Observational constraints on the r-process nucleosynthesis

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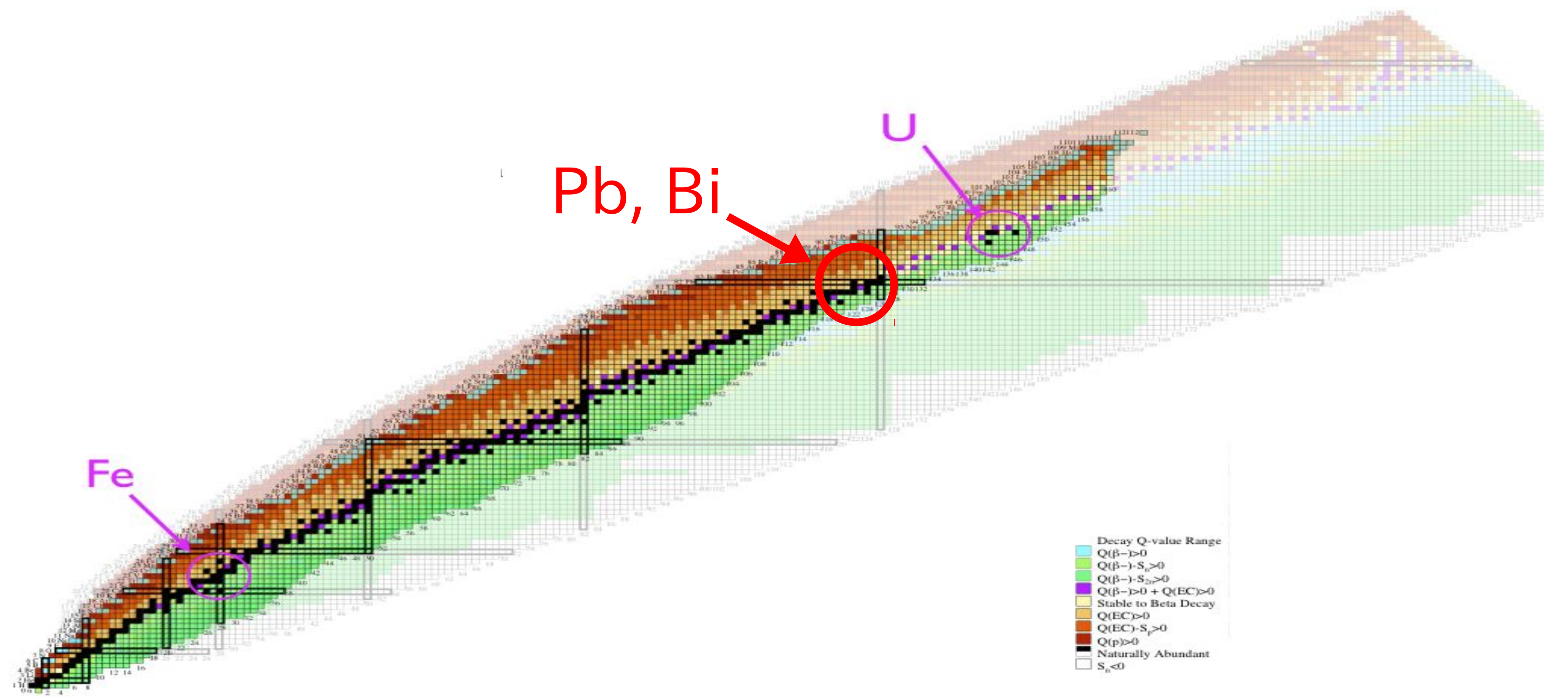
Background

- Existence of the r-process (explosive synthesis of heavy elements) is obvious from the existence of actinides (Th and U).
- However, the astrophysical site(s) of the process is still unknown. Observations provide useful constraints on the r-process.



Observational constraints on the r-process nucleosynthesis

(1) Chemical abundance patterns of r-process enhanced stars

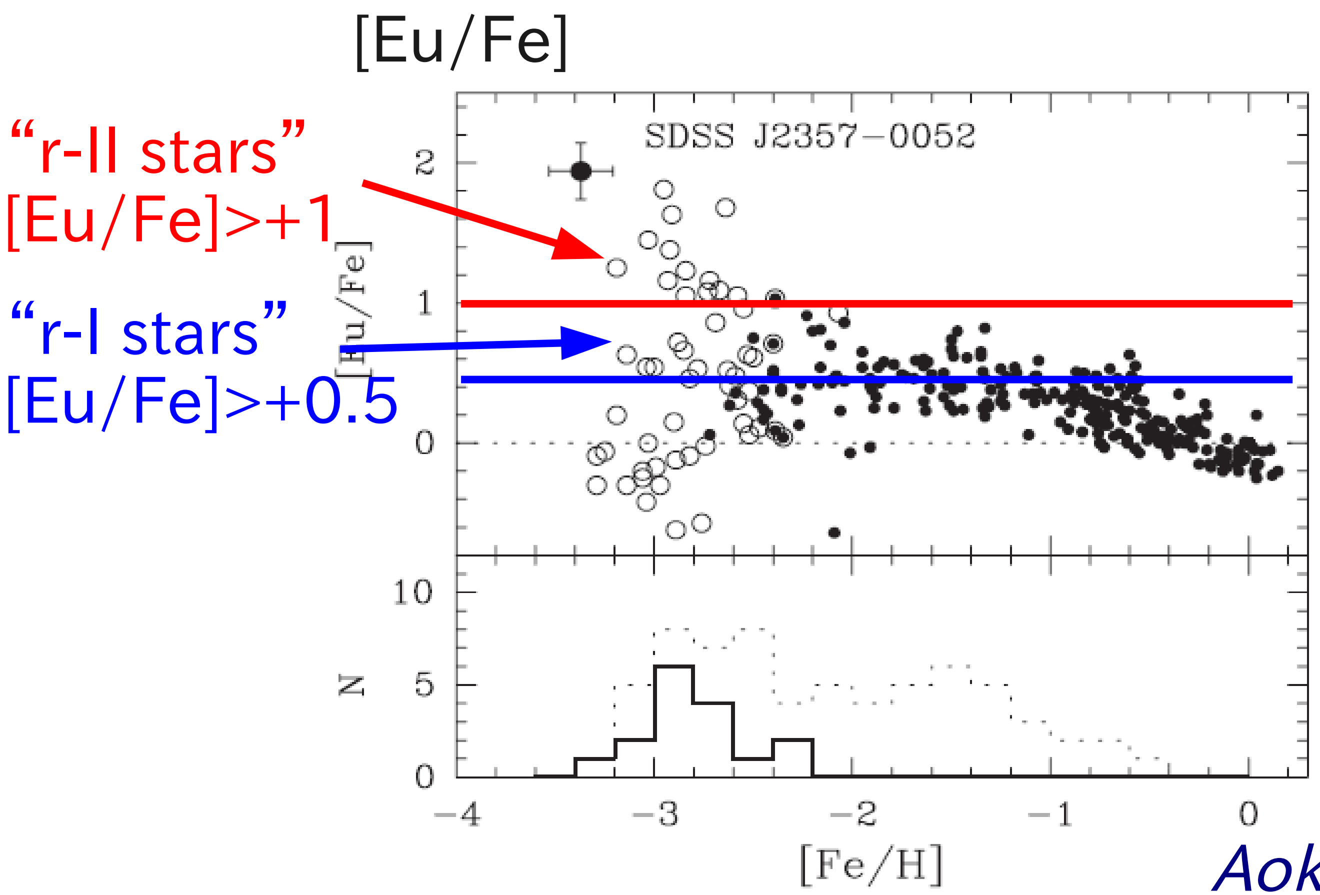
(2) Abundance distribution/trend of heavy elements
-large scatter of Eu abundance ratios
-distribution of Sr and Ba abundance ratios
-heaviest elements: Th and Pb
-(No) correlation with lighter elements

