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Observational studies of r- and s-process elements for Milky Way stars

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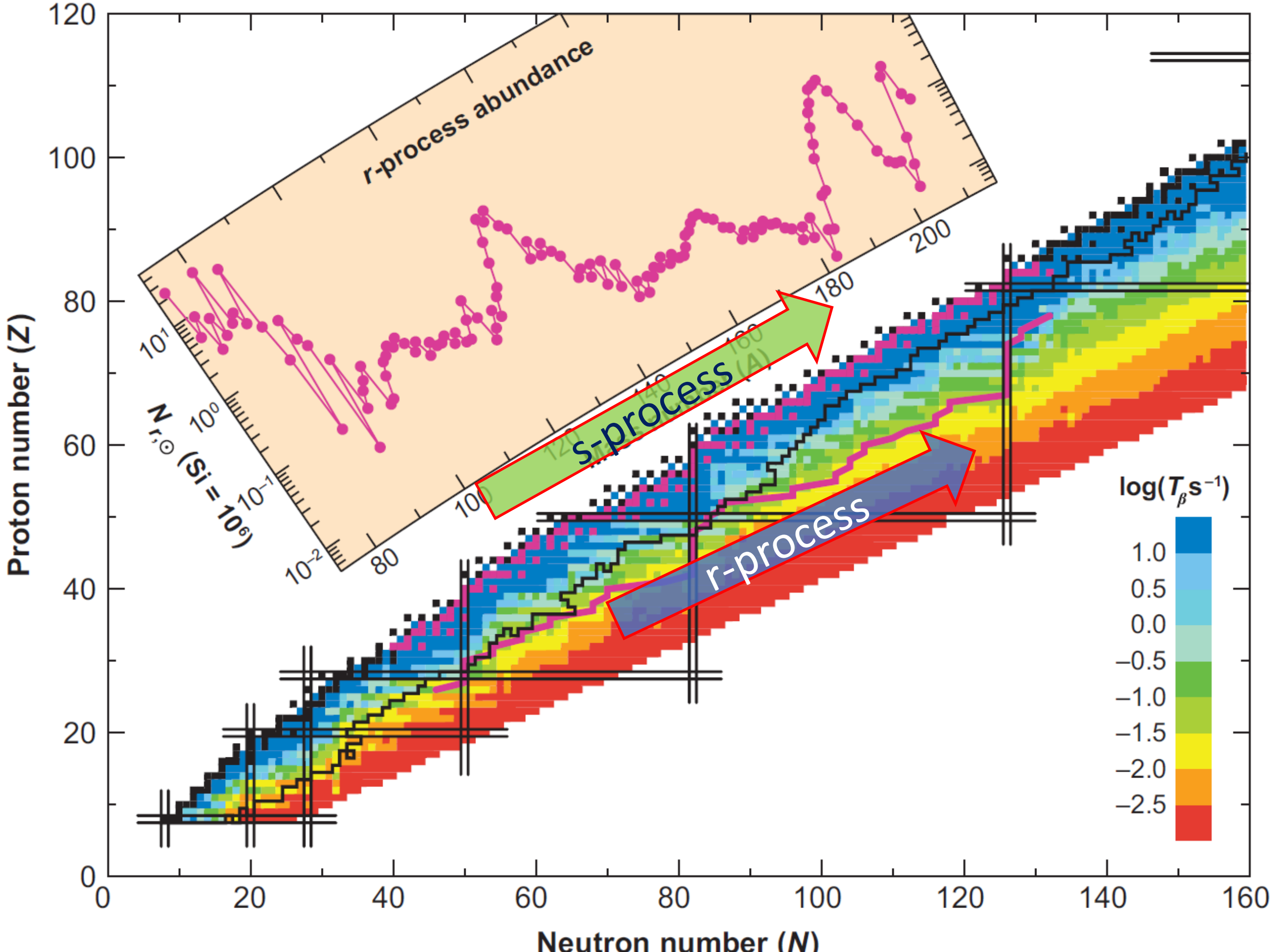
Observational studies of r- and s-process elements for Milky Way stars

- r- and s-process elements recorded in the solar-system material
- **Constraints from metal-poor stars**
  Contributions to Galactic chemical evolution
  Elements recorded in companion stars in binary systems
- **r-process observations**
  statistics obtained from large sample (R-Process Alliance: RPA)
  origins of r-process enhanced stars
    connection to Galactic halo formation
  astrophysical site(s) of r-process
- **Metal-poor stars studied with LAMOST and the Subaru Telescope**
  Abundance distributions of neutron-capture elements
  Extreme CEMP-s star
  r-rich star with dwarf galaxy origin

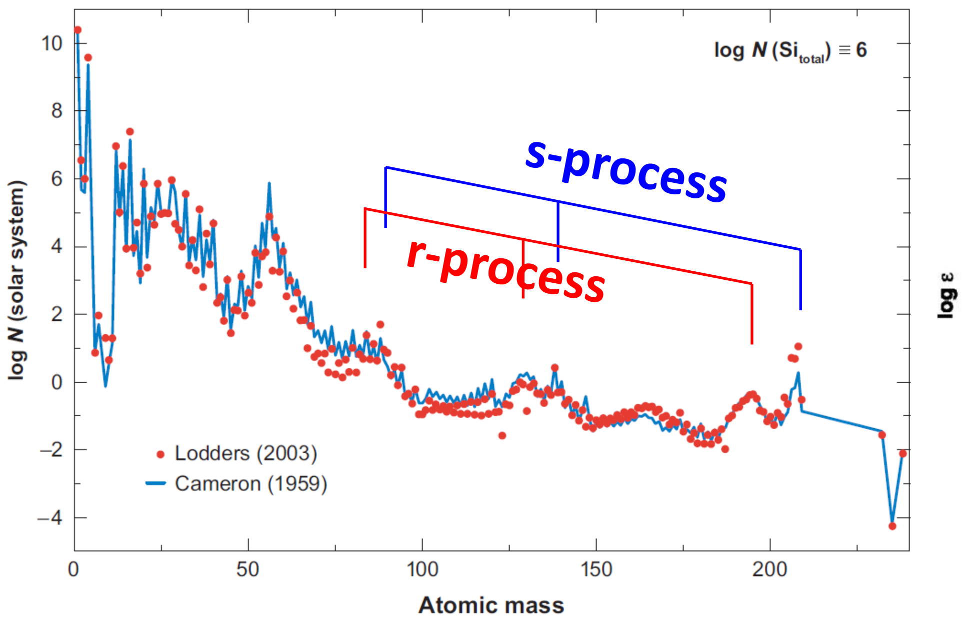
Neutron-capture processes: s-process and r-process



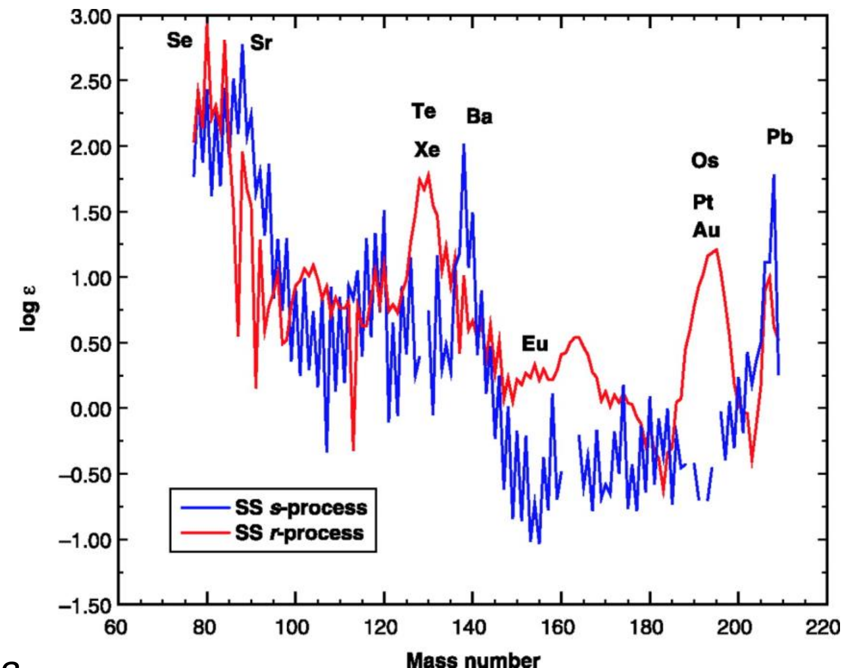
Sneden et al. (2008)

Elemental abundances of solar-system material

- Abundances of elements heavier than Fe-group are separated into s-process and r-process components using s-process models.
- Their abundance patterns are compared with stellar observations and model predictions.

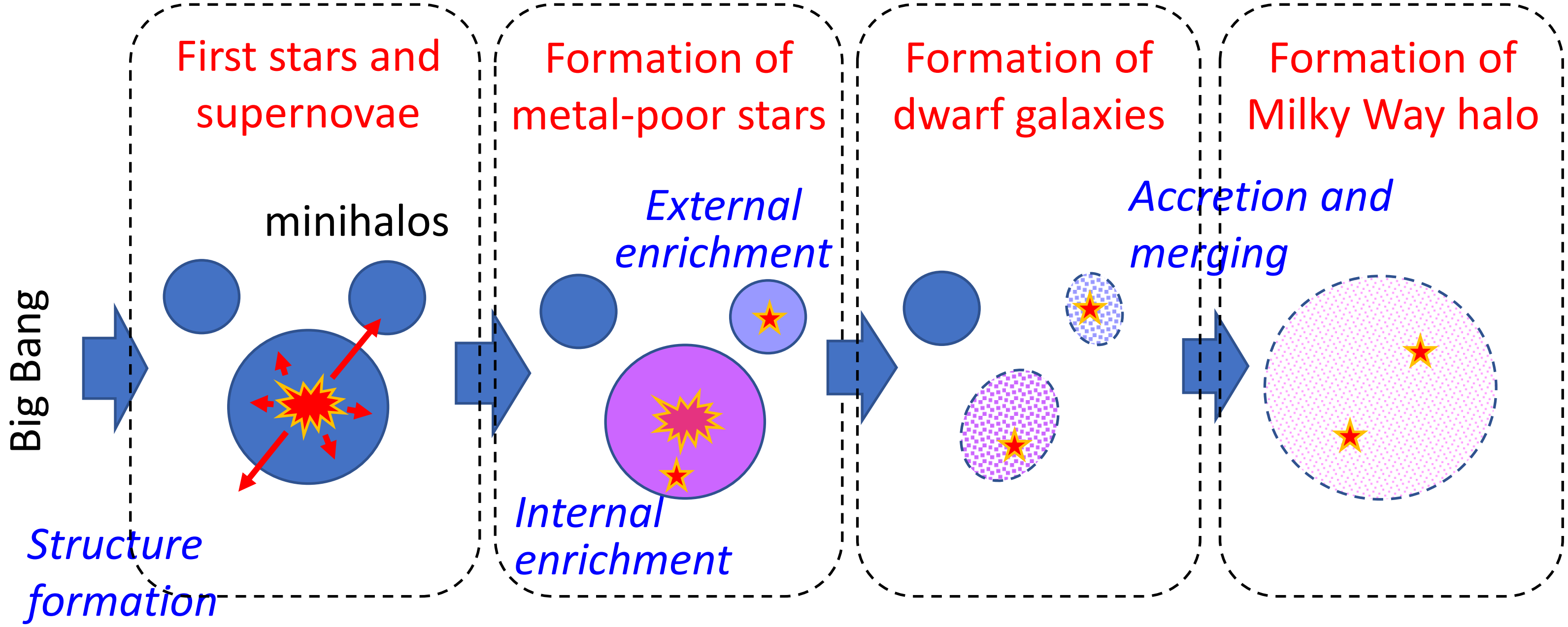


Sneden et al. (2008)



