Heavy elements in globular clusters and dwarf galaxies as probes of the origin of r-process elements

Satoshi Honda
(Kyoto University, Kwasan Observatory)

Wako Aoki (NAOJ)
Nobuo Arimoto (NAOJ)
Kozo Sadakane (Osaka Kyoiku University)
Kaori Otsuki (Fukuoka University)
Toshitaka kajino (NAOJ)
Grant J. Mathews (University of Notre Dame)

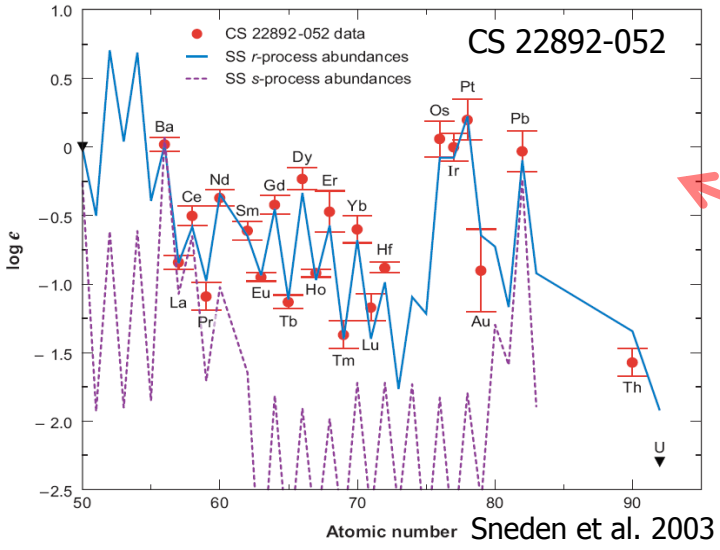
The purpose of this study

- We try to derive the hint of the astronomical site of r-process from the observations of Extremely Metal-Poor (EMP) stars.

- The behavior of r-process elements in Milky Way (MW) halo is compared with the trend in globular clusters and dwarf galaxies.

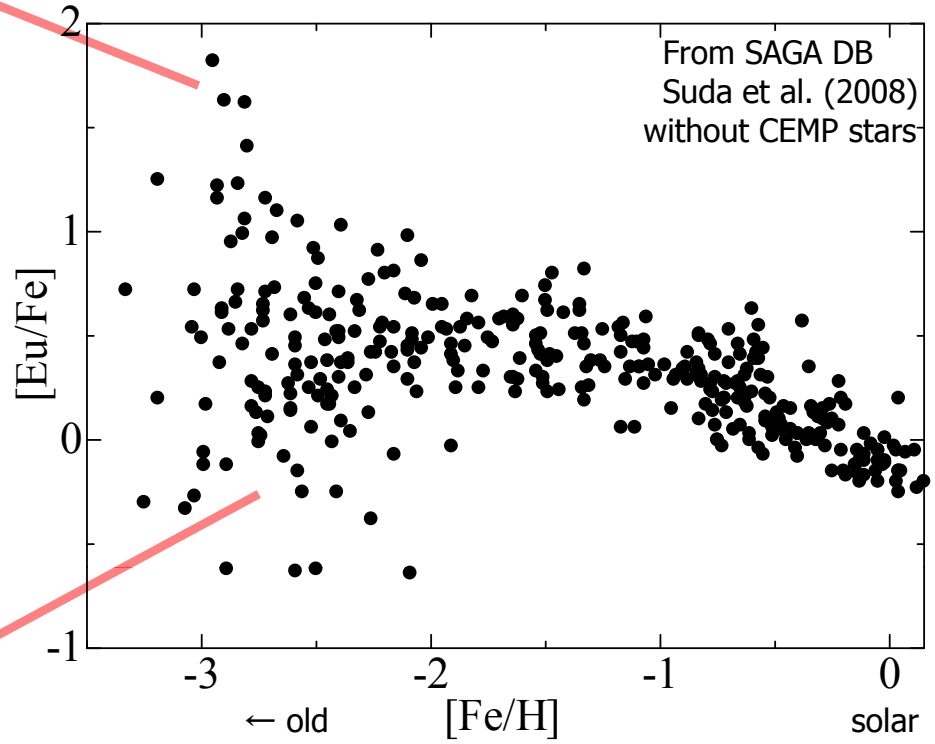
Chemical evolution of r-process in our Galaxy