(3) Searches for r-process elements in supernova remnants

(4) Other systems
-globular clusters
-dwarf galaxies

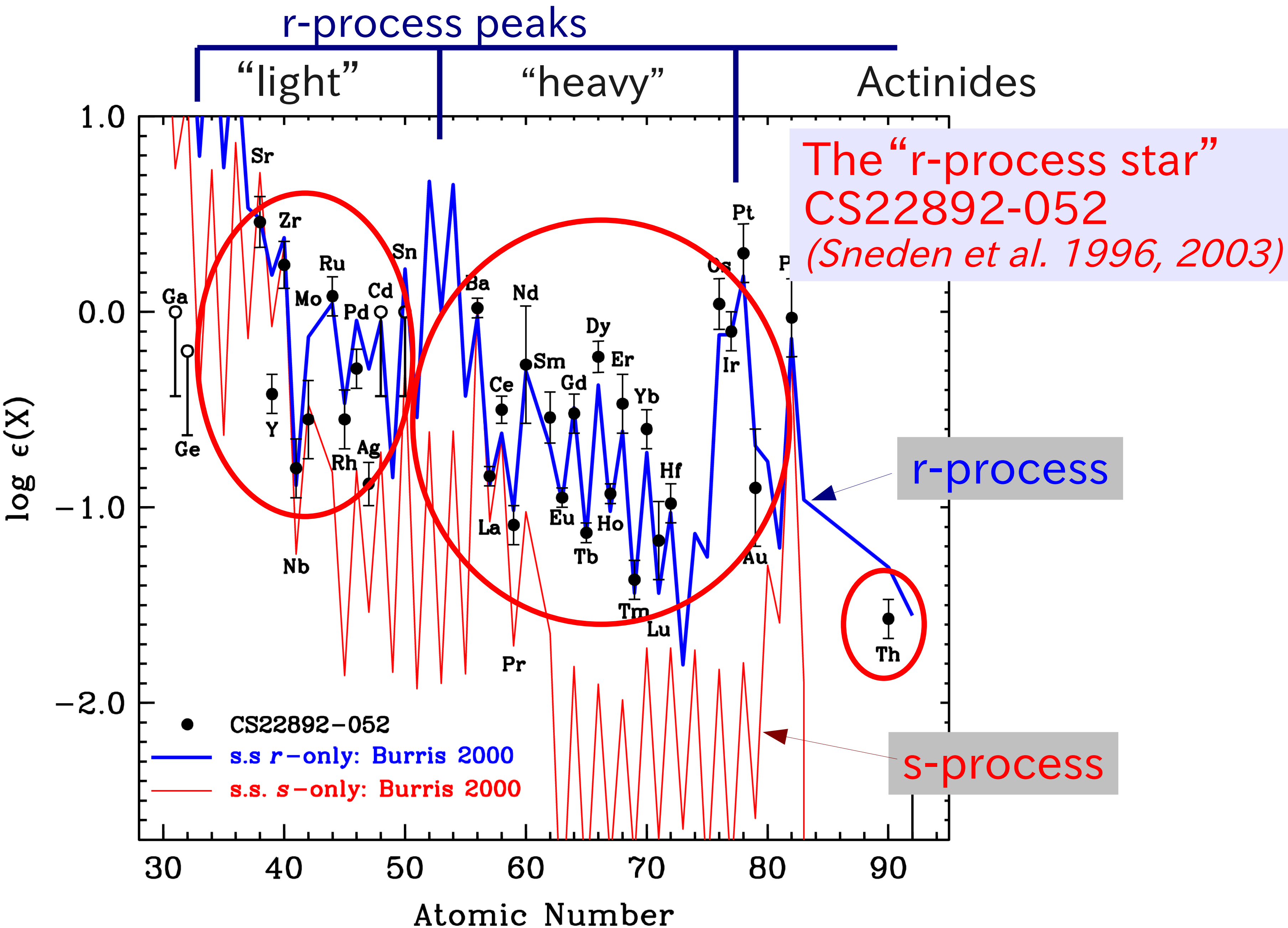
Summary and discussion

(1) Constraints from abundance patterns of r-process enhanced stars

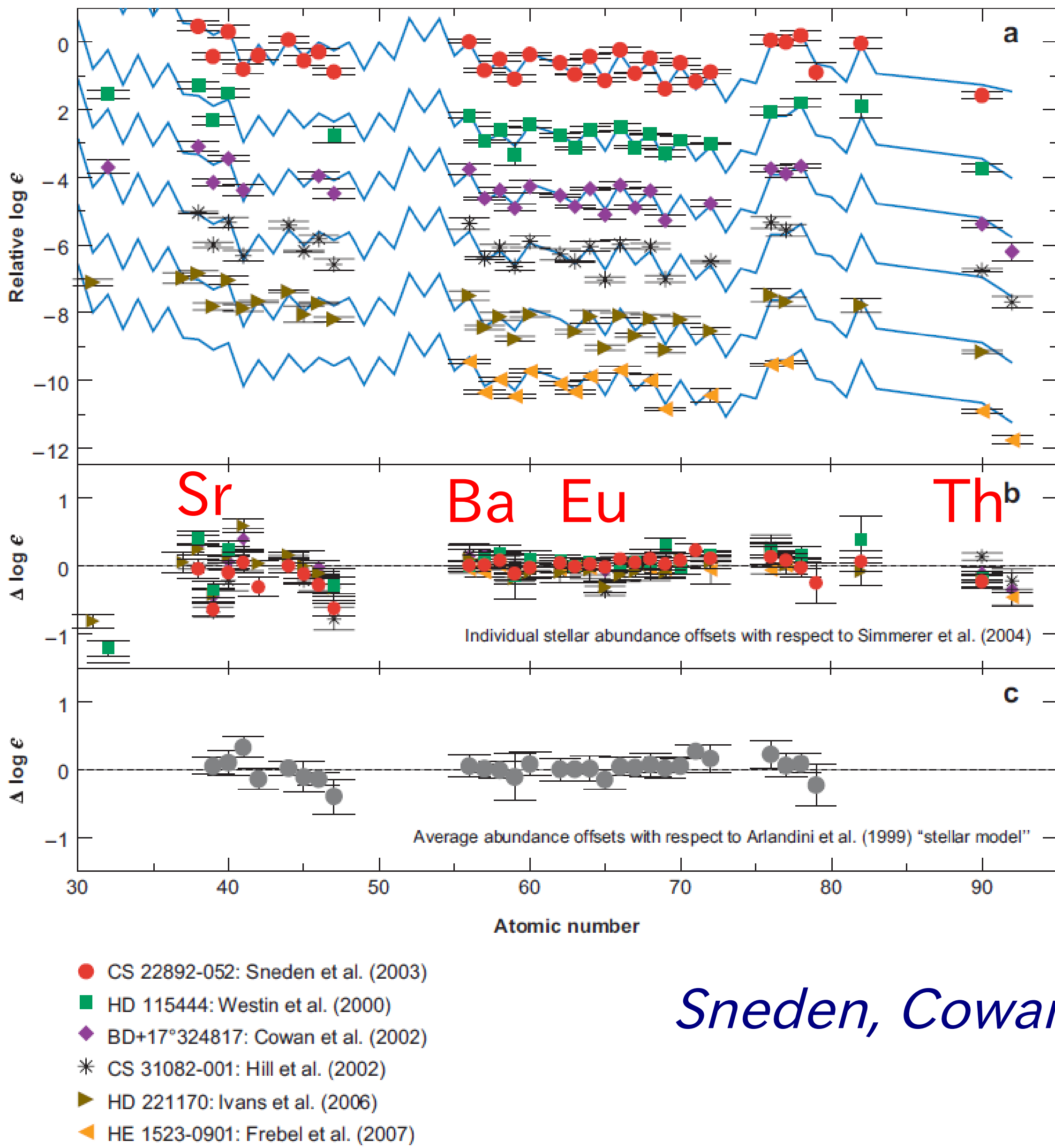


Aoki et al. 2010

r-process-enhanced stars



Similar abundance patterns are also found for other r-process-enhanced stars

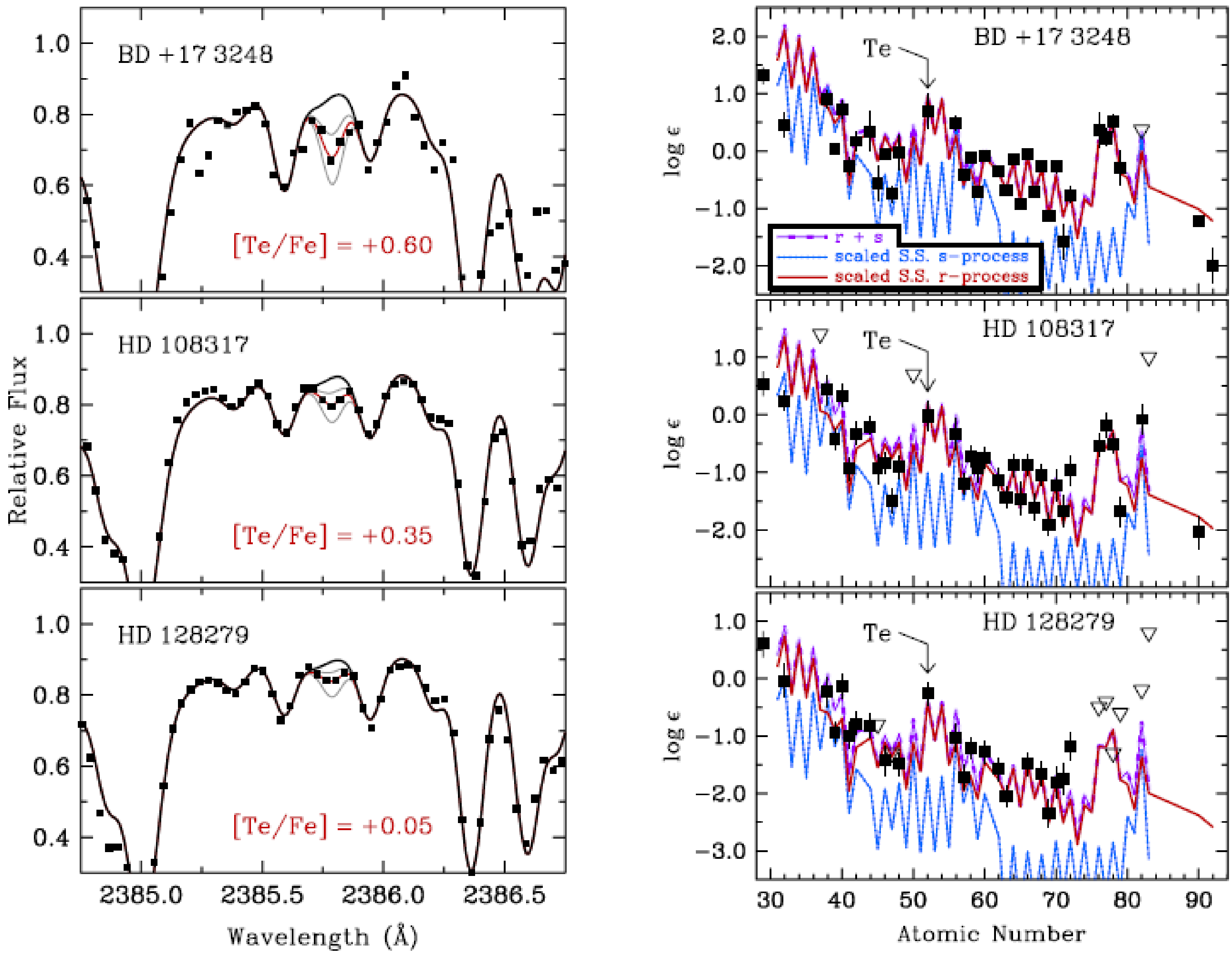


Comparisons with solar-system r-process pattern

Sneden, Cowan, Gallino 2008

Detection of the 2nd peak element Te

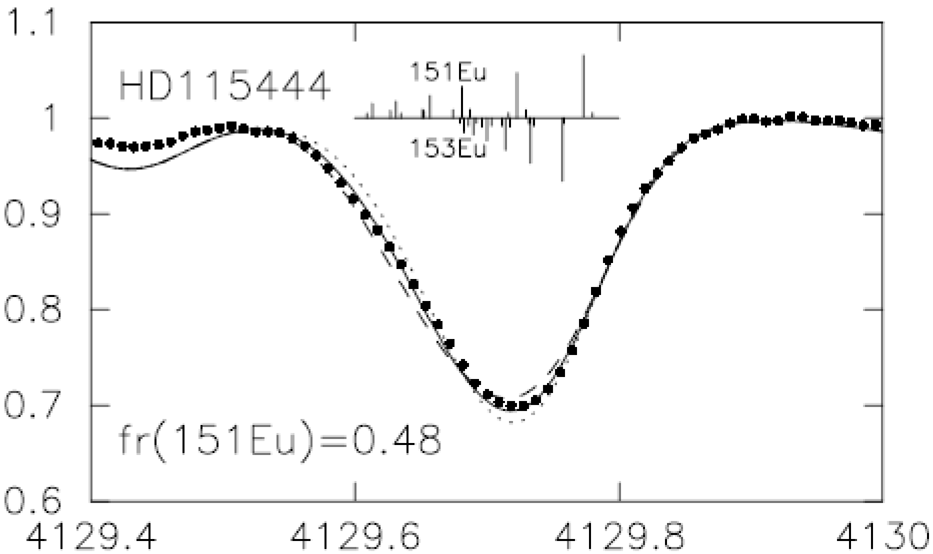
Roederer et al. (2012)

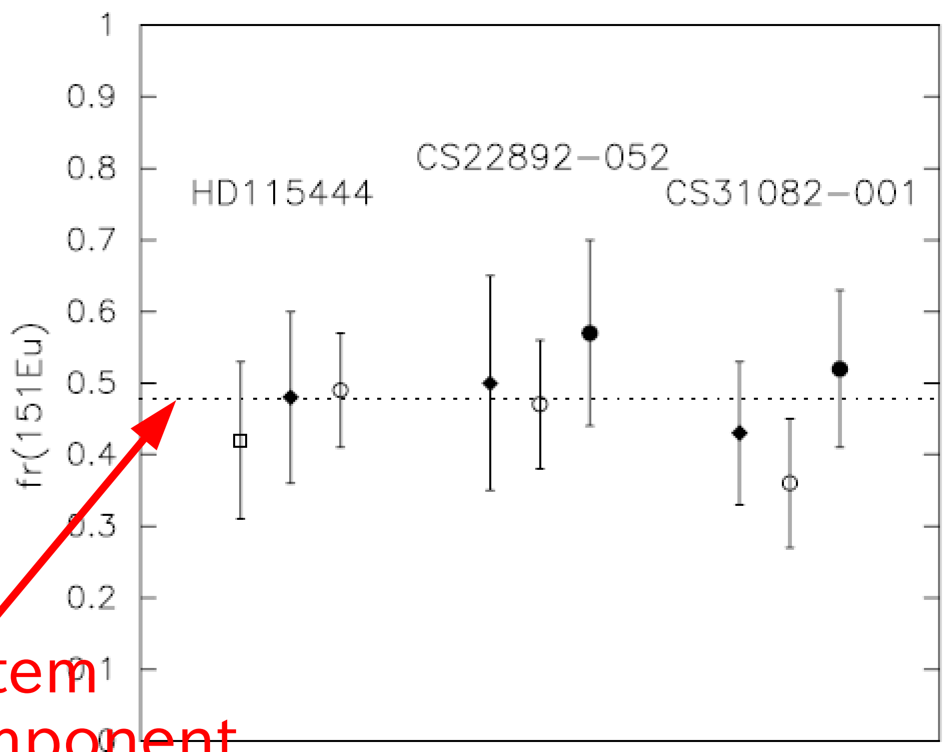


Agreement with the solar-system r-process component is also found for Eu isotope ratio

Measurement of Eu isotope ratio (^{151}Eu:^{153}Eu)

Aoki et al. (2003)





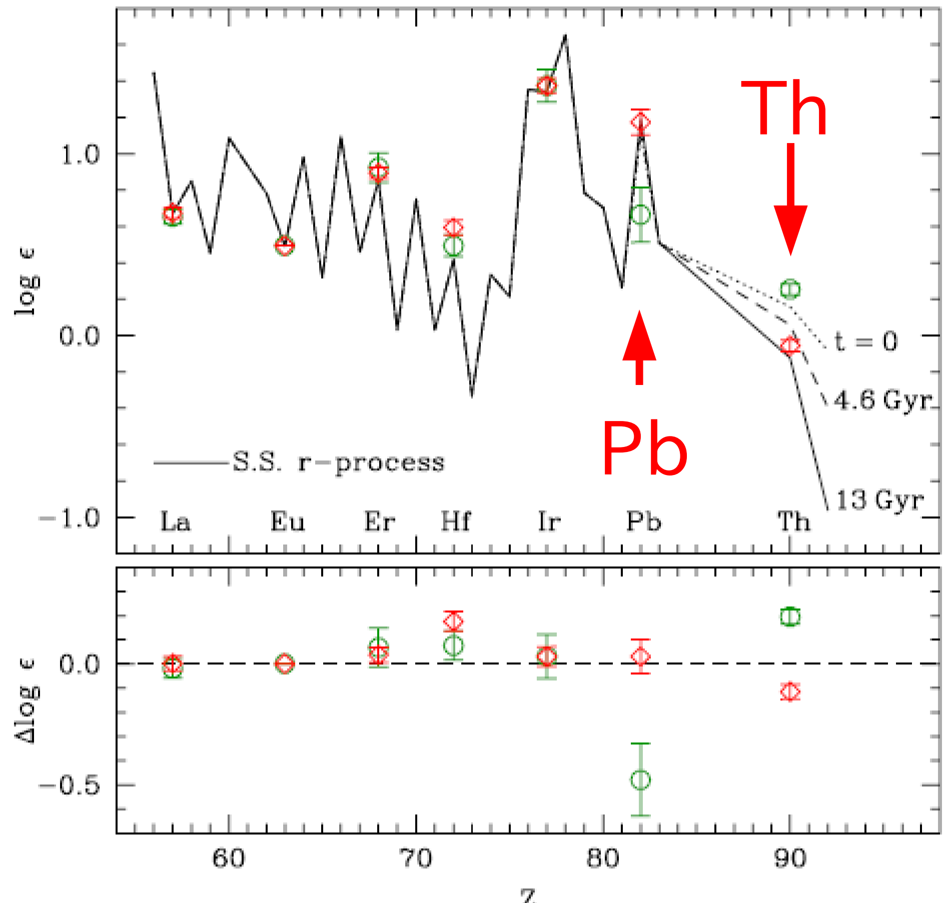
The solar-system
r-process component

Heaviest elements: Th and Pb

- Scatter exists in the actinides abundance ratios (e.g. Th/Eu), but that is small (<0.5 dex).