Sneden et al. (2003)

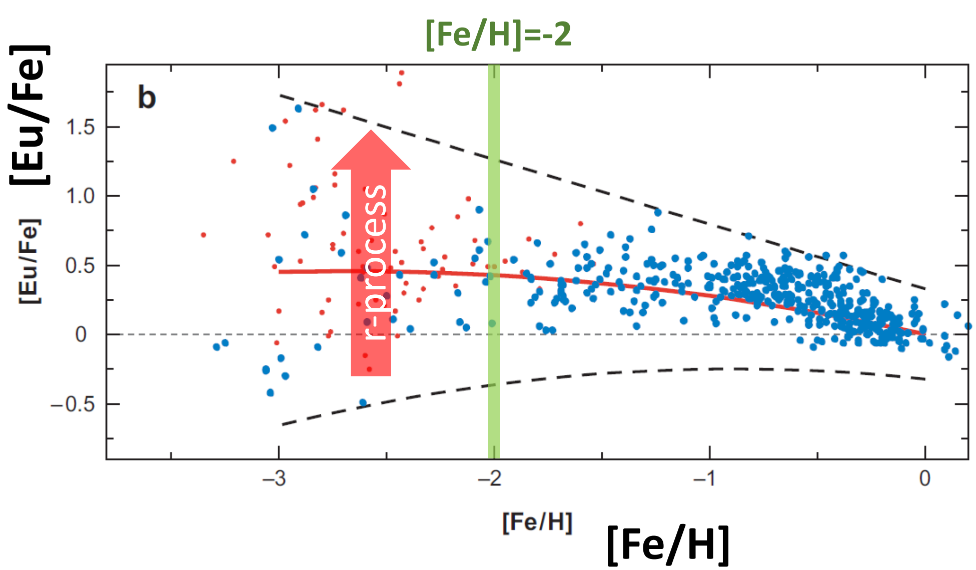
Constraints from metal-poor stars



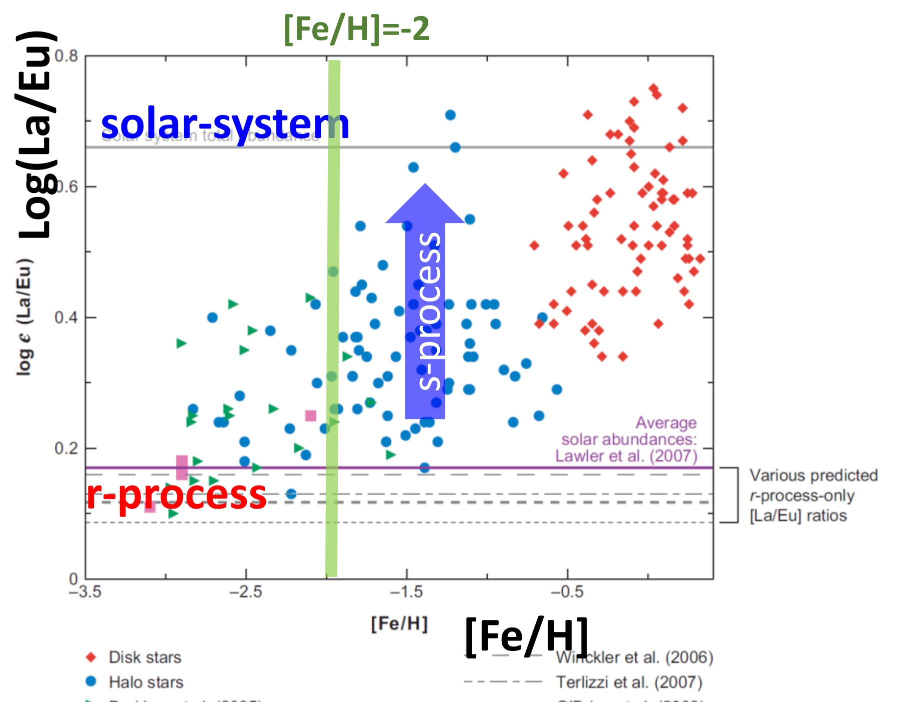
Chemical abundances of extremely metal-poor stars
→ Nucleosynthesis of first stars/supernovae
→ r-process by neutron star mergers? Magneto-rotational supernovae?
s-process by low-mass AGB stars would contribute to relatively metal-rich stars

Contributions of r-process and s-process to metal-poor stars

- Eu is overabundant in many stars at low metallicity, indicating that r-process is effective even in early phase of the Galactic chemical evolution.
- La/Eu (and Ba/Eu), representing s-process/r-process, suggests that contributions of s-process increase with increasing metallicity.



Sneden et al. (2008)

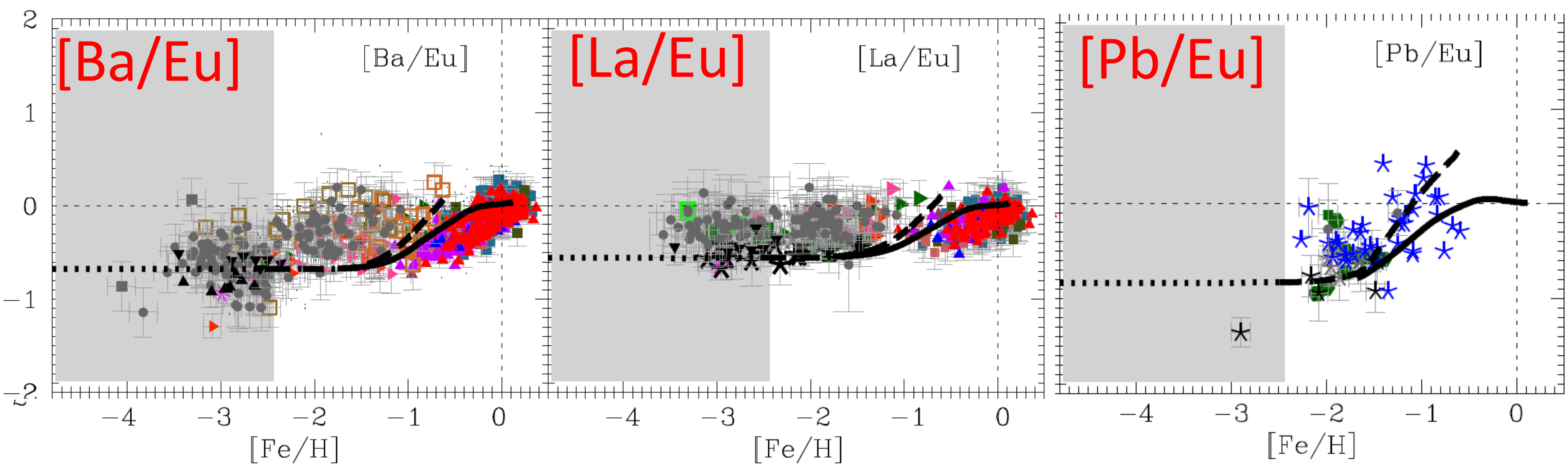


Contributions of r-process and s-process to metal-poor stars

- Eu is provided by the r-process. Ba and La is mostly provided by the s-process in low-mass AGB stars at high metallicity, while Ba and La in metal-poor stars is explained by the r-process. → [Ba/Eu]=-0.7, [La/Eu]=-0.5
- Moderately metal-poor (-2<[Fe/H]<-1) stars show [Ba/Eu] and [La/Eu] higher than the r-process values.

  → AGB contributions even at low metallicity?
  Other sources of Ba and La at low metallicity?

Bisterzo et al. (2017)

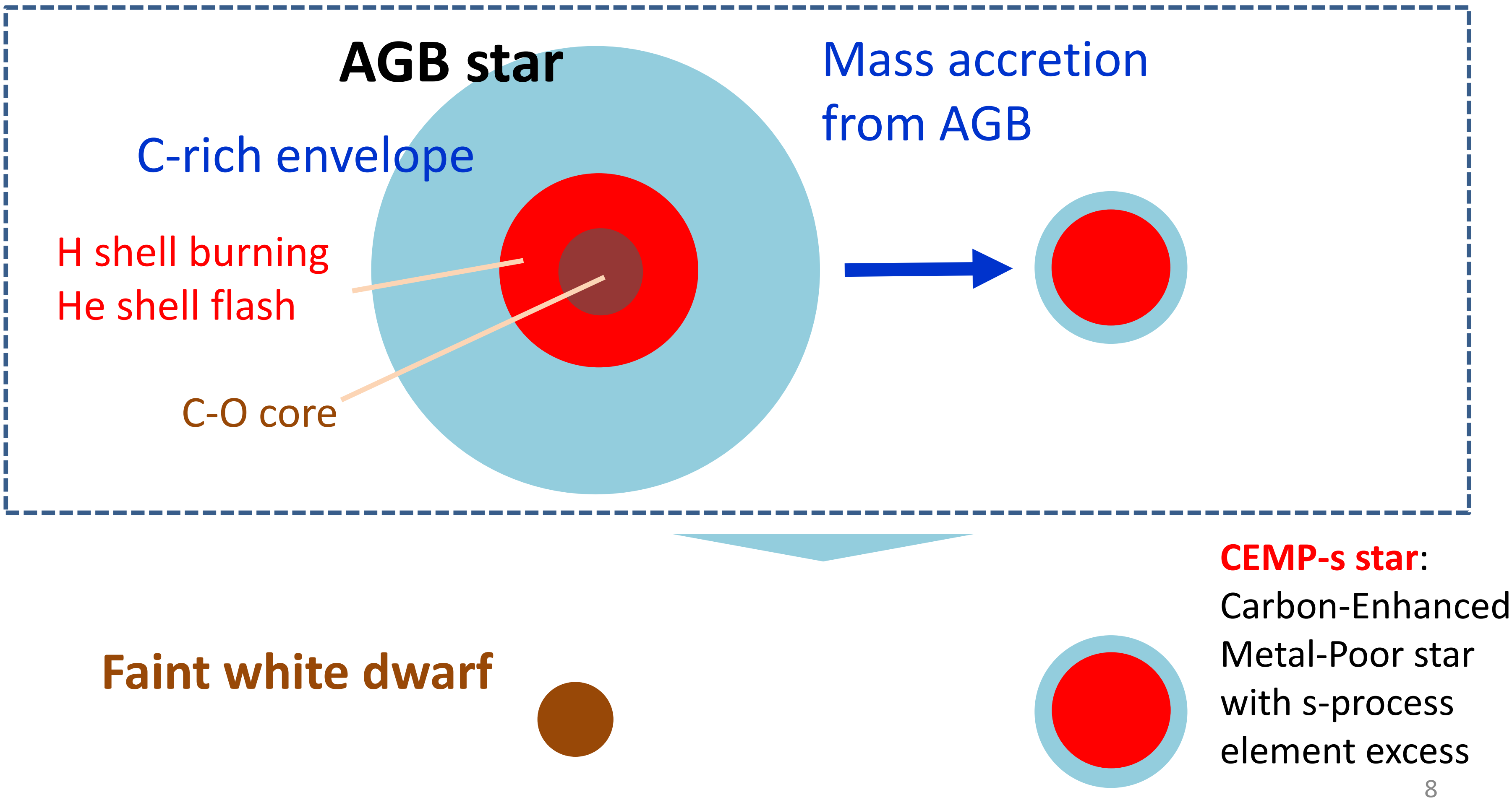


cf. discussion based on chemo-dynamical simulation: *Hirai et al. (2017)*

Constraints from metal-poor stars: binary stars

Interaction between stars in binary systems: AGB yields with carbon and s-process elements recorded on a companion star