r-rich stars

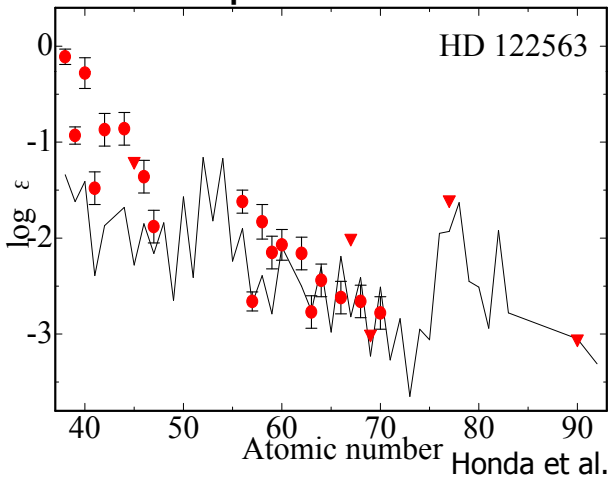


Sneden et al. 2003

These stars show pure r-process patterns.



r-poor stars



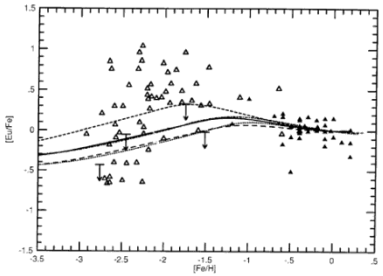
Honda et al. 2006

LEPP (Travaglio et al. 2004)
weak r-process (Wanajo et al. 2006)

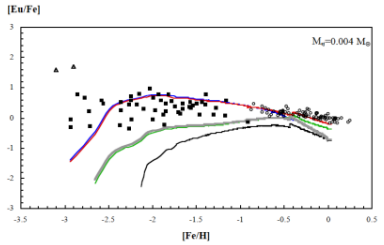
Large dispersion in [Fe/H]< −2
→ Spatial inhomogeneity of chemical composition
r-process is dominant source in EMP stars
(e.g., Honda et al. 2004, Francois et al. 2007)

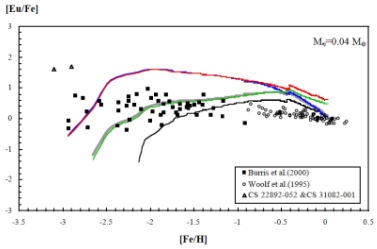
Models of galactic chemical evolution

Neutron star mergers

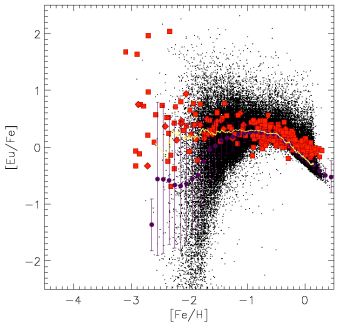


Mathews et al. 1992





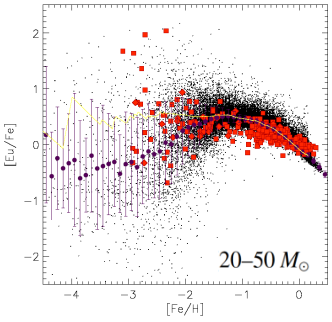
Donder & Vanbeveren 2003

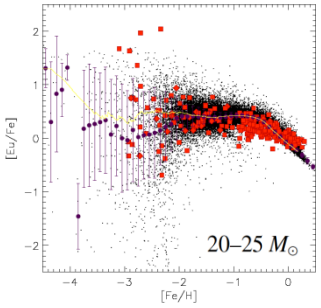


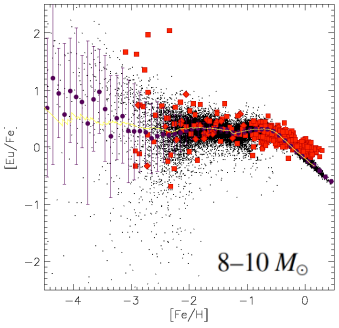
Argast et al. 2004

The chemical evolution models are built based on the observations of metal-poor stars in our Galaxy.