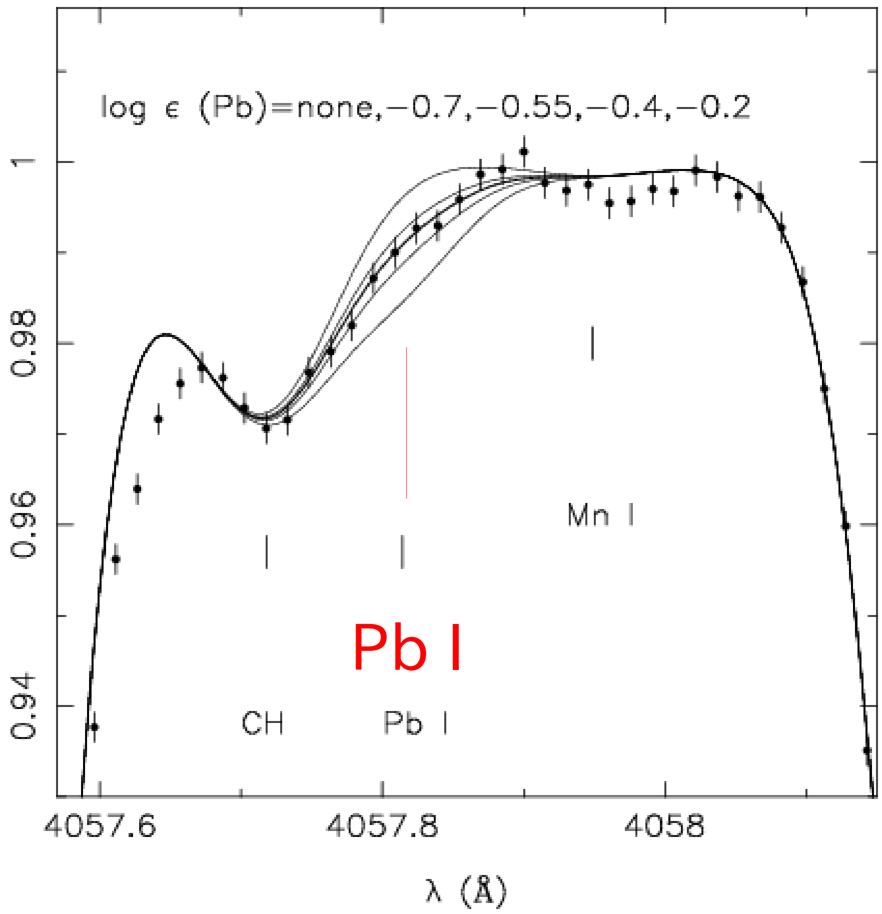
- Pb abundances are low in r-process-enhanced stars (?)

○"standard" r-enhanced stars
○"actinide-boost" stars



Roederer et al. 2009

Heaviest elements: Pb problem



Plez et al. (2004)

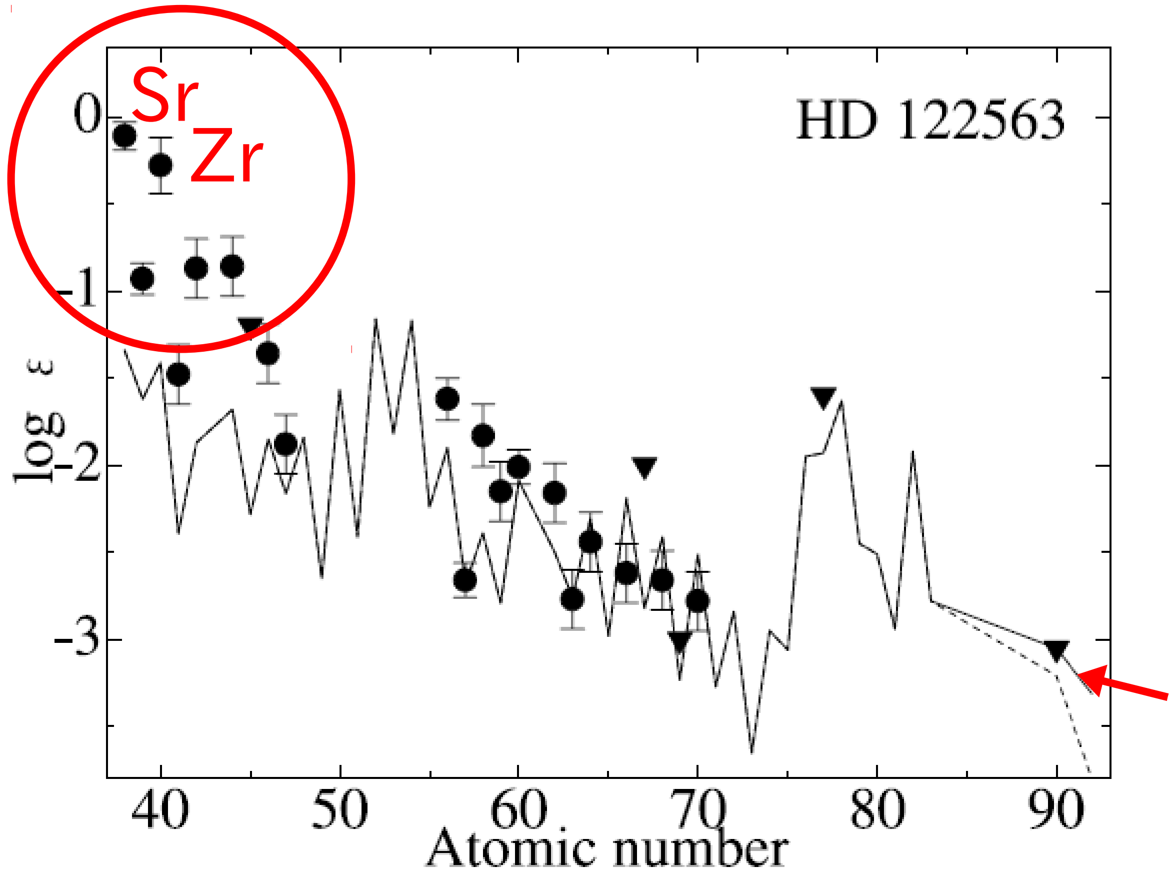
r-process-enhanced star CS31082-001
→Pb abundance is much lower than expected from Th, U abundances

Pb is also deficient in another r-II star (HE1523-0901: Frebel et al. 2007)

cf. Wanajo et al. (2007)
"cold r-process"?

Notice for discussion from abundance patterns

- "r-II stars" may be special class
- There are many "r-process-poor" stars. Some of them show large excesses of light (1[st] peak) neutron-capture elements.

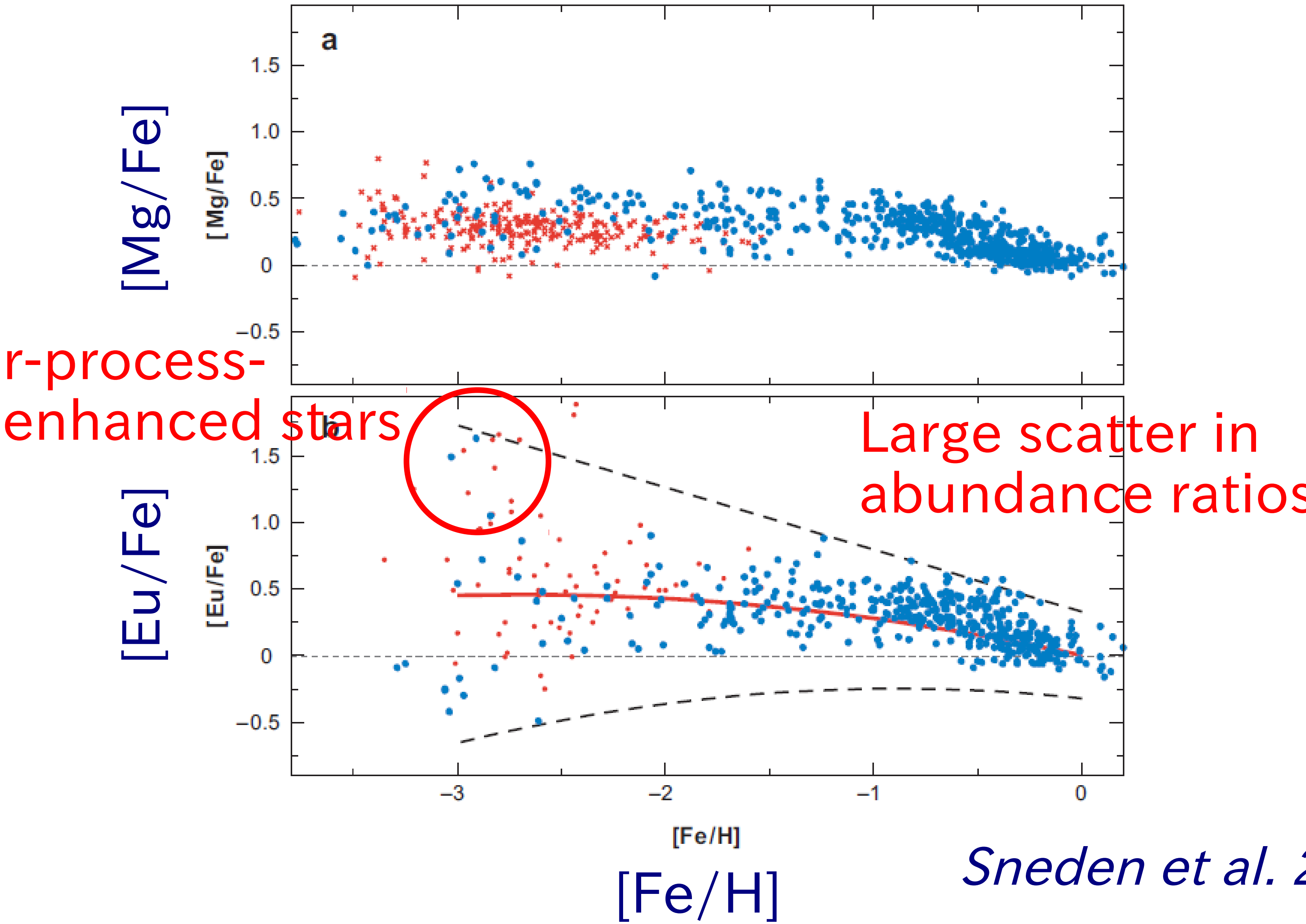


HD122563
([Fe/H])=-2.7

Honda et al. 2006

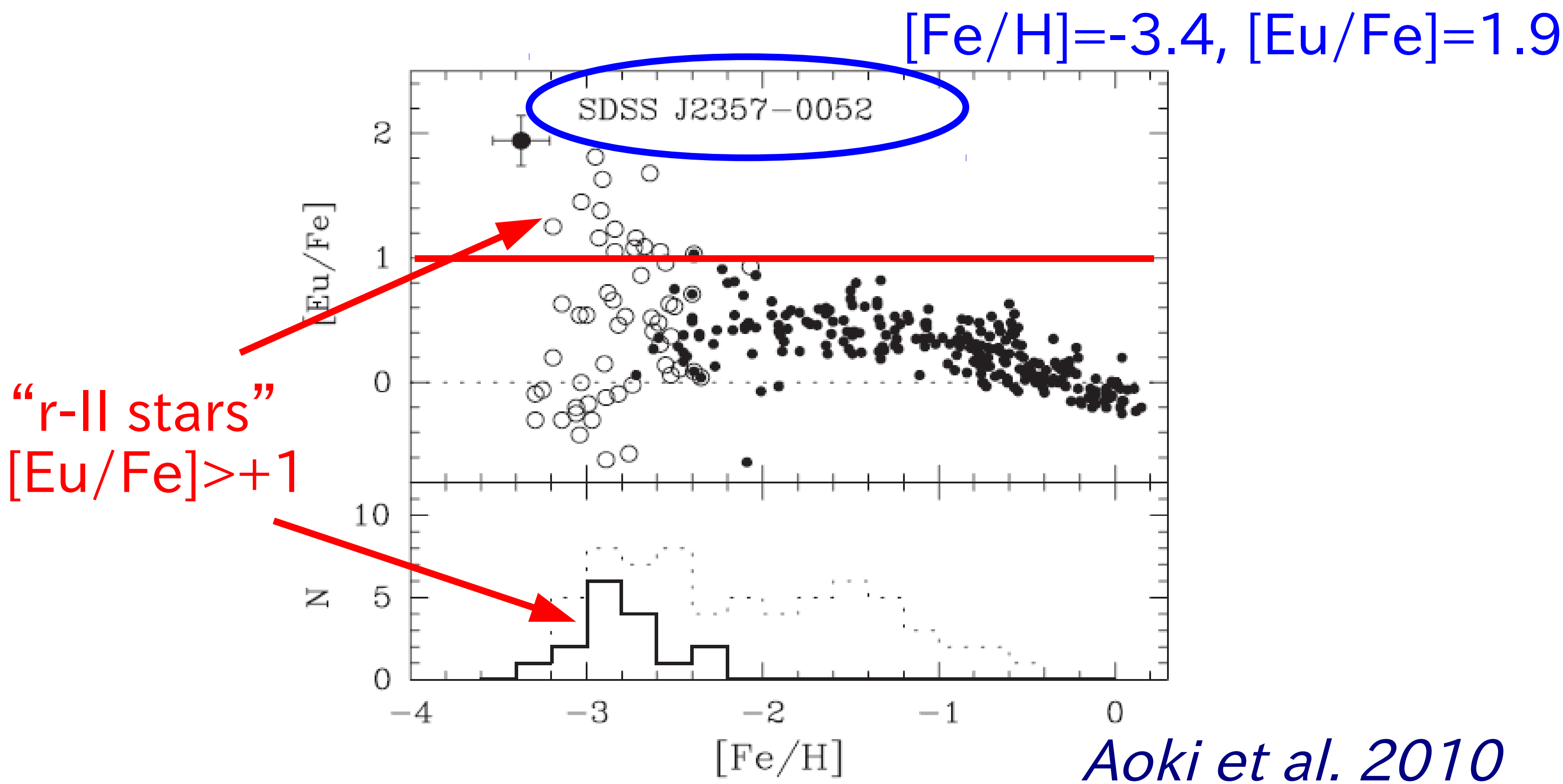
(2) Abundance distribution / trend of heavy elements

(2-1) Large scatter of the r-process abundance ratios



Sneden et al. 2008

Metallicity distribution of r-process-enahnced stars



Aoki et al. 2010

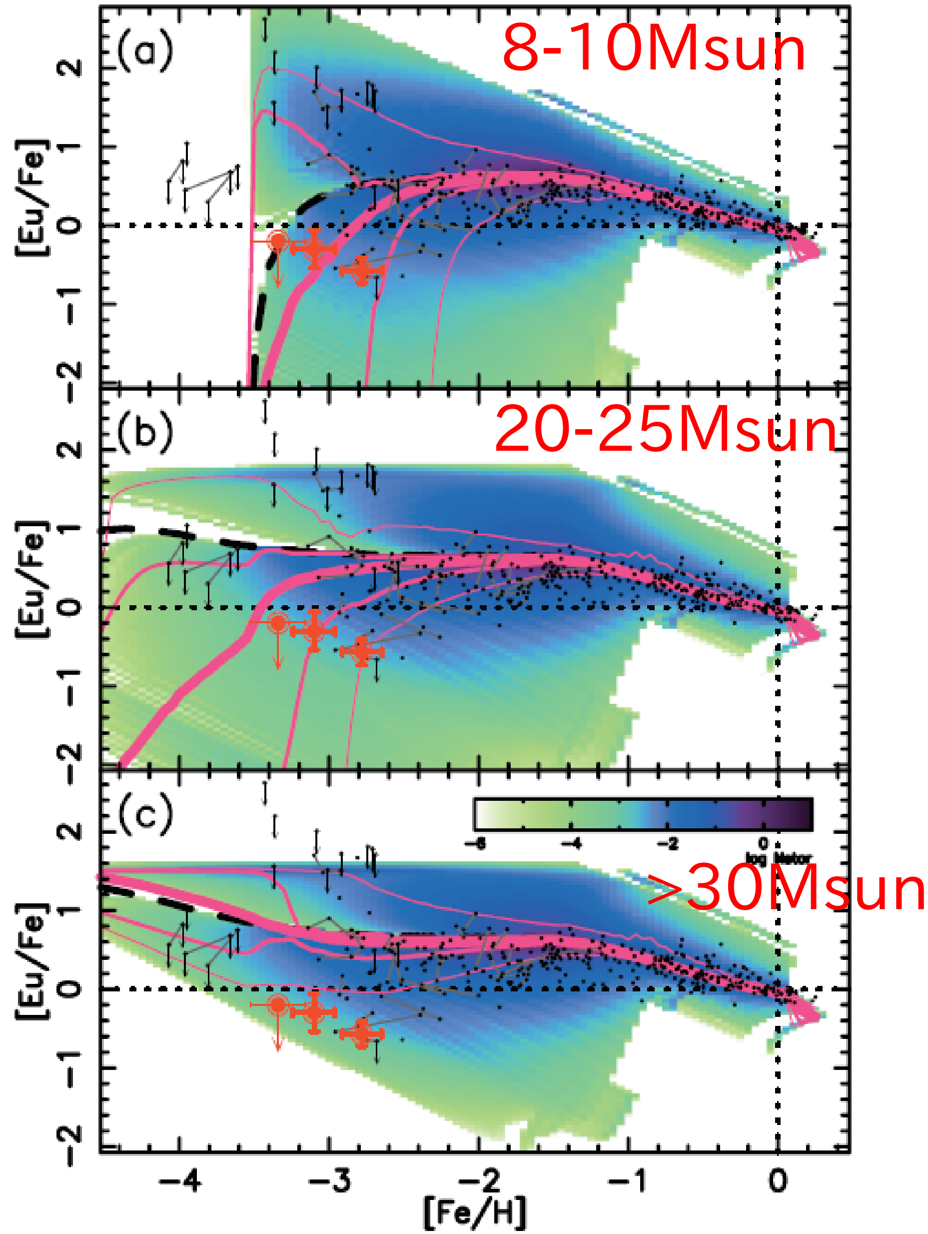
Eu is the best indicator of the (main) r-process, but spectral lines are too weak in extremely metal-poor stars

Metallicity dependence of abundance ratios as a probe of the astrophysical sites

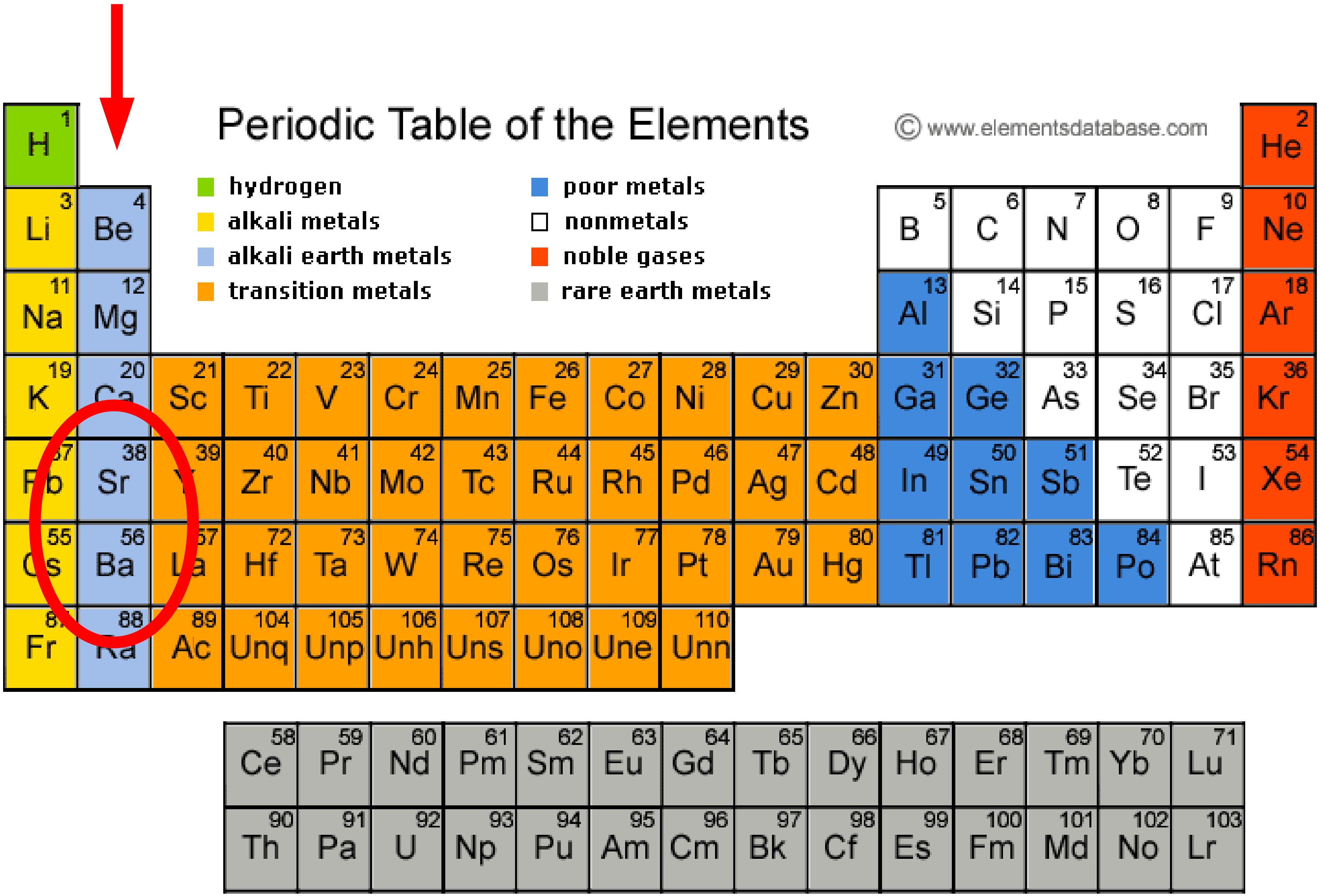
Metallicity dependence
→indirect estimate for mass of progenitors
(model dependent)

Example:
Trend and scatter of Eu abundances
→ less massive stars (8-10 Msun) are preferable as astrophysical sites of the main r-process.

Ishimaru et al. 2004

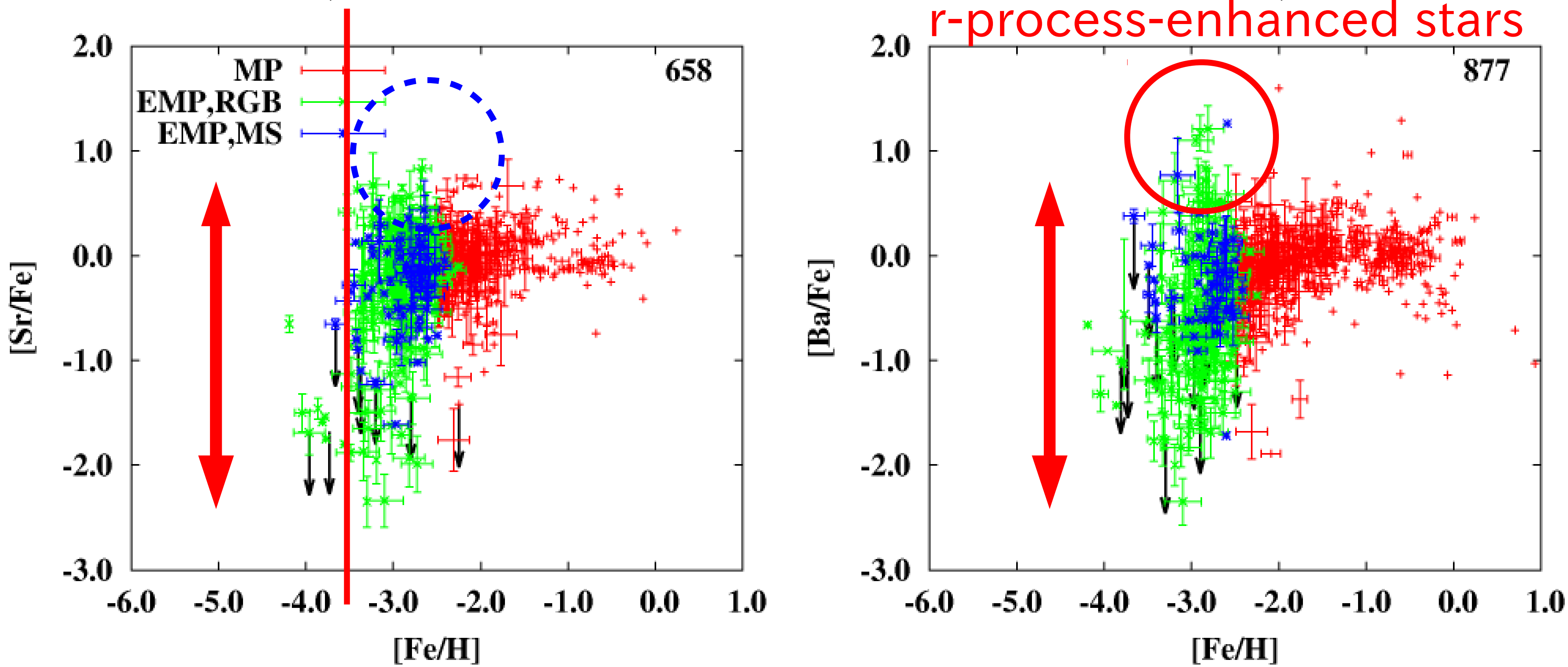


(2-2) Sr and Ba: representatives of light and heavy neutron-capture elements



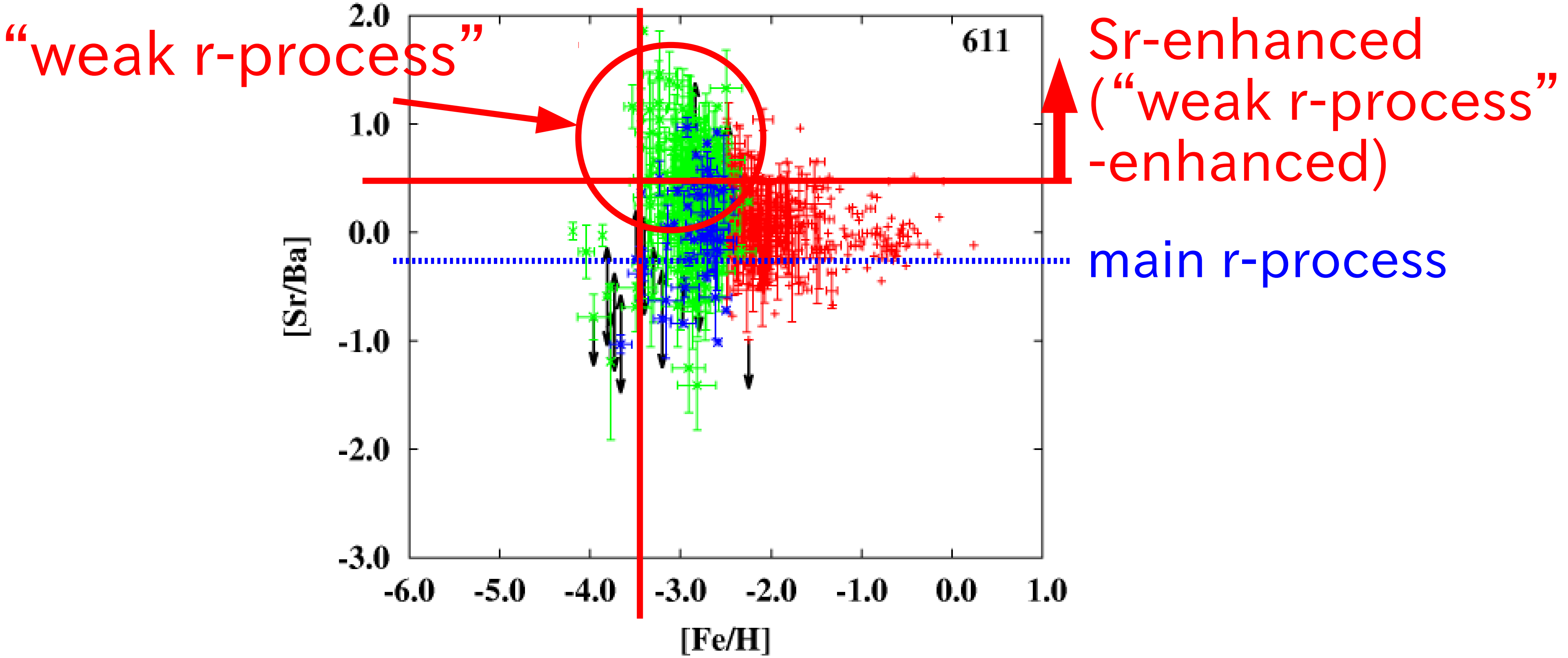
Trend and scatter in abundance ratios of Sr and Ba from SAGA database

(Carbon-enhanced stars are excluded)



•Very large scatter in [Sr/Fe] and in [Ba/Fe] in [Fe/H]<-2.5.
•A group of stars show very high [Ba/Fe] at [Fe/H]=-3.. Such stars are not found in the [Sr/Fe] diagram.

Trend and scatter in Sr/Ba abundance ratios of from SAGA database



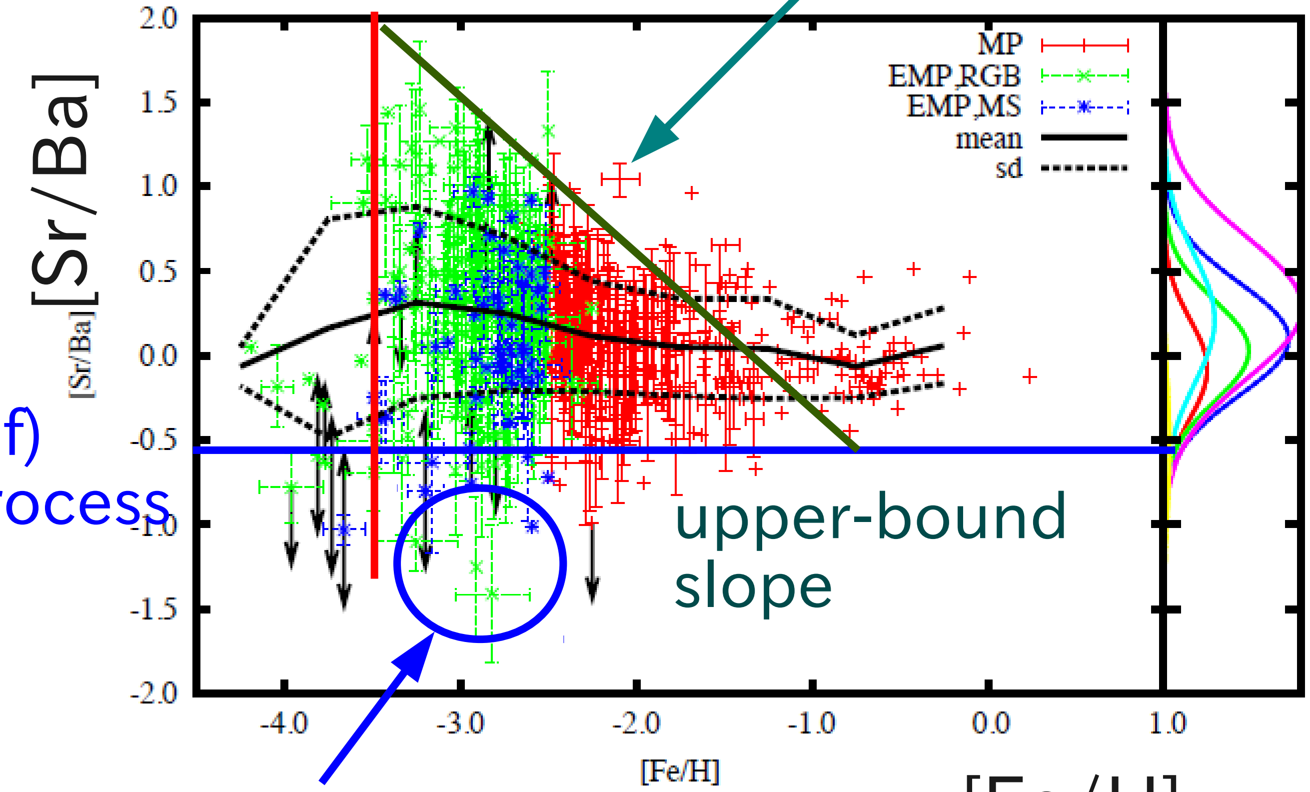
A tentative definition of Sr-enhanced stars:

[Sr/Ba]> +0.5 → "weak r-process"-enhanced stars

Sr/Ba diagam … in more detail

cut-off at [Fe/H]=-3.5

BD+80 245:
low α, Sr and Ba



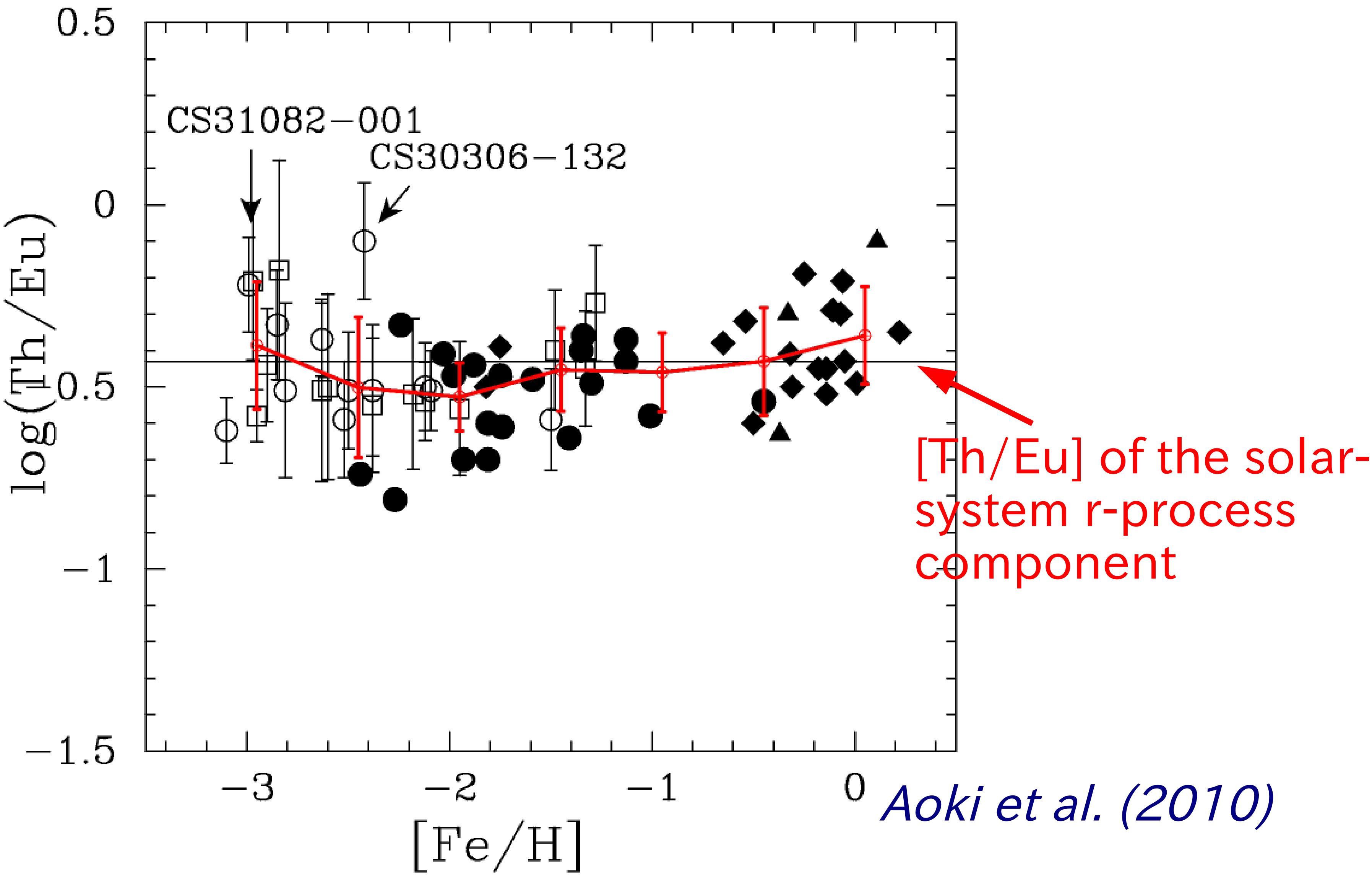
(lower limit of)
the main r-process

upper-bound
slope

[Fe/H]

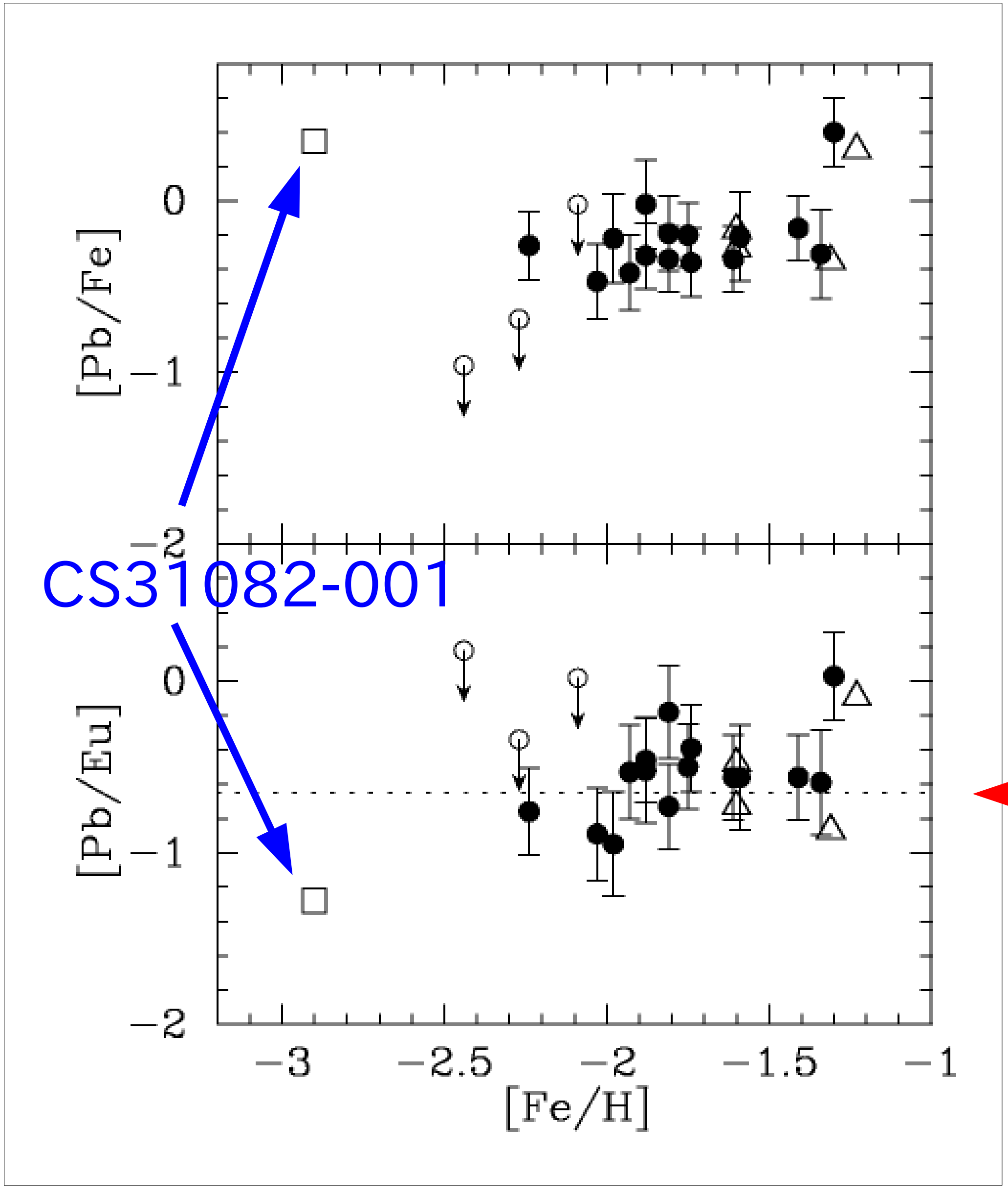
Moderately C-rich and/or binary
… affected by s-process

(2-3) Heaviest elements: Th



Aoki et al. (2010)

(2-3) Heaviest elements: Pb



Carbon-enhanced stars are not included.

●○*Aoki et al. (2008)*
△*Yong et al. (2006, 2008)*

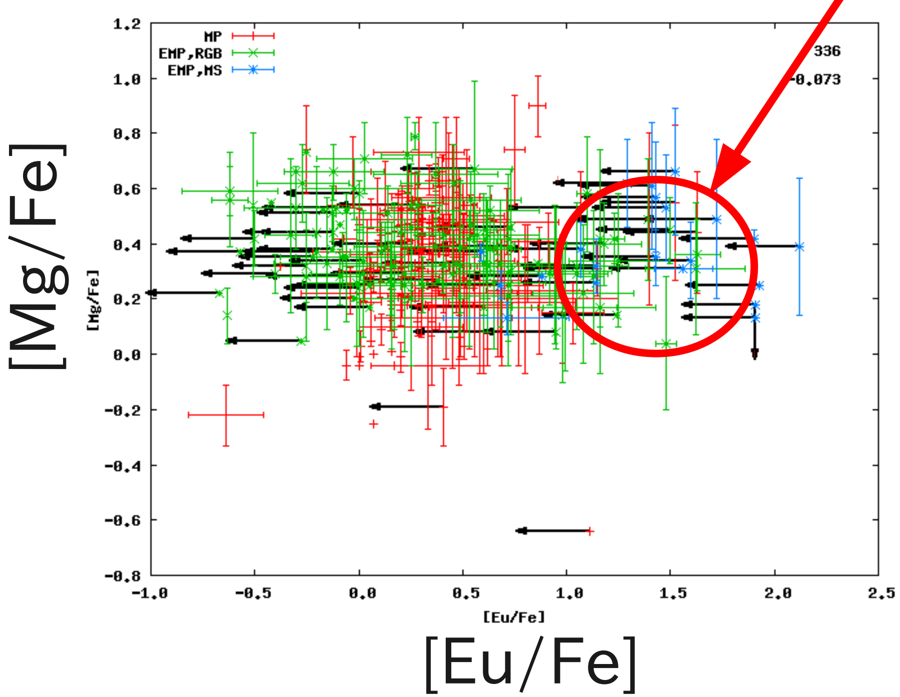
[Pb/Eu] trend agrees with the solar-system r-process component in general. But the [Pb/Eu] of the r-II star CS31082-001 is exceptionally low.

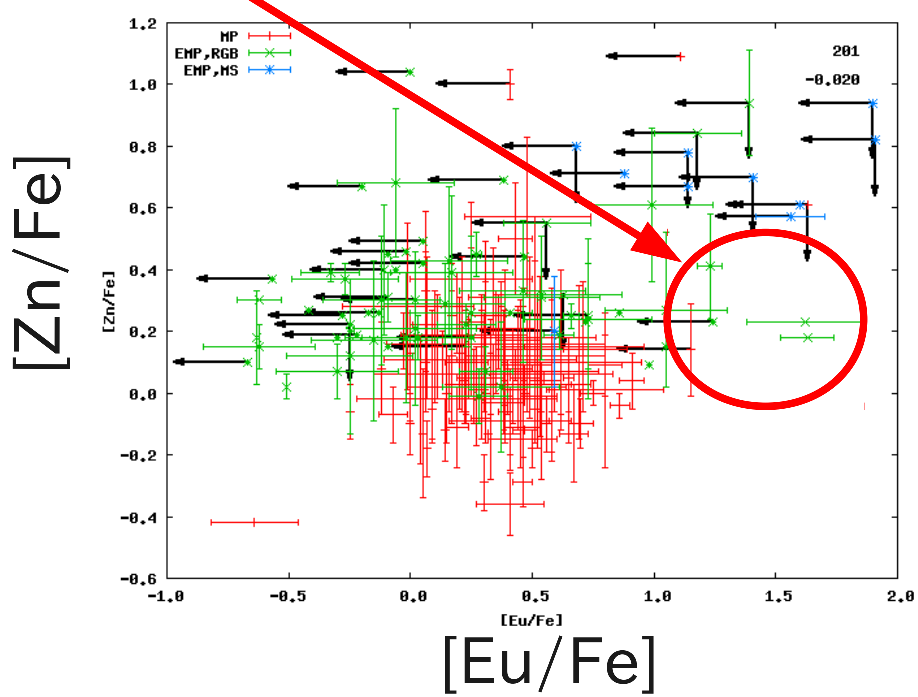
[Pb/Eu] of the solar-system r-process component (uncertain)

(2-4) NO correlation between neutron-capture elements and lighter elements (within the current measurement accuracy)

r-II stars

SAGA database





(3) r-process elements in supernova remnants?

Wallerstein et al. (1995)

A SEARCH FOR *r*-PROCESS ELEMENTS IN THE VELA SUPERNOVA REMNANT[1]

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ABSTRACT

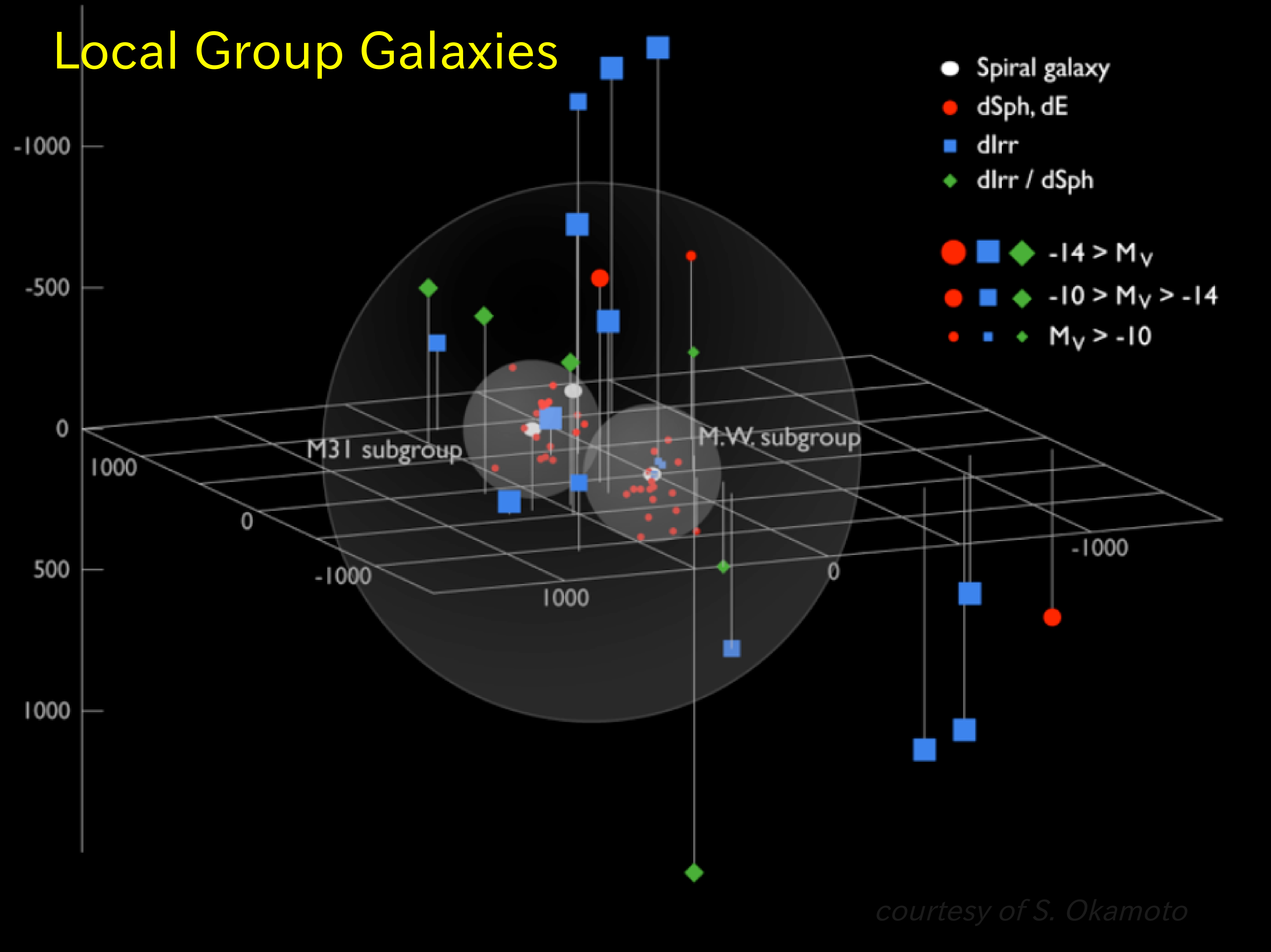
After a description of recent developments in the physics of rapid neutron capture in Type II supernovae and a discussion of the detectability of supernovae ejecta, we present the data from a search for Ge, Kr, Yb, Os, and Hg in five stars behind or within the Vela remnant. Only Ge II was detected, but its column density and the upper limits of the other species show no excess above the estimated contribution of ambient gas. Finally, we discuss the extent that clumping and the improved performance of the GHRS may make *r*-process ejecta from Vela detectable in the future.

(4) r-process elements in other systems

- Globular clusters → S. Honda (this WS)
  -overabundance of r-process elements
  -scatter in abundance ratios in a cluster

- Dwarf galaxies around the Milky Way
  -different chemical evolution from the Milky Way (halo)
  -surviver of building blocks of the halo?

Local Group Galaxies

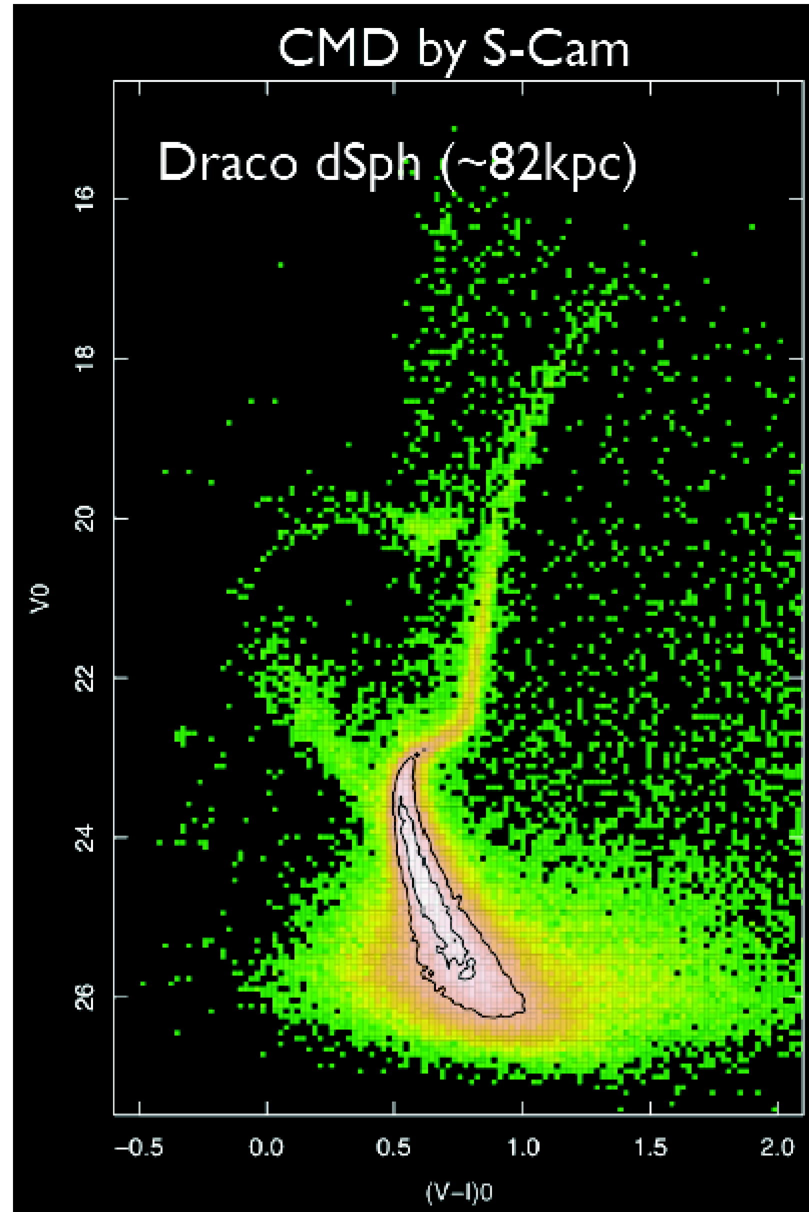


Dwarf galaxies around the Milky Way

Short distance + low stellar density
→not easy to identify as a galaxy
→possible to observe individual stars

Draco (82kpc)

Okamoto et al. 2008



Ultra-Faint Dwarf Galaxies (UFDG) newly found by SDSS (and Subaru follow-up)

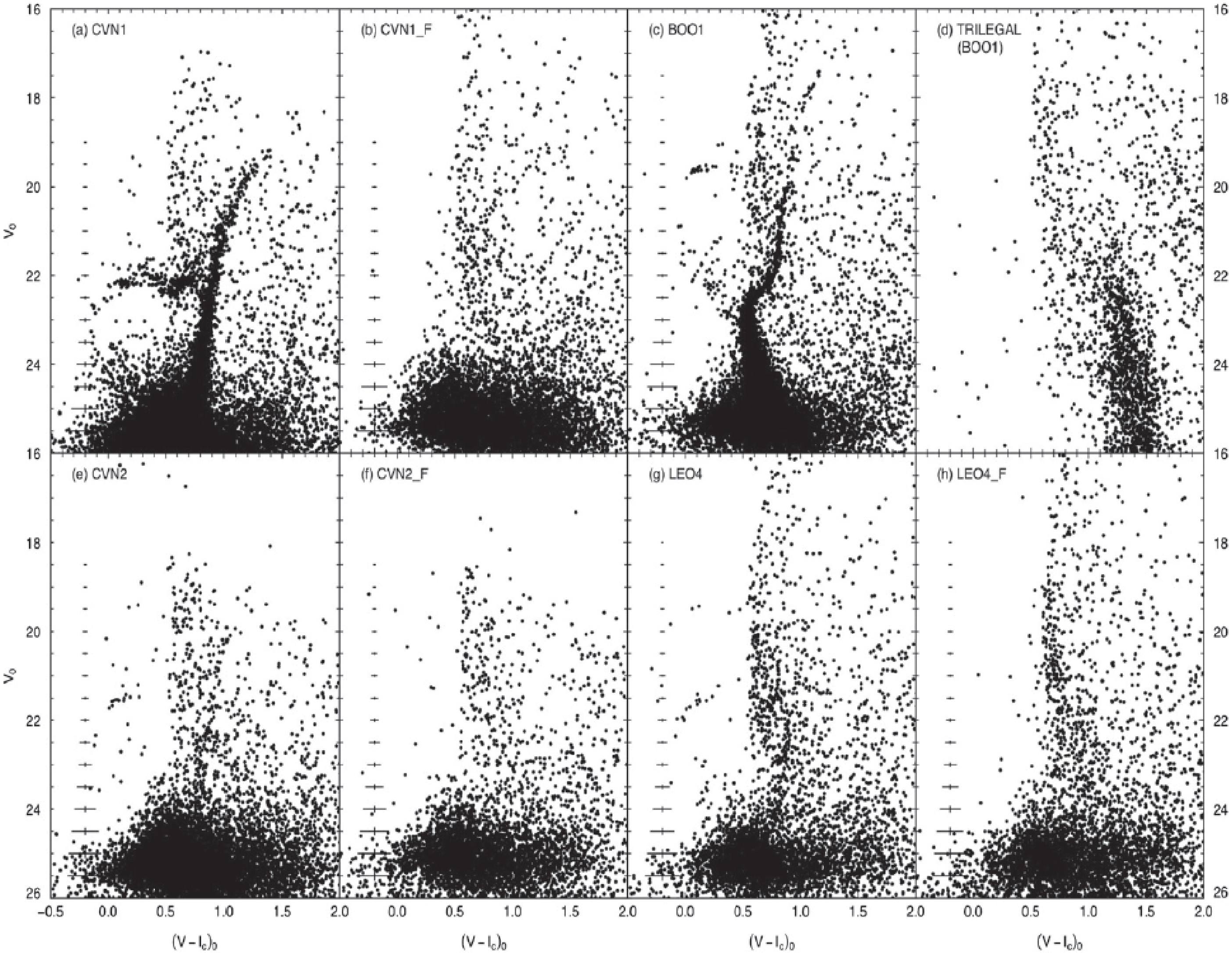
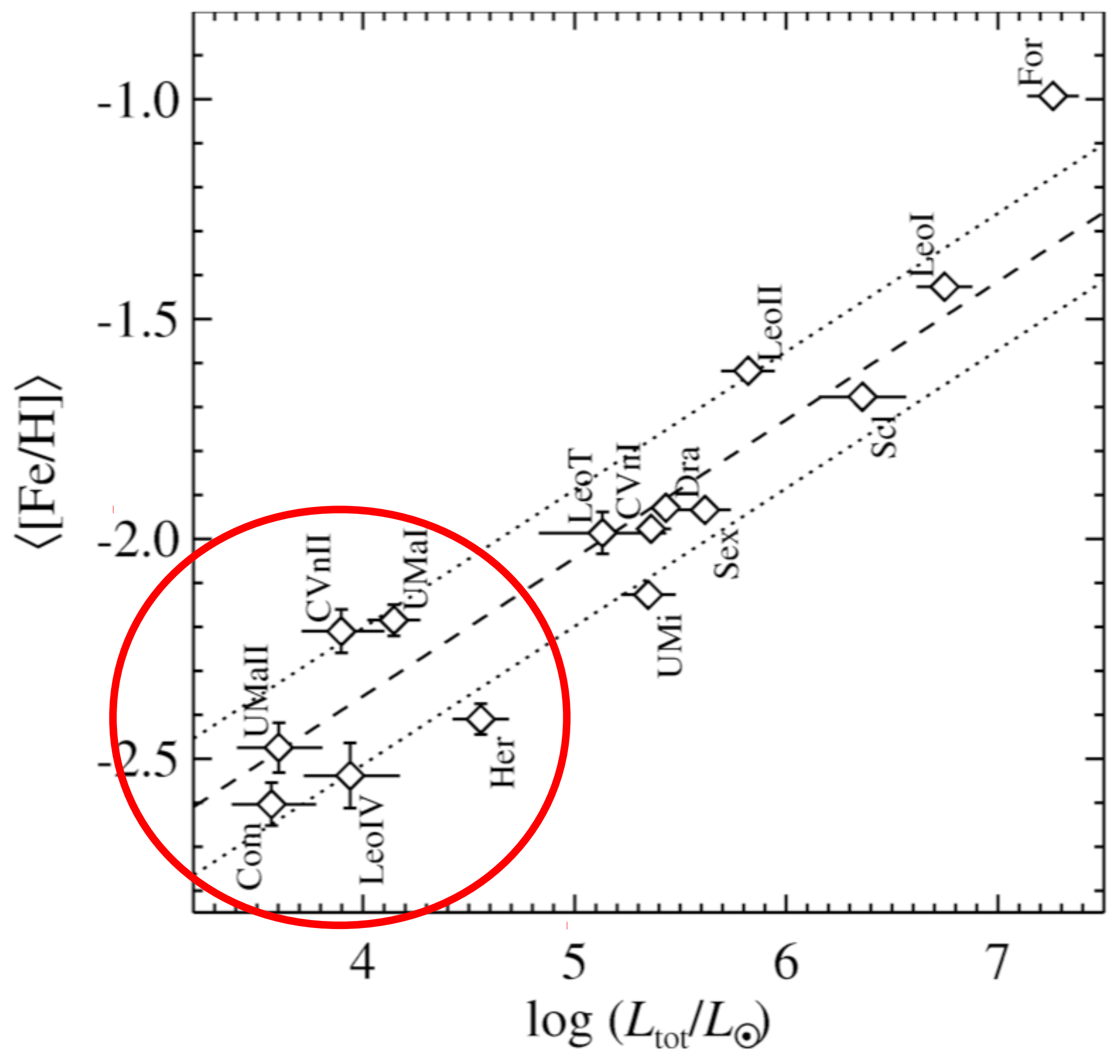


Figure 3. CMDs of the star-like objects in all observed fields and the simulated CMD. The magnitude errors are estimated by the artificial star test. In panel (d), the TRILEGAL model is used to simulate the CMD of Galactic foreground stars in the direction of the BOO1 field.

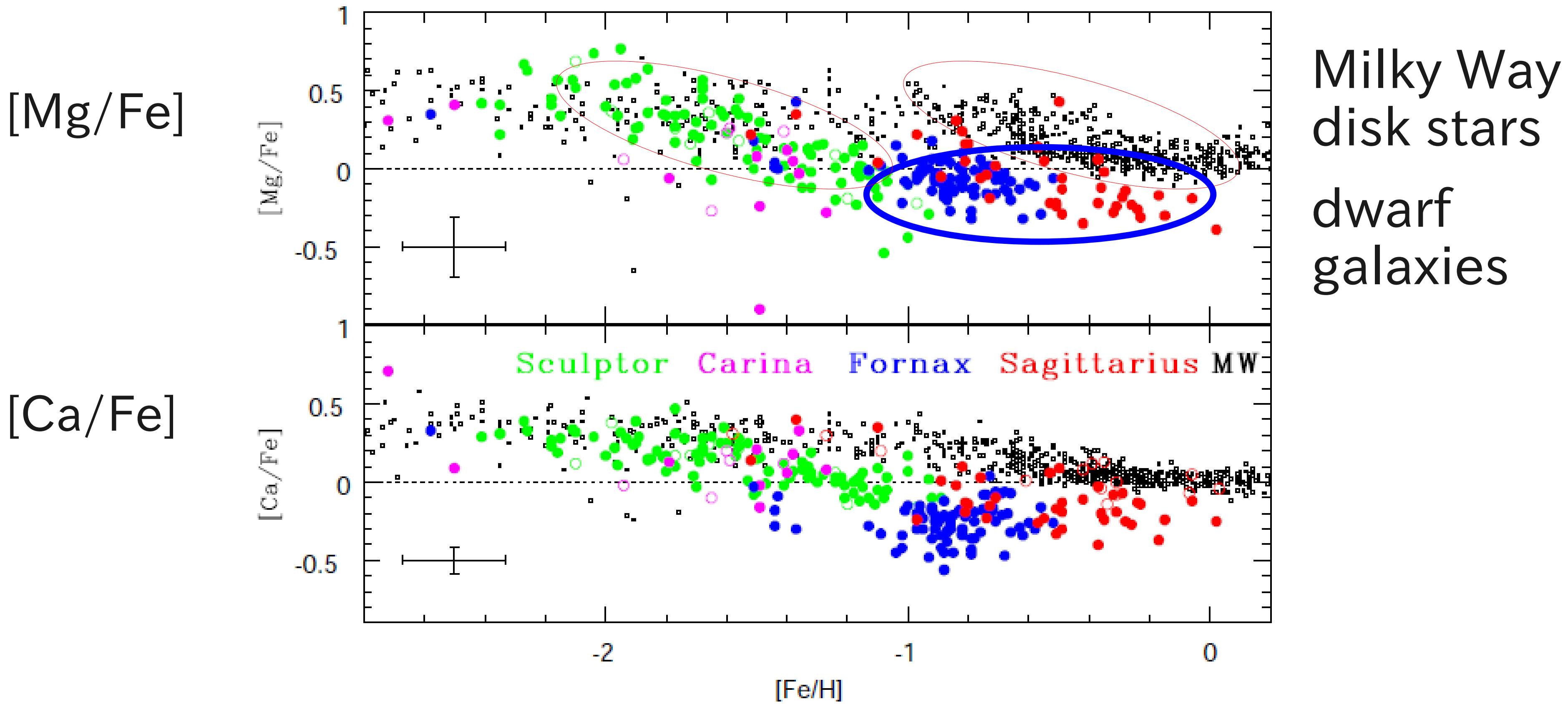
Okamoto et al. (2012)

Fainter galaxies (with smaller stellar mass) have lower metallicity



Kirby et al. (2008), updated by Frebel et al. (First Stars IV)

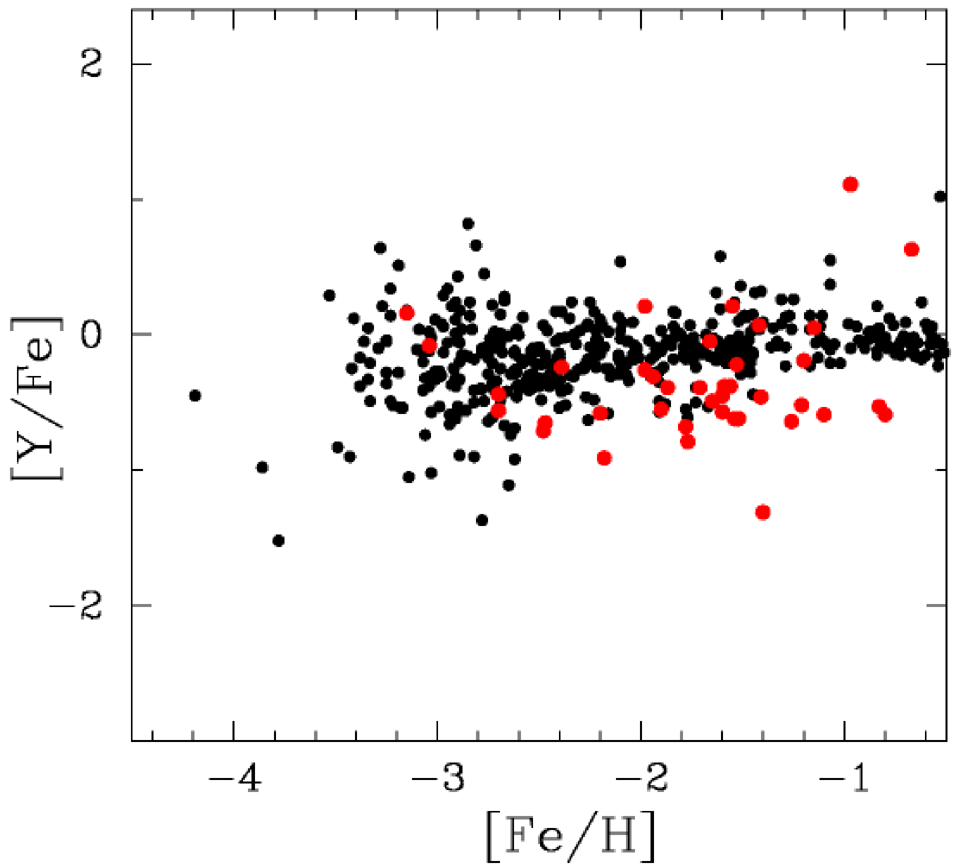
Dwarf galaxy stars have different abundance trend from Milky Way stars



Tolstoy et al. (2009, ARAA)

Neutron-capture elements in dwarf galaxies

•We are extending the SAGA database to dwarf galaxy stars (T. Suda, J. Hidaka, W. Aoki)
•There are significant differences of abundance trend between dwarf galaxies and Milky Way.

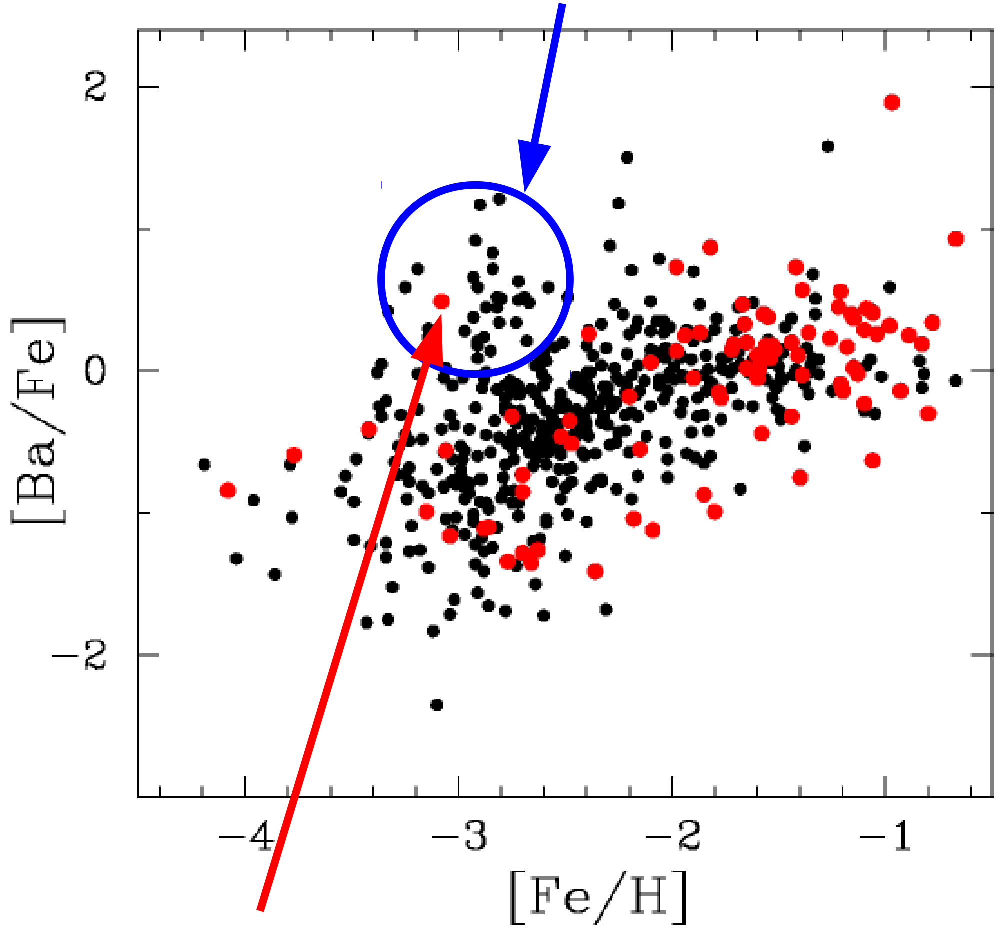


●:dwarf galaxy stars
●:field stars

Y is under-abundant in dwarf galaxies
→smaller contribution by weak s-process (+weak r-process?) from very massive stars?

Neutron-capture elements in dwarf galaxies

r-process-enhanced stars in the Milky Way



●:dwarf galaxy stars
●:field stars

※carbon-enhanced stars are excluded
→Ba is mostly r-process origin

Ba is more under-abundant in dwarf galaxies
→no r-process-enhanced stars in dwarf galaxies?

The Ba of this object is attributed to s-process (Honda et al. 2011)

Summary and discussion (1)

- "Universality" exists in abundance patterns produced by the "main r-process".

-Abundance patterns of r-process enhanced stars are very similar between 1st peak and 3rd peak. The patterns also agree well with that of the solar-system r-process component, except for some light neutron-capture elements.

-The abundance ratios of actinides (e.g. Th/Eu) also show only small scatter. → some mechanism that regulates the production of actinides.

-Pb abundances in (some) "r-II stars" are very low. → the r-process that produced the r-II stars is not typical?

Summary and discussion (2)

- Large scatter is found in the Sr/Ba ratios → existence of the two separated processes (producing light and heavy elements) or variation of r-process?

- No correlations between neutron-capture elements and lighter elements (within the measurement accuracy).
→ the r-process is not accompanied by other processes.

- No evidence of the r-process has been derived from observations of supernova remnants.

- Heavy elements (Ba, Eu) are deficient in the lowest metallicity range ([Fe/H]<-3.5), and rapidly increases at [Fe/H]∼-3.
→ production of heavy elements in less massive stars (or other process with relatively long time-scale) is suggested.

Summary and discussion (3)

- Scatter of [Eu/Fe] in (a) Globular cluster(s)
→ similar timescales between the r-process and cluster formation?

- Deficient light neutron-capture elements in dwarf galaxies
→smaller contribution of massive stars (weak s-process, weak r-process) in dwarf galaxies?

- No r-II stars in dwarf galaxies, but more data are required.

Current and future projects

•Follow-up spectroscopy of field metal-poor stars found by the SDSS to study the lowest metallicity range

•Spectroscopy of dwarf galaxy stars
←upgrade of Subaru/HDS to add "multi-object" function

•More future (2020s) … next generation extremely large telescopes

TMT
Thirty Meter Telescope