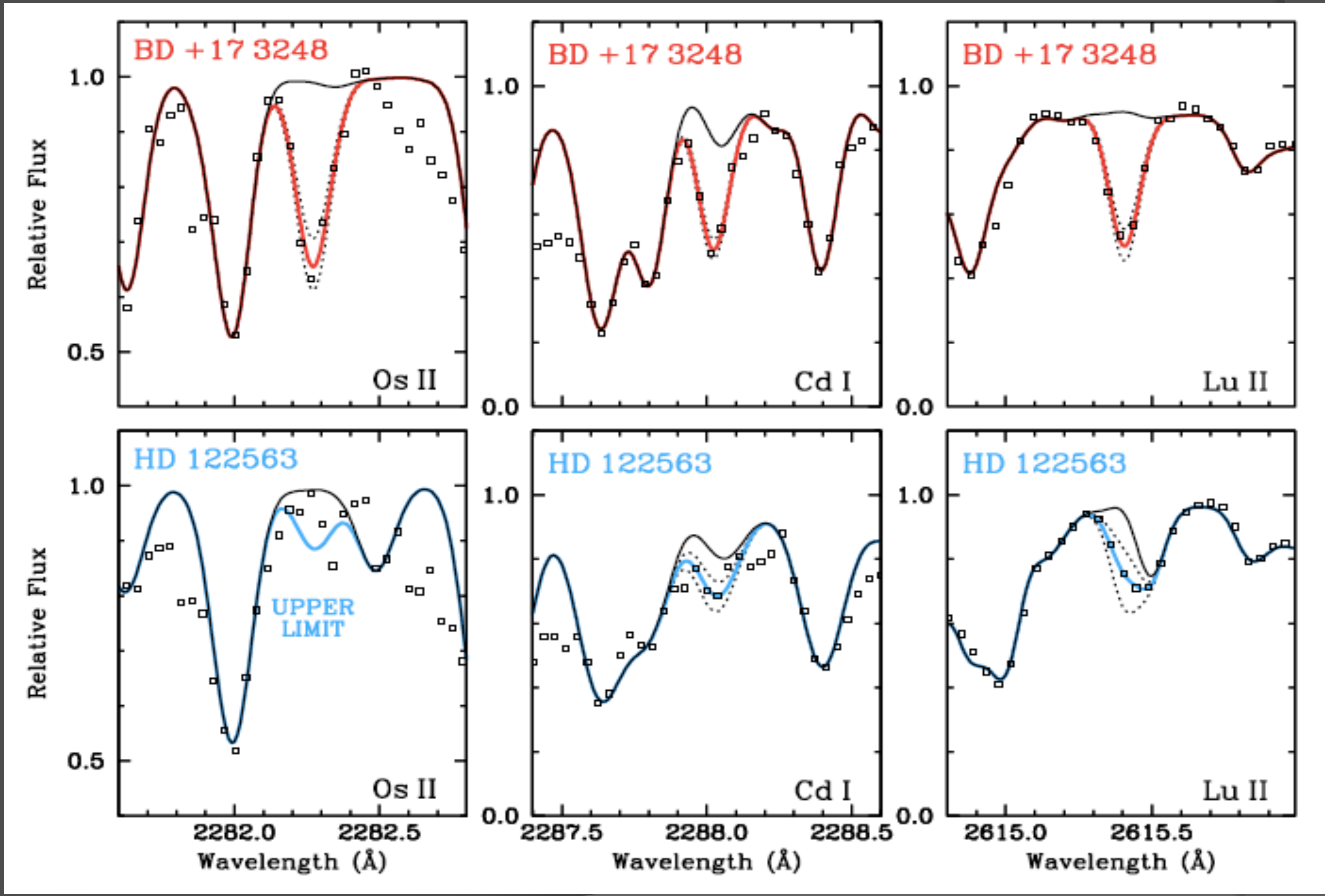
Why is Niobium such a challenge?

Simple: all reasonably strong lines are in the vacuum UV



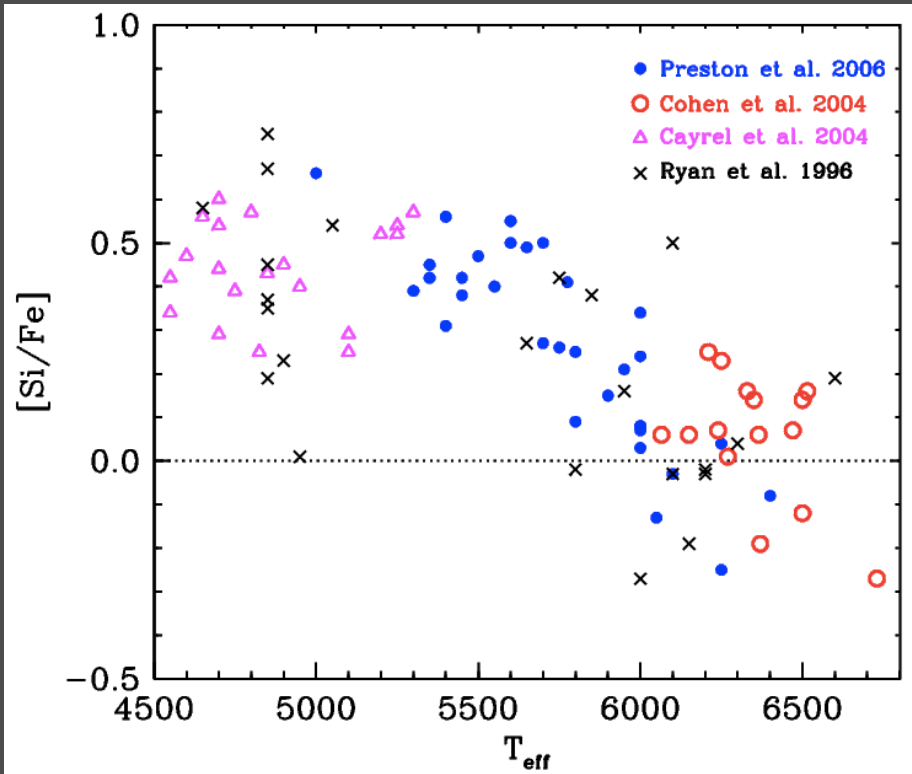
Nilsson et al. 2010

The vacuum UV can be explored in extreme cases

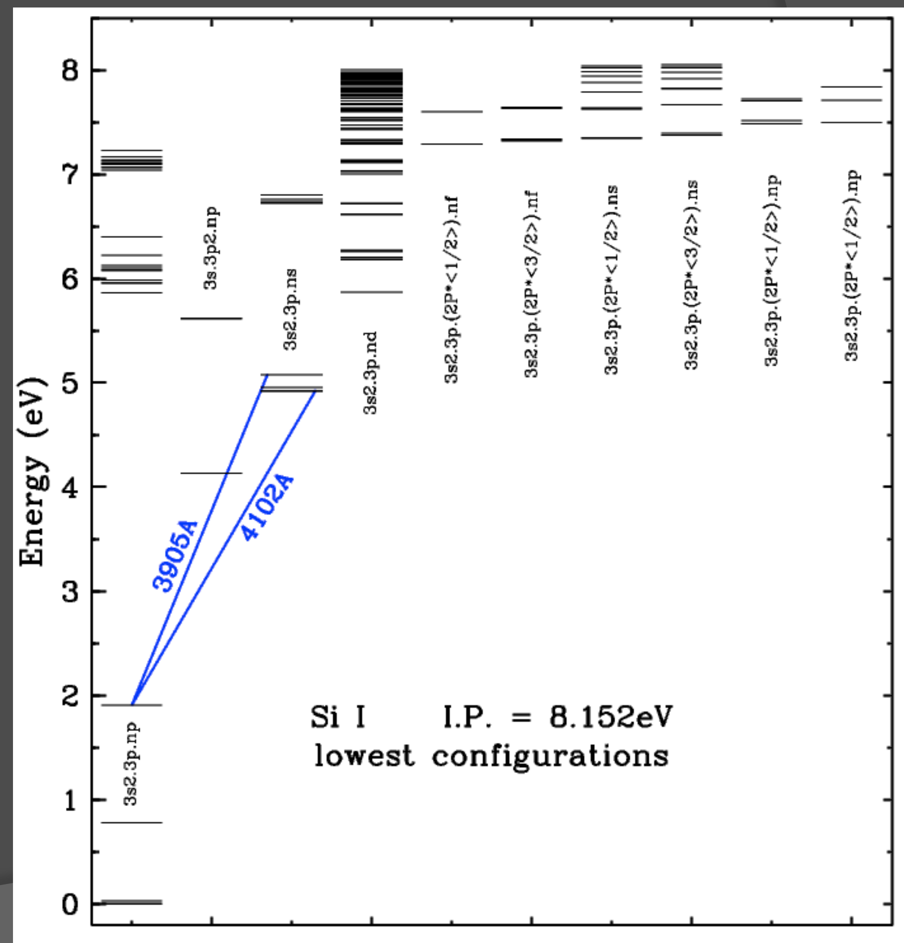


Roederer et al 2010

non-LTE worries: a light element example

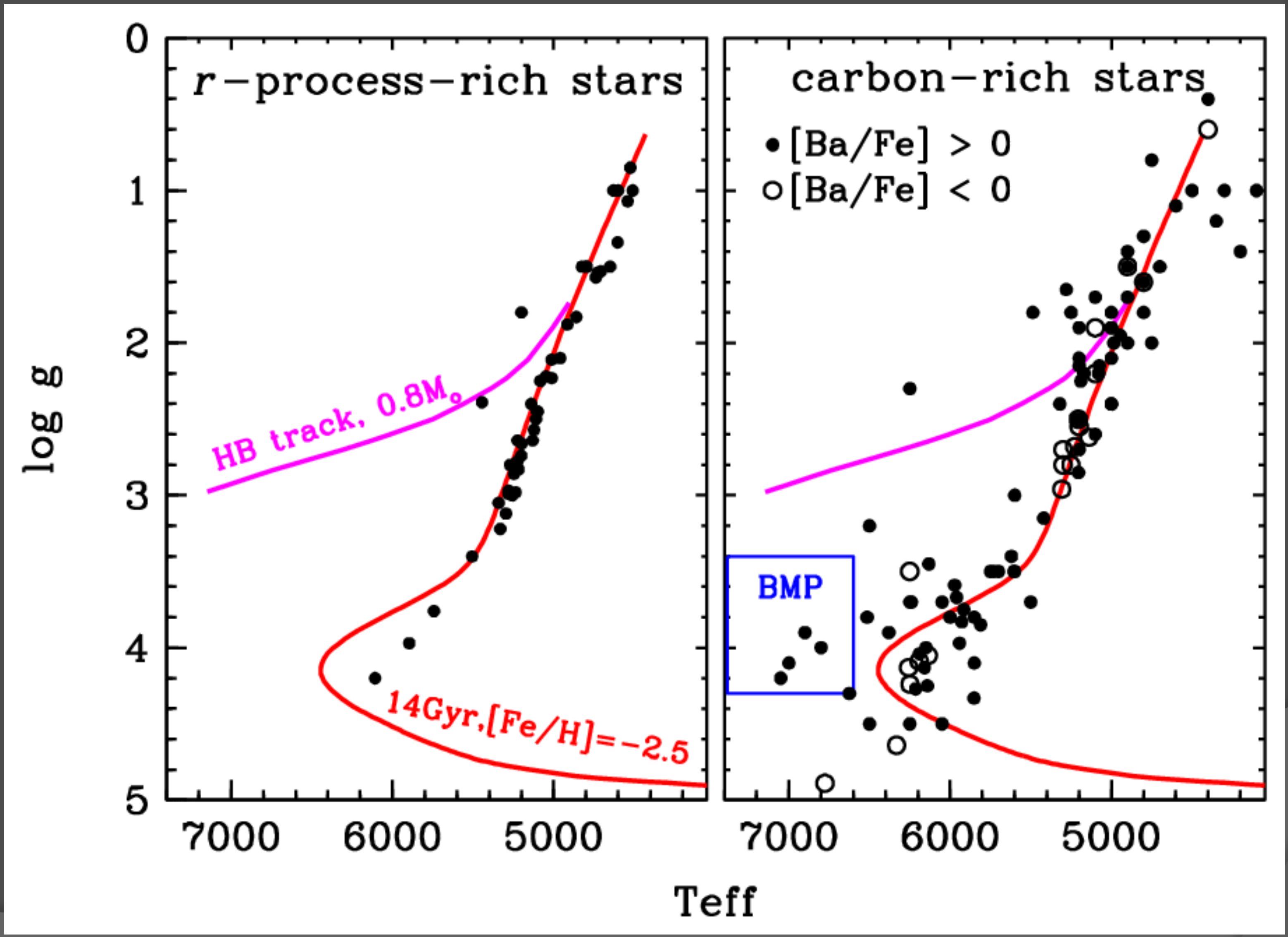


of some concern for elements like Ag, Cd, …



Sneden et al 2008

majority of r-rich stars are red giants; observational selection (I hope)



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Suggestions for future work

- Must continue the lab efforts: gf, hfs, iso work
  - *special needs: elements 42-50*
- Must devote serious big telescope time to n-capture-rich stars
- Better efforts to detect isotopic substructure
- More uniform surveys of La, Eu, Pb
- Pb is a key; we do not understand its synthesis
- must find more super-r-rich stars with U
- better understanding of Th/Eu ratios