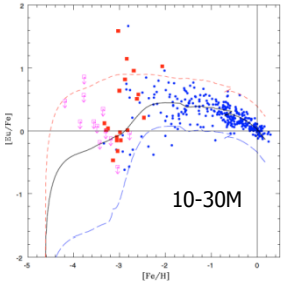
Supernovae



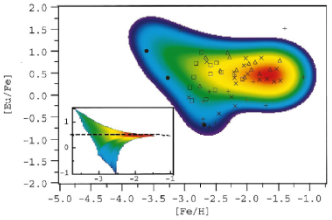




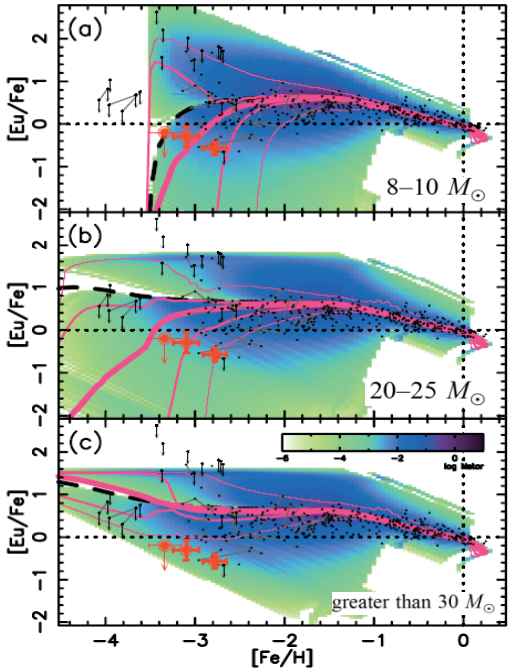
Argast et al. 2004



Cescutti et al. 2006



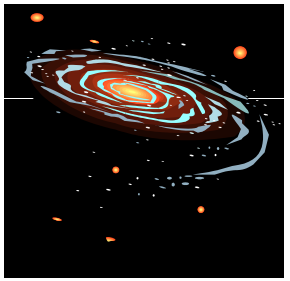
Tsujimoto et al. 1999

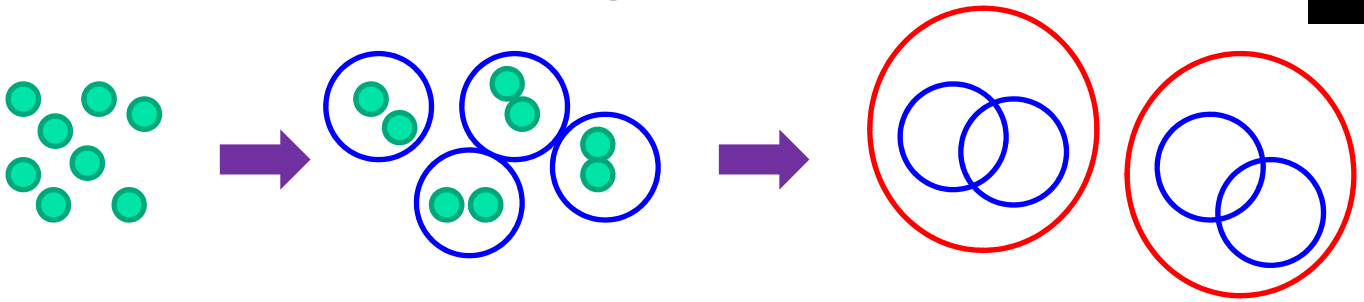


Ishimaru et al. 2004

Dwarf galaxies around the Milky Way

- Building blocks of Galaxy ?
  - ΛCDM hierarchical structure formation
  - Remnants of building blocks of Galaxy