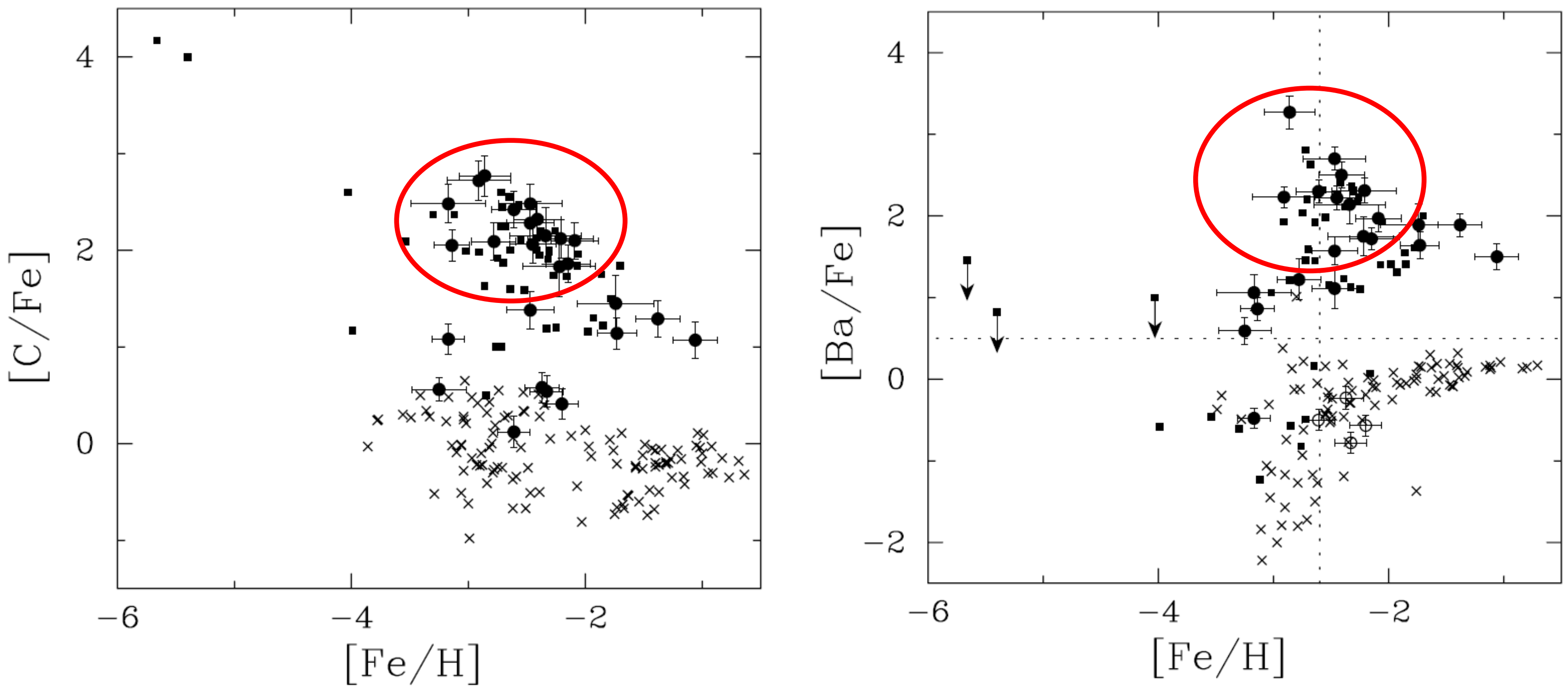
AGB: Asymptotic Giant Branch



s-process studies for Carbon-Enhanced Metal-Poor stars

- **The companion star affected by mass accretion from AGB star is observed as a CEMP-s star.**
- **Detailed elemental abundances are determined for CEMP-s stars, and used to constrain s-process models.**

Aoki et al. (2007)



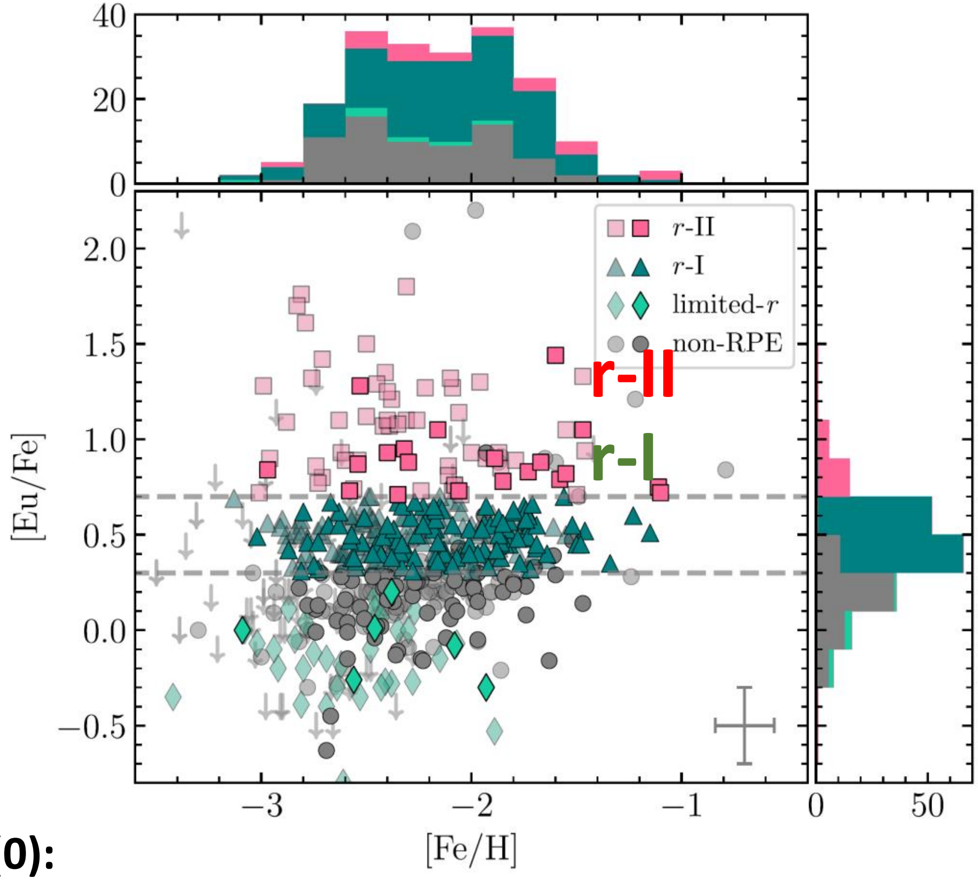
Statistics studied by R-Process Alliance (RPA)

The 4 Data Releases report 595 metal-poor stars.

Holmbeck et al. (2020)

1. **Definition of r-II and r-I stars**
   r-II: [Eu/Fe]>0.7 (12%)
   r-I :0.3<[Eu/Fe]<0.7 (39%)
   [Ba/Eu]<0

2. **Metallicity distribution**
   r-II stars have been found in [Fe/H]<-2.5. However, existence of r-II stars with higher metallicity ([Fe/H]>~-2) was confirmed.

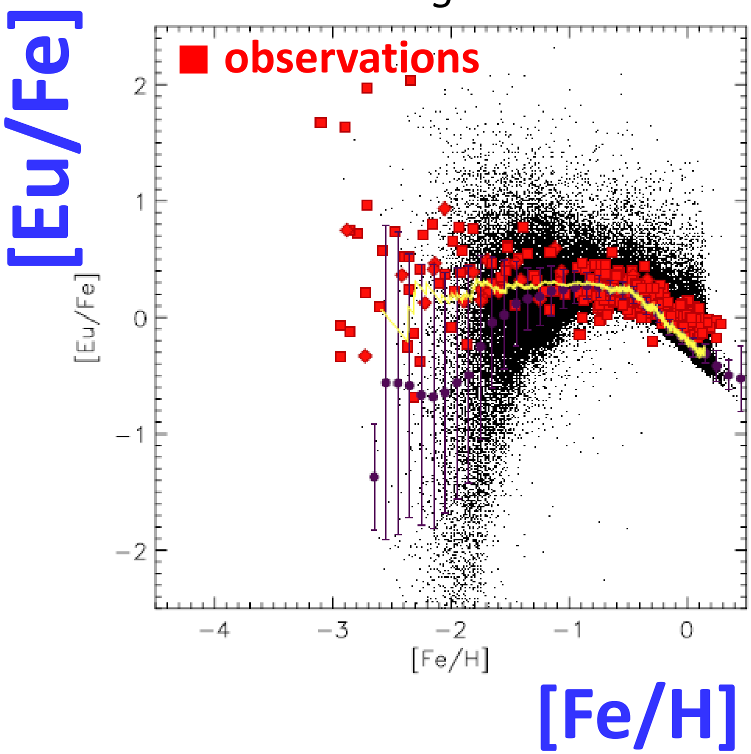


→[Eu/H] is as high as solar value (0): how can this be achieved.

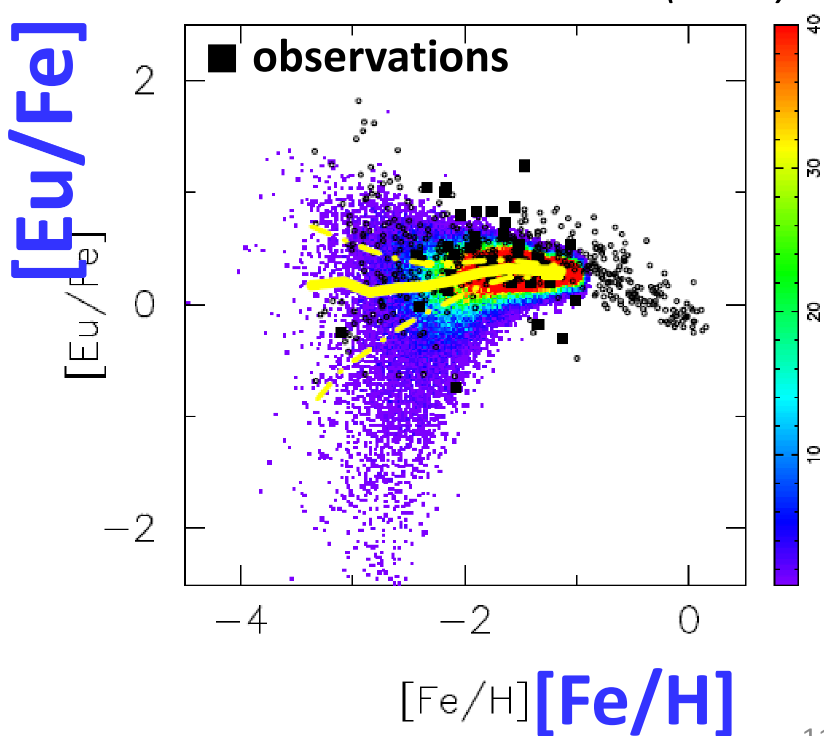
r-process site: mergers of binary neutron stars?

- Neutron star mergers (NSMs) are promising site that explain bulk of r-process elements in the current universe.
- The long timescale expected for NSM is not preferable for enhancement of Eu at low metallicity.
- However, recent chemo-dynamical simulations reproduce the Eu abundance distribution assuming NSMs as the r-process source.

Argast et al. 2004

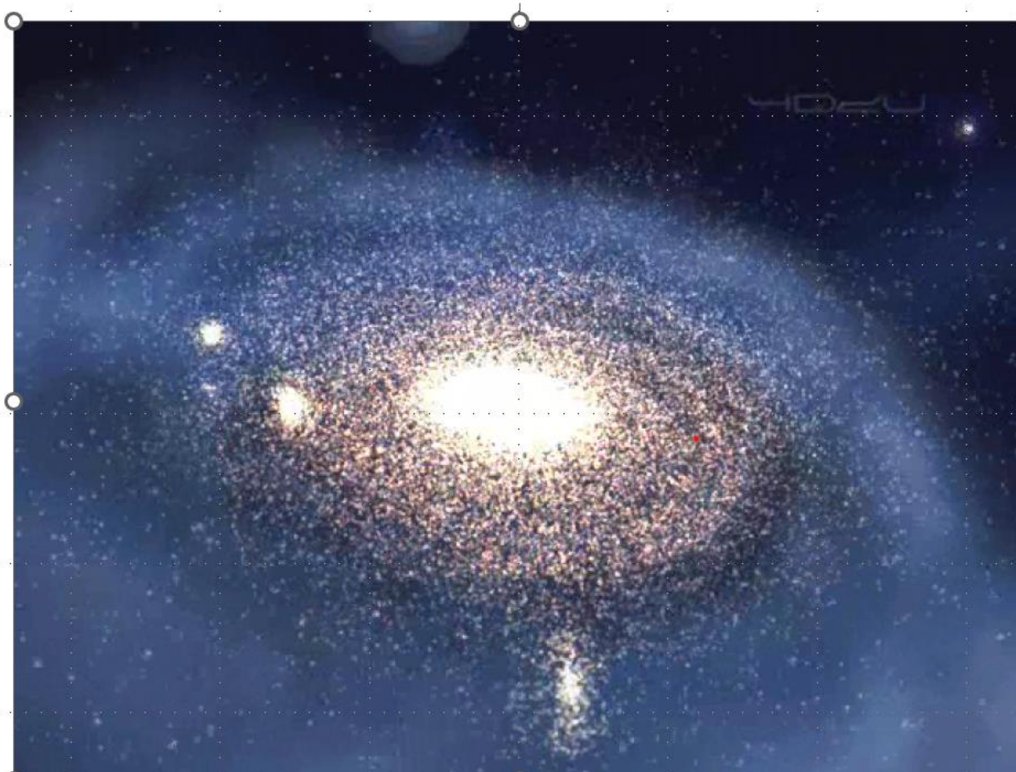


Hirai et al. (2015)



r-process observations

The Milky Way Galaxy has been formed from small stellar systems (mergers of mini-halos).

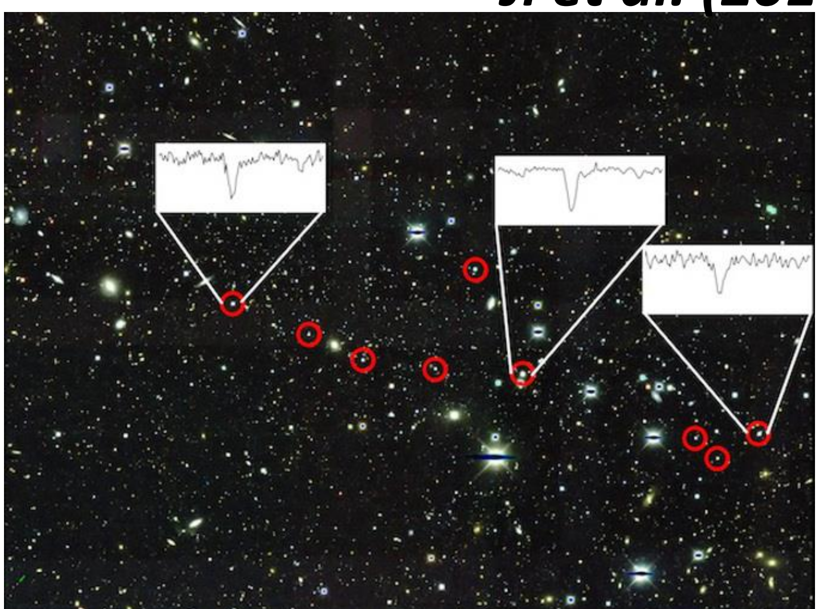


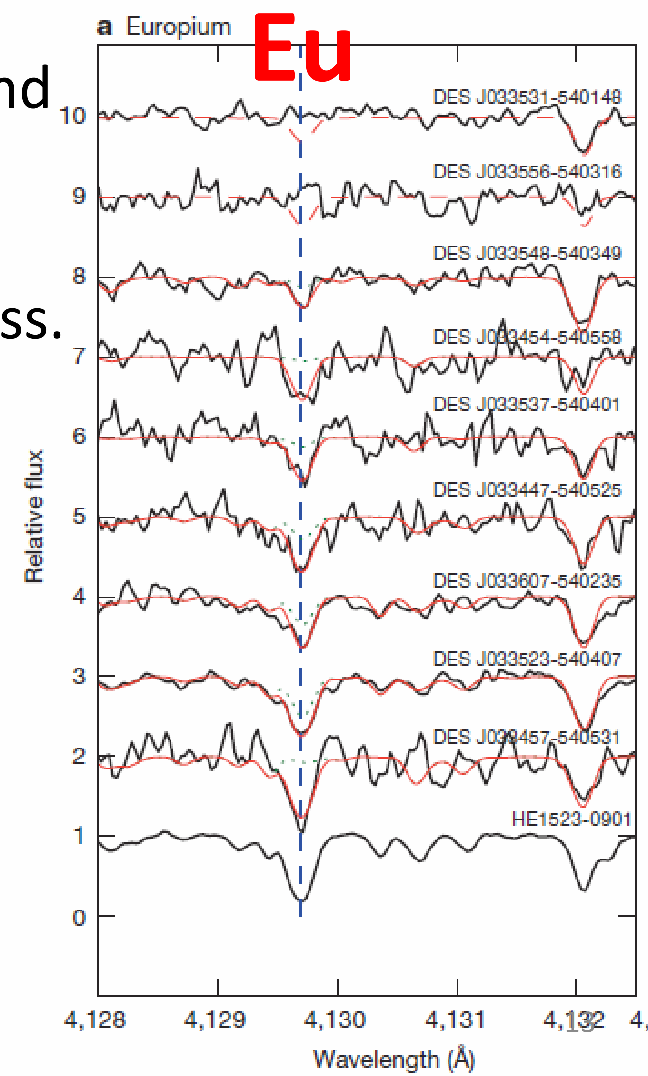
Discovery of an r-process-enhanced dwarf galaxy Reticulum II

Ji et al. (2016)
Roederer et al. (2016)

- r-II stars have been formed in small stellar systems (like a dwarf galaxies), and have later accreted into the Milky Way, forming the halo structures.
- NSM could be the source of the r-process.

Ji et al. (2016)

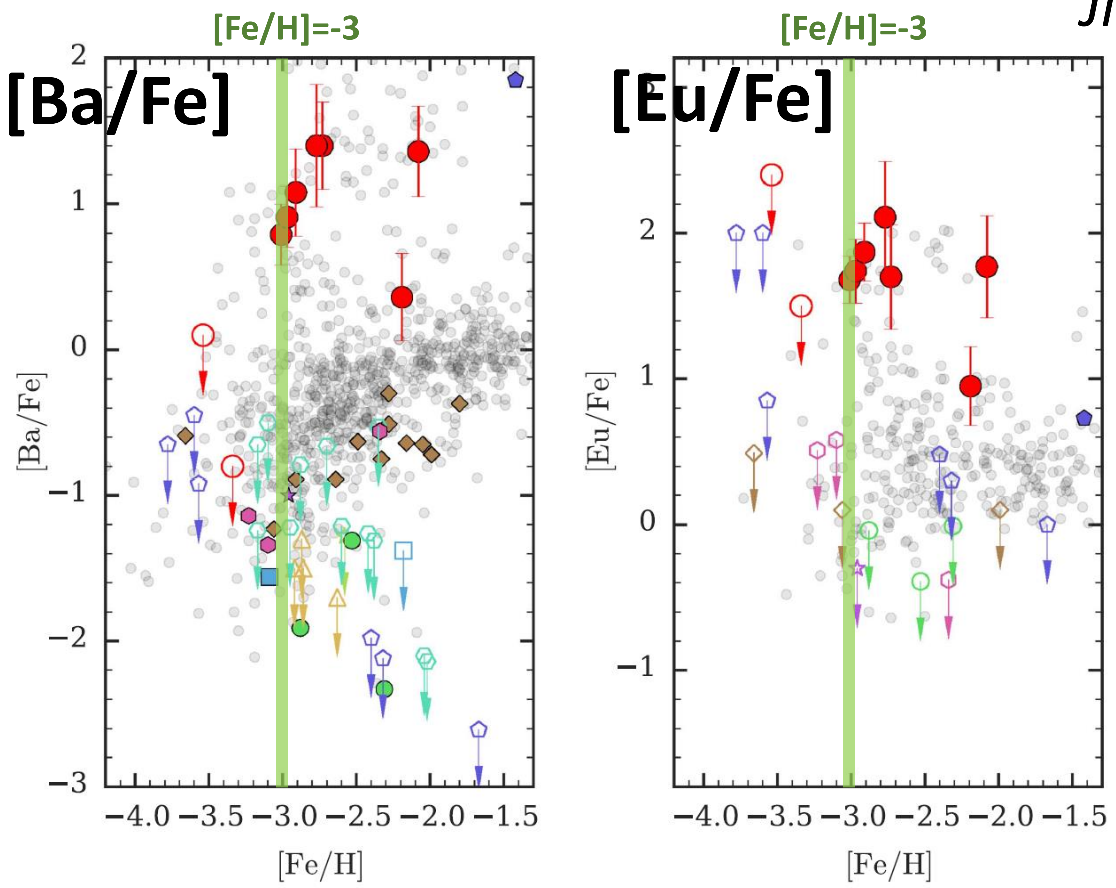




Eu and Ba in Reticulum II stars

- Eu and Ba are significantly enhanced in all 7 stars with [Fe/H]>-3
- Eu nor Ba are not detected in the 2 stars with [Fe/H]<-3

Ji et al. (2016b)

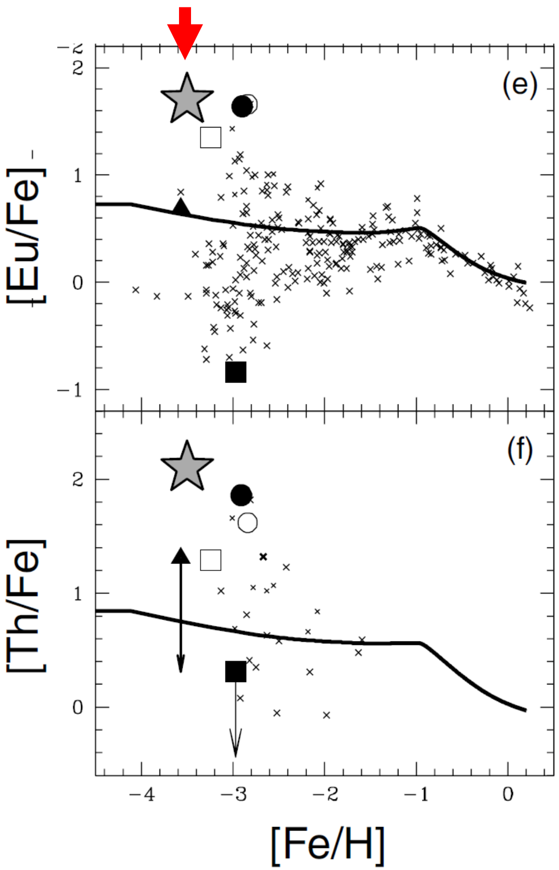


Another r-process source at lowest metallicity?

- It could be still a challenge to explain r-II stars at the lowest metallicity ([Fe/H]<-3). The two most metal-poor stars in Ret II are not r-process-rich.
- Another source of r-process, e.g. magneto-rotational supernovae could work at the lowest metallicity.

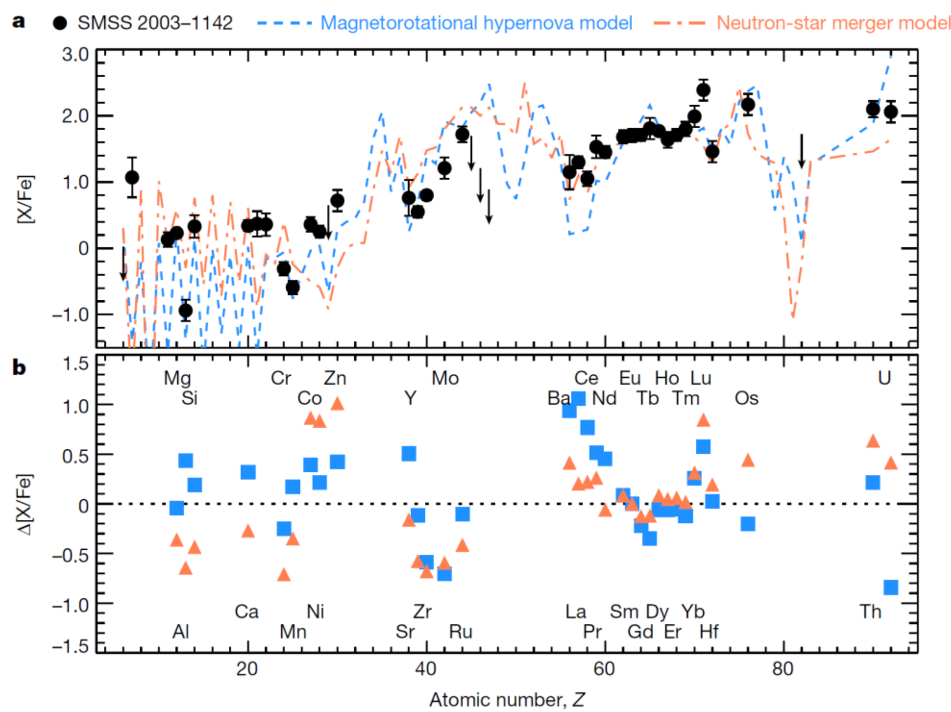
Yong et al. (2021)

SMSS J2003-1142



SMSS J2003-1142

- **[Fe/H]=-3.4, [Eu/Fe]=+1.7**
- **Abundance pattern is explained by magneto-rotational *hypernovae***



Stellar elemental abundances constraining nucleosynthesis and chemical evolution of the universe studied with LAMOST and Subaru

Neutron-capture elements

Aoki et al., 2022, ApJ 931, 146
Li et al. 2022, ApJ 931, 147
Xing et al. 2019, Nature Astronomy 3, 631
Zhang et al. 2019, PASJ, 71, 89

Metal-poor stars studied with LAMOST and Subaru

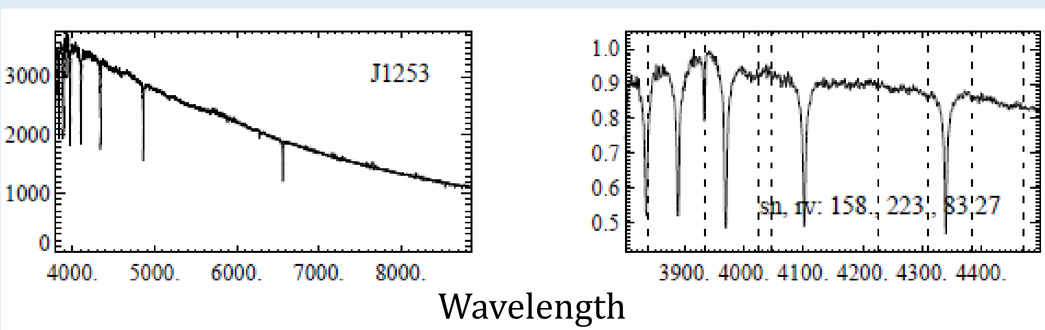
The spectroscopic survey telescope LAMOST is used to searches for candidates of very metal-poor stars, and the Subaru Telescope High Dispersion Spectrograph (HDS) is applied to abundance measurements.

LAMOST

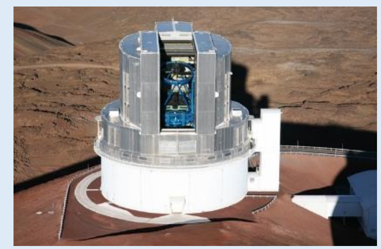
R=1800 4000 fibers

\> 5 million stars

- \>10,000 candidates of very metal-poor stars

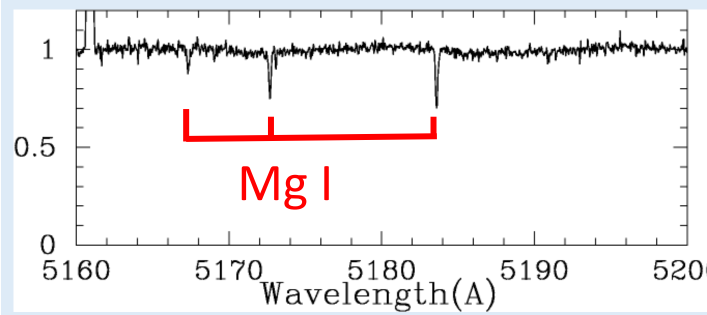


Subaru



R=36,000

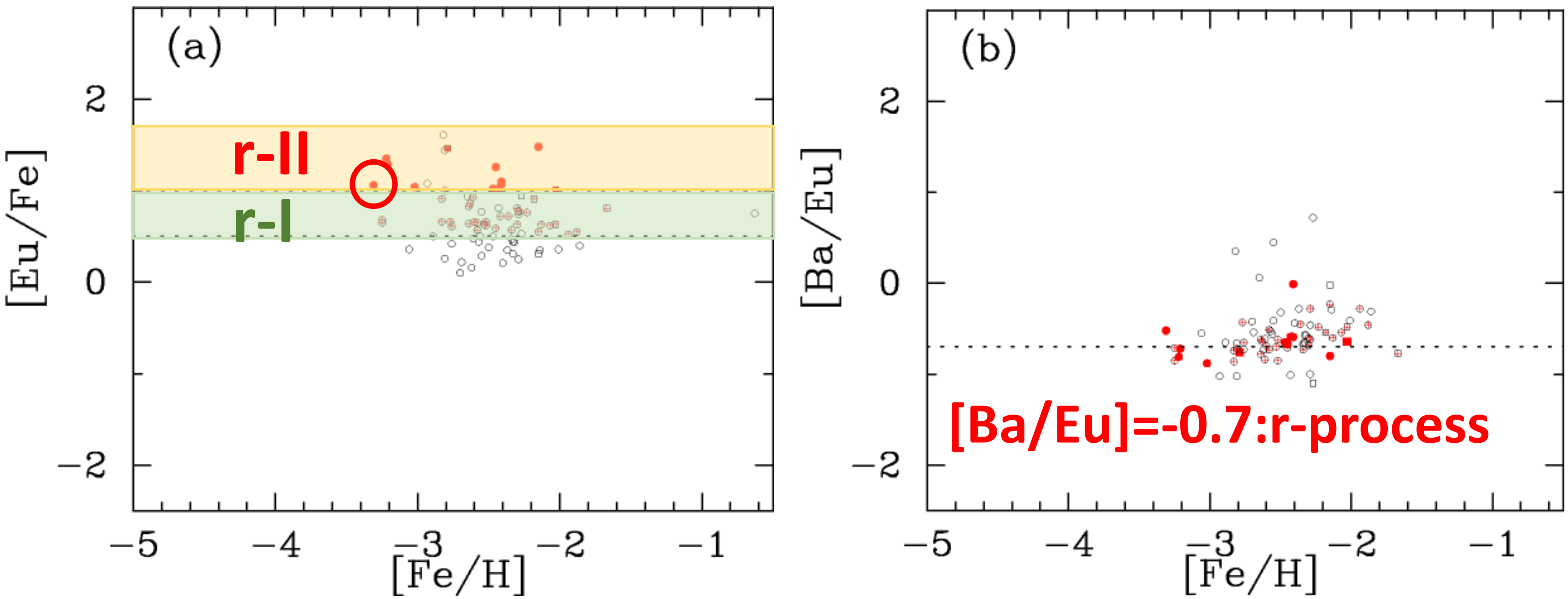
386 stars



Europium (Eu, *Z*=63) and Barium (Ba, *Z*=56)

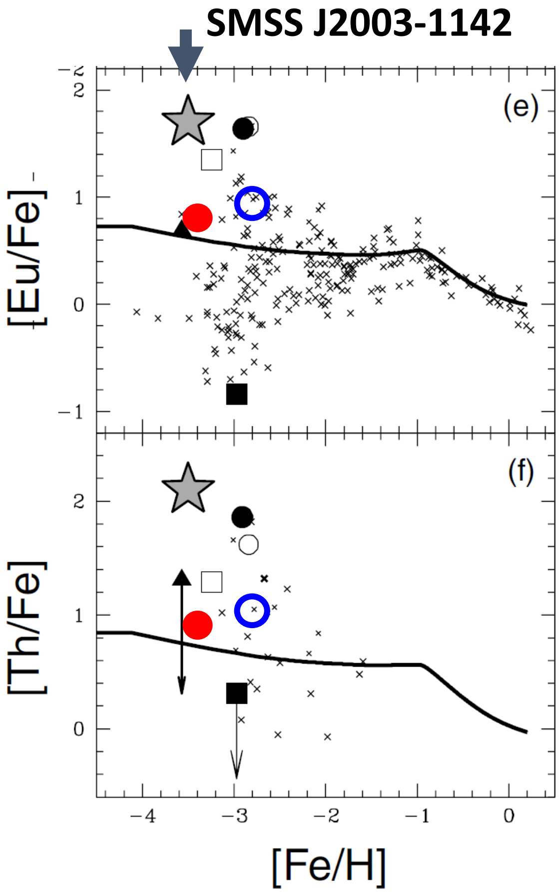
- 12 r-II stars ([Eu/Fe]>1) are newly found. About 20 stars are classified into r-I stars ([Eu/Fe]>0.5) .
- [Ba/Eu] of these stars agree well with the r-process value (-0.7).
- No increasing trend of [Ba/Eu] is found in our sample that covers [Fe/H]<-2.
- The metallicity distribution of r-II stars extends to [Fe/H]=-3.4.

Li et al. (2022)



The extremely metal-poor r-II star J1109+0754

- Abundance pattern of heavy elements agrees very well with the solar r-process pattern.
- The extremely low metallicity may prefer magnetrotational supernova as the source of heavy elements.

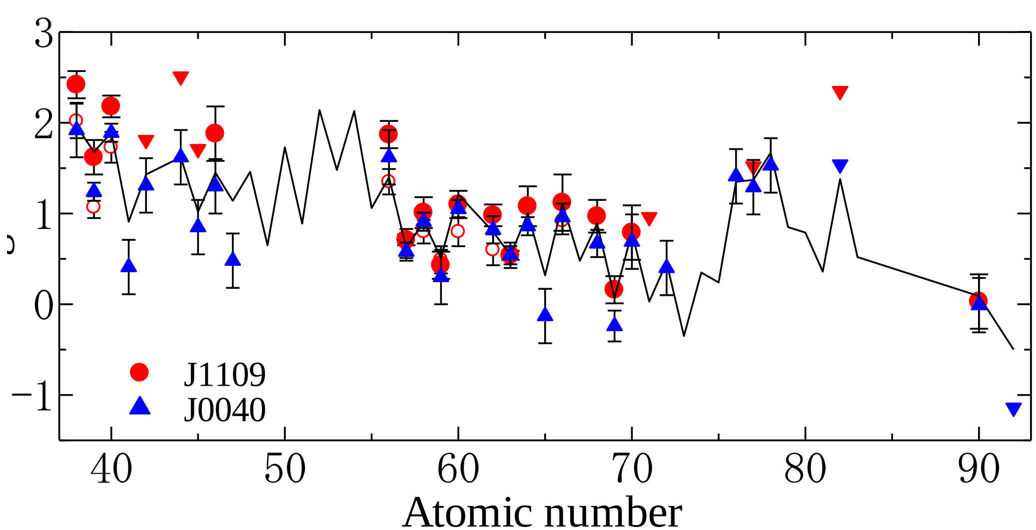


J1109+0754

[Fe/H]=-3.4,[Eu/Fe]=0.8

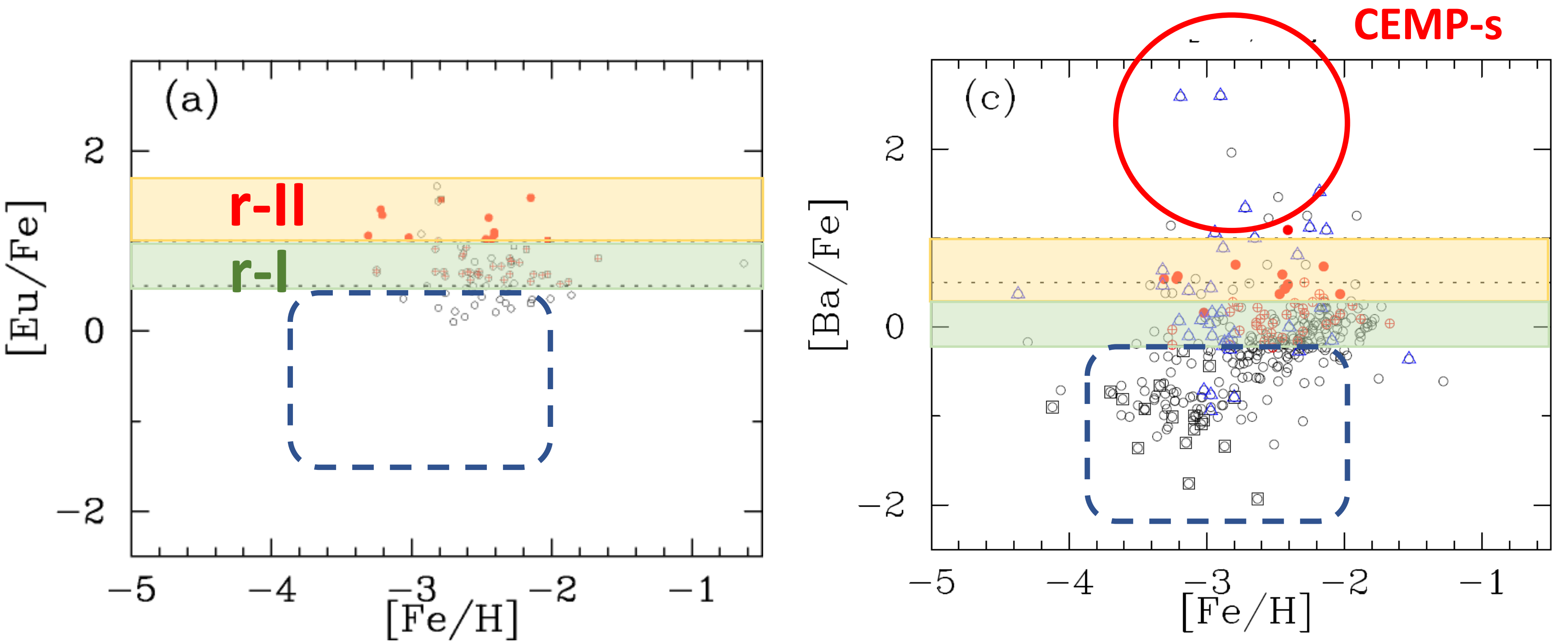
J0040+2729 [Fe/H]=-2.9,[Eu/Fe]=1.1

Li et al. (2015, RAA)
Honda et al. (in prep.)



Europium (Eu, *Z*=63) and Barium (Ba, *Z*=56)

- Lack of low [Eu/Fe] is due to the detection limit of Eu lines.
- Assuming Ba to be originated from r-process at very low metallicity with [Ba/Eu]=-0.7, [Ba/Fe] is used to estimate the distribution of r-process elements.
- There would be low [Eu/Fe] stars at lowest metallicity though their Eu lines are below detection limit in this study.
- The high [Ba/Fe] stars are CEMP-s stars.



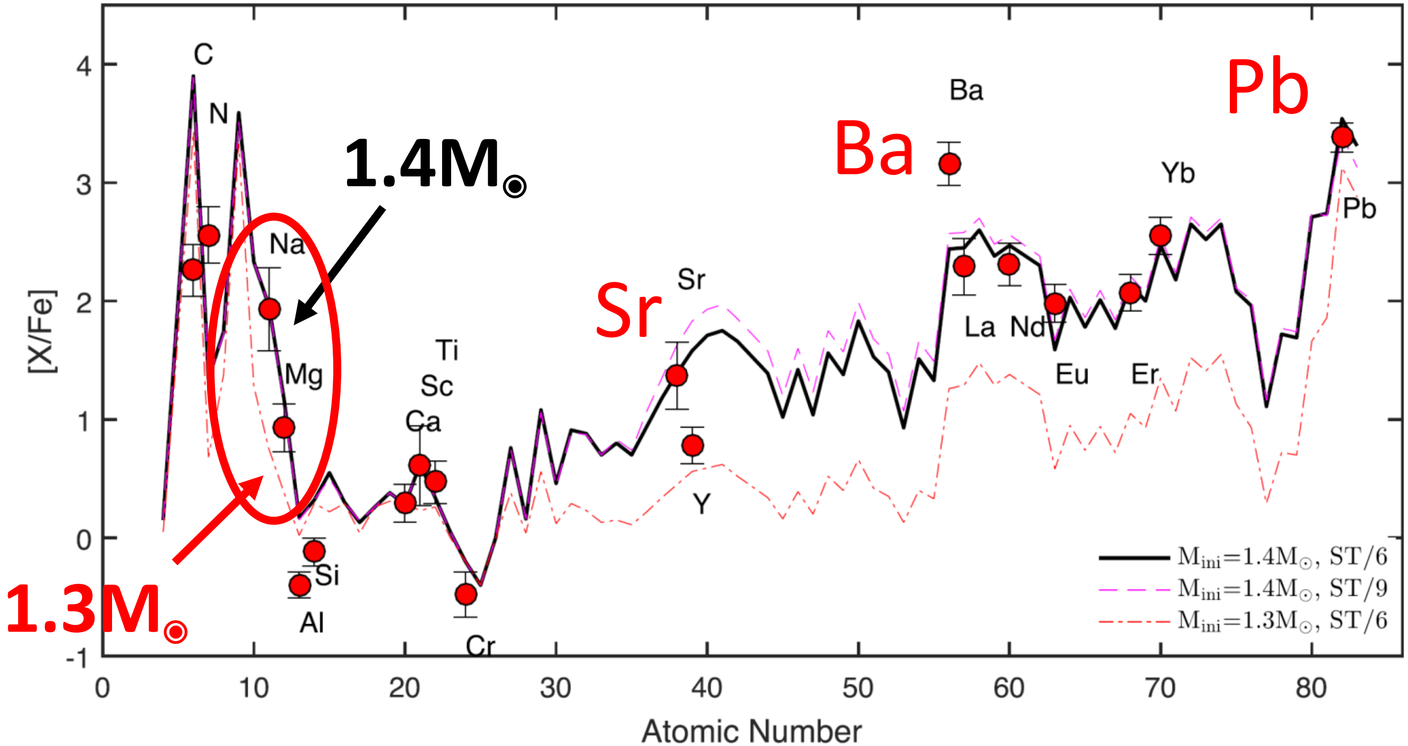
LAMOST J0119-0121: CEMP-s star showing largest excess of s-process elements

Direct comparison of AGB models (e.g. Bisterzo et al. 2010)

- Abundance pattern of neutron-capture elements (Sr-Ba-Pb) are reproduced by models of s-process for low metallicity
- Na and Mg abundances are useful to constrain AGB mass.

→1.4M$_\odot$ model AGB star

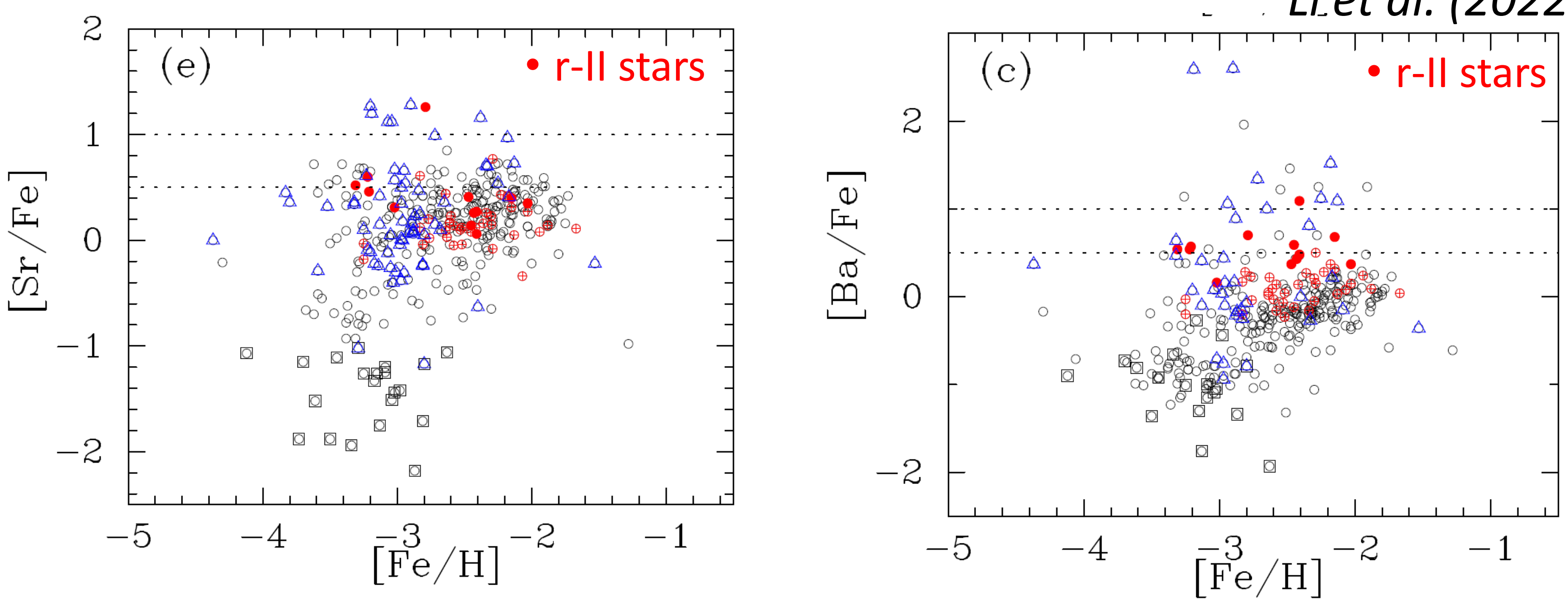
Zhang et al. (2019, PASJ)



Strontium (Sr) and Barium (Ba)

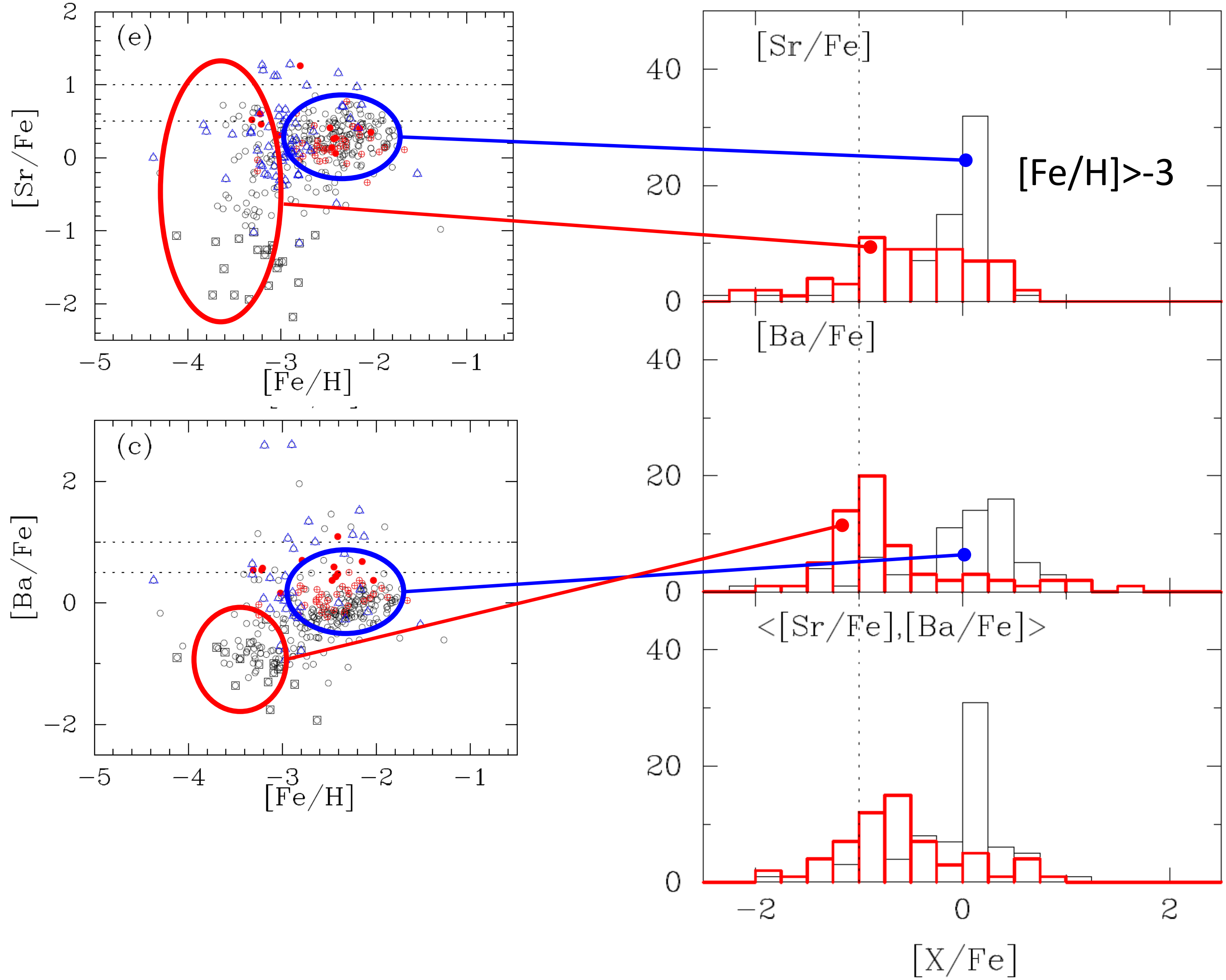
- Large scatter both in [Sr/Fe] and [Ba/Fe] (~3dex). Sr and Ba are detected in most of giant stars … almost all objects have some Sr and Ba ([Sr/H]>~-5, [Ba/H]>~-5)
- Majority of stars with [Fe/H]>-3 have solar abundance ratios ([Sr/Fe]~[Ba/Fe]~0)
  [Sr/Fe] values show stronger concentration
- A fraction of stars have very low Sr and Ba abundances ([Sr/Fe] ~-2, [Ba/Fe]~-2)
  The fraction of low-Ba stars is larger
  …what is the source of Sr and Ba in these stars? cf. Tarumi (this conference)

Li et al. (2022)



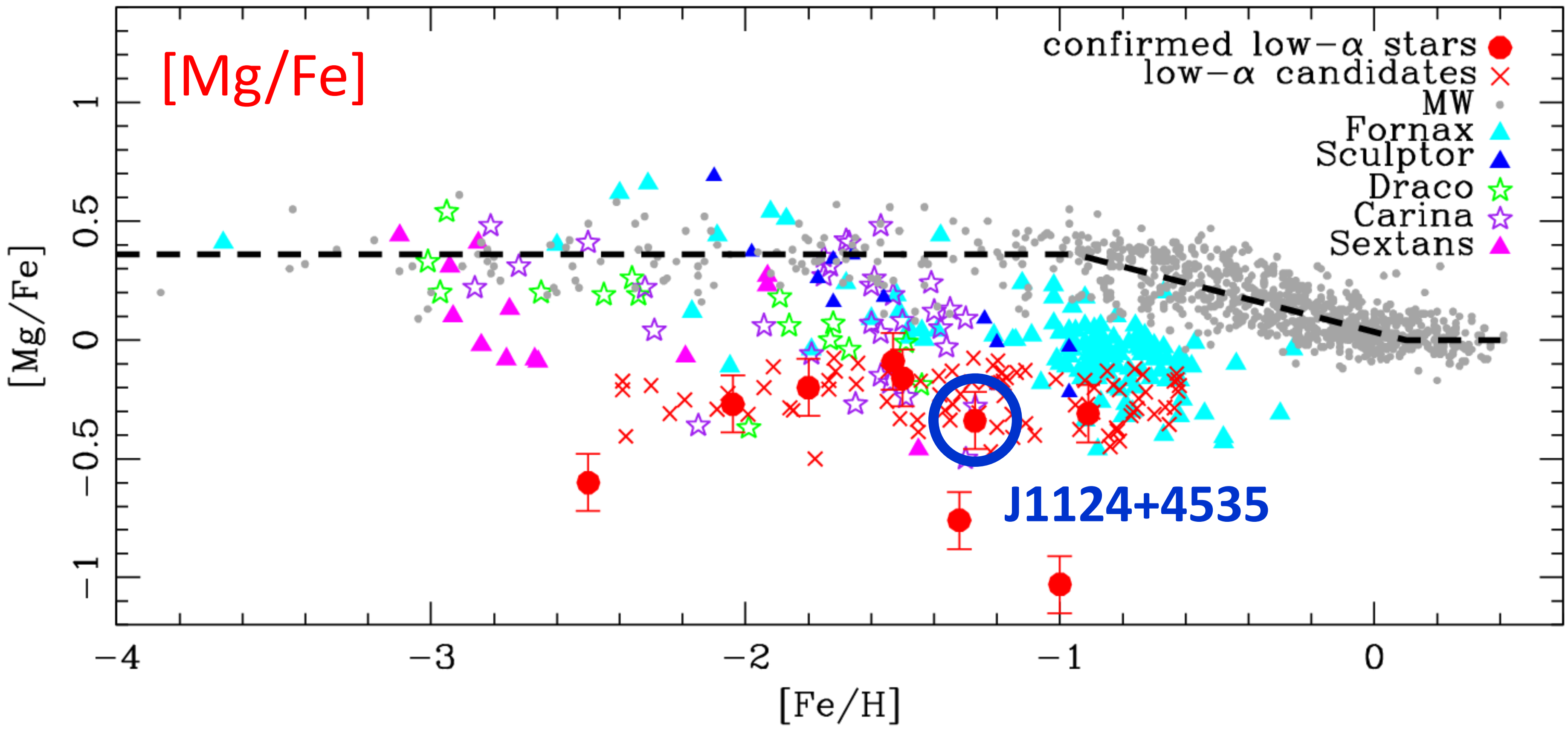
Strontium (Sr) and Barium (Ba)

Li et al. (2022)



r-II star with low alpha elements: a clear signature of accretion from a dwarf galaxy

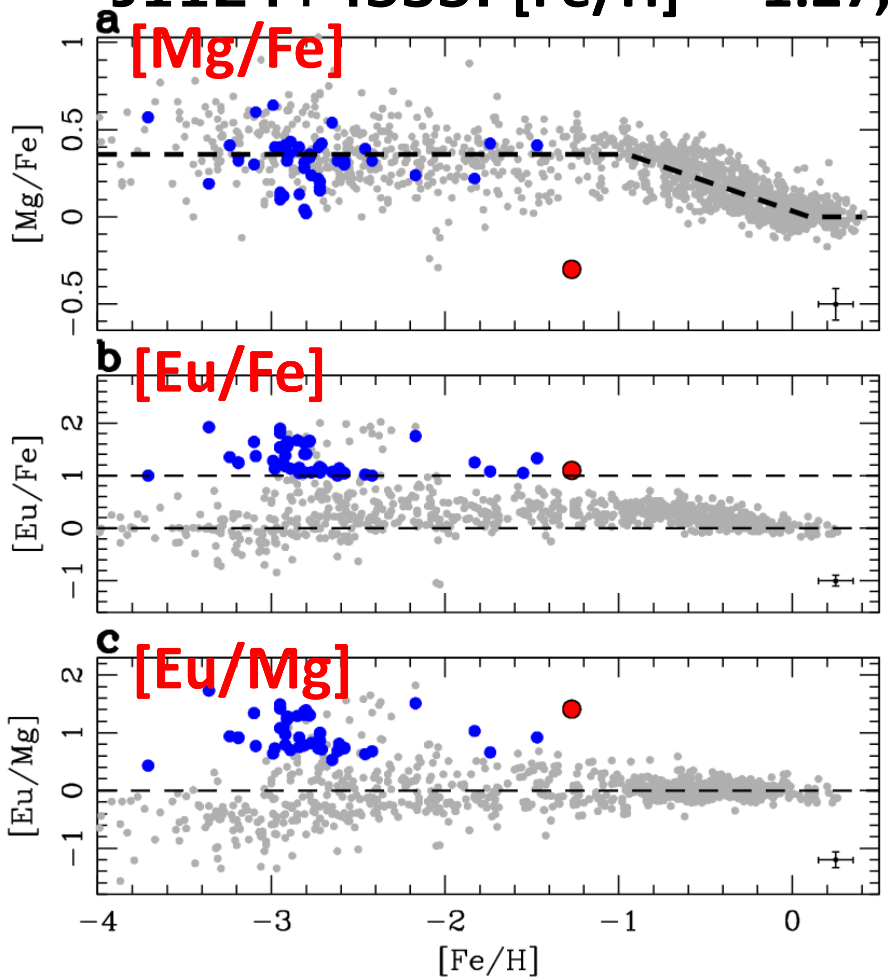
- Searches for alpha-element deficient stars with LAMOST, and follow-up detailed abundance studies with the Subaru Telescope.
- Low alpha stars are candidates that were the members of dwarf galaxies that have been accreted into the Milky Way.



Metal-poor stars studied with LAMOST and Subaru

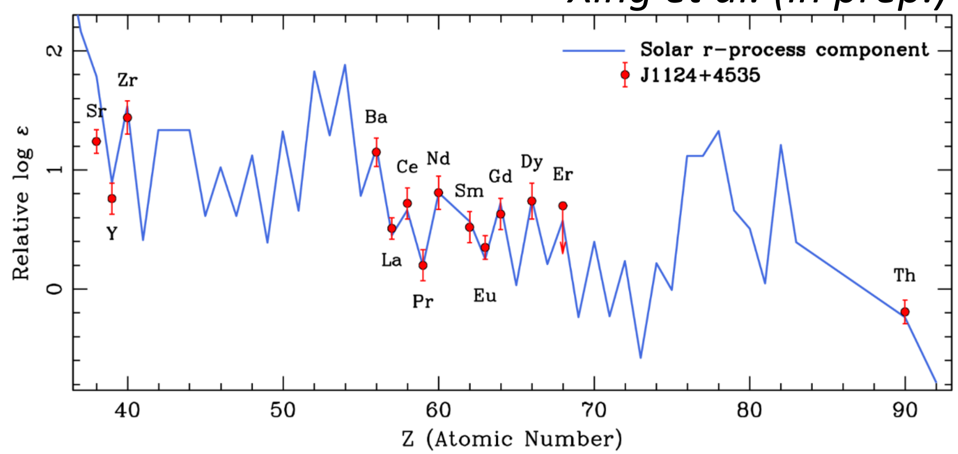
r-II star with low alpha abundances: a clear signature of accretion from a dwarf galaxy

J1124+4535: [Fe/H] = -1.27,[Mg/Fe] = -0.31, [Eu/Fe] = 1.1



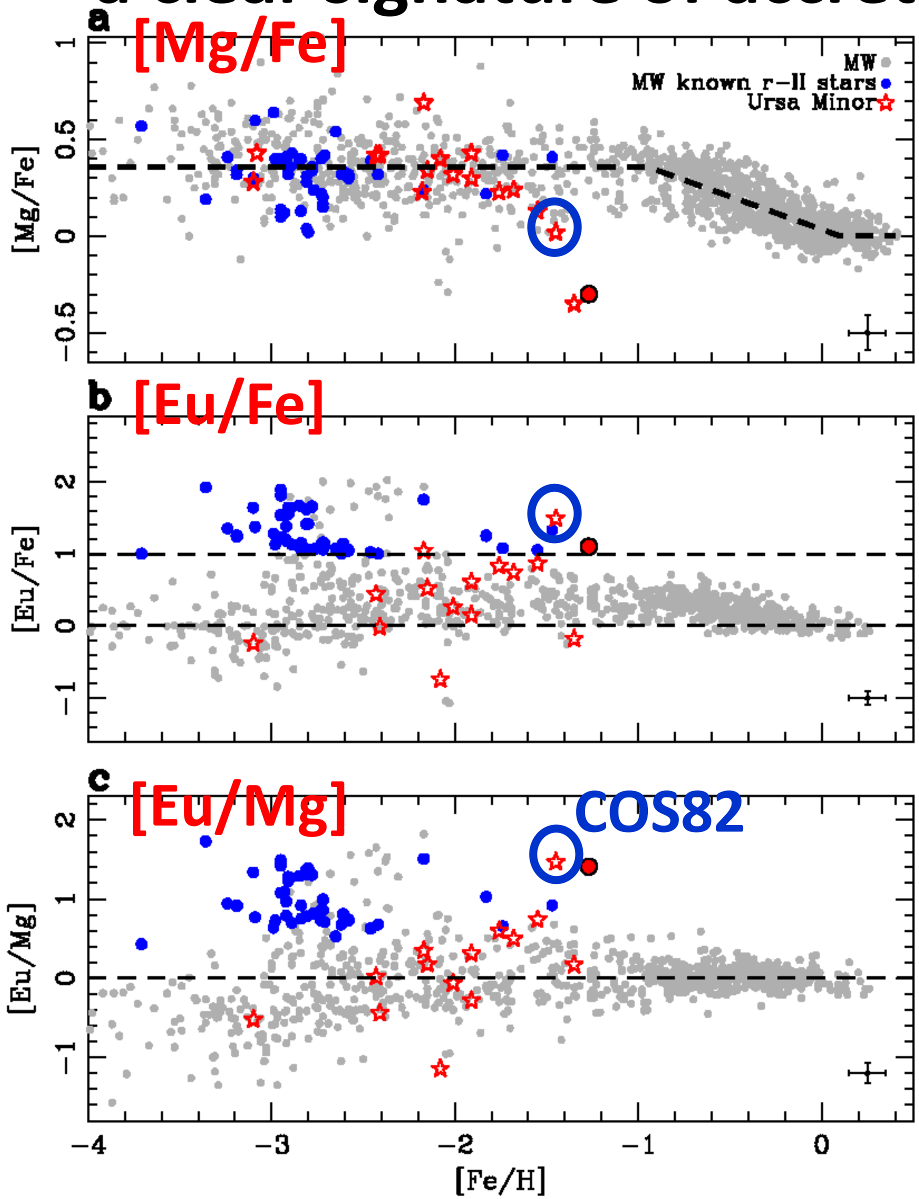
Xing et al. (2019)

Xing et al. (in prep.)



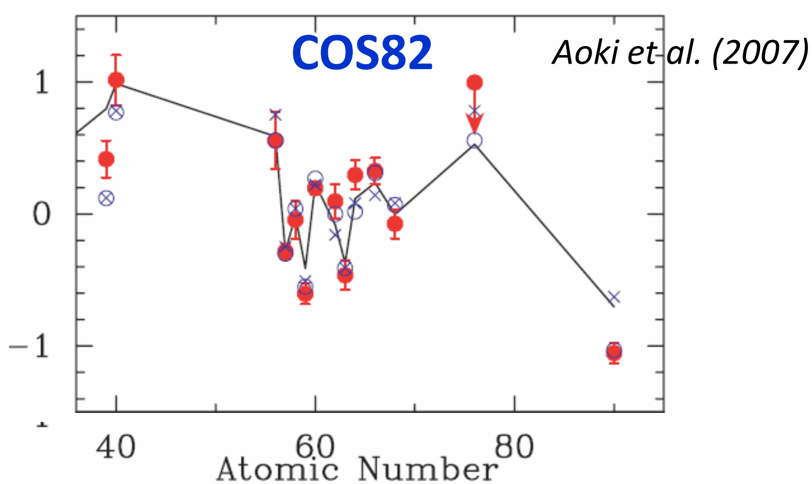
- r-process abundance pattern
- Extremely large excess of r-process elements among moderately metal-poor stars

r-II star with low alpha abundances: a clear signature of accretion from a dwarf galaxy



r-II star with low alpha abundances are found in dwarf galaxies

Example: COS82 in Ulsa Minor (UMi) dwarf galaxy:
[Fe/H]=-1.5, [Eu/Fe]=+1.5
r-process abundance pattern



J1124+4535 would be formed in a dwarf galaxy and has accreted into Milky Way.

Observational studies of r- and s-process elements for Milky Way stars
Summary

- Elemental abundance distributions of large samples of metal-poor stars (RPA, LAMOST/Subaru) provide useful constraint on chemical evolution models and origins of r- and s-process elements.
- r-process-enhanced (r-II) stars would have been formed in small stellar systems (dwarf galaxies) and later accreted into the Milky Way, forming the halo structure.
- Mergers of binary neutron stars could be an important r-process source even at low metallicity, but other sources are also suggested for the lowest metallicity ([Fe/H]<-3).
- Some Carbon-Enhanced Metal-Poor stars (CEMP-s stars) record almost pure products of AGB stars, and are useful to constrain s-process models and progenitor masses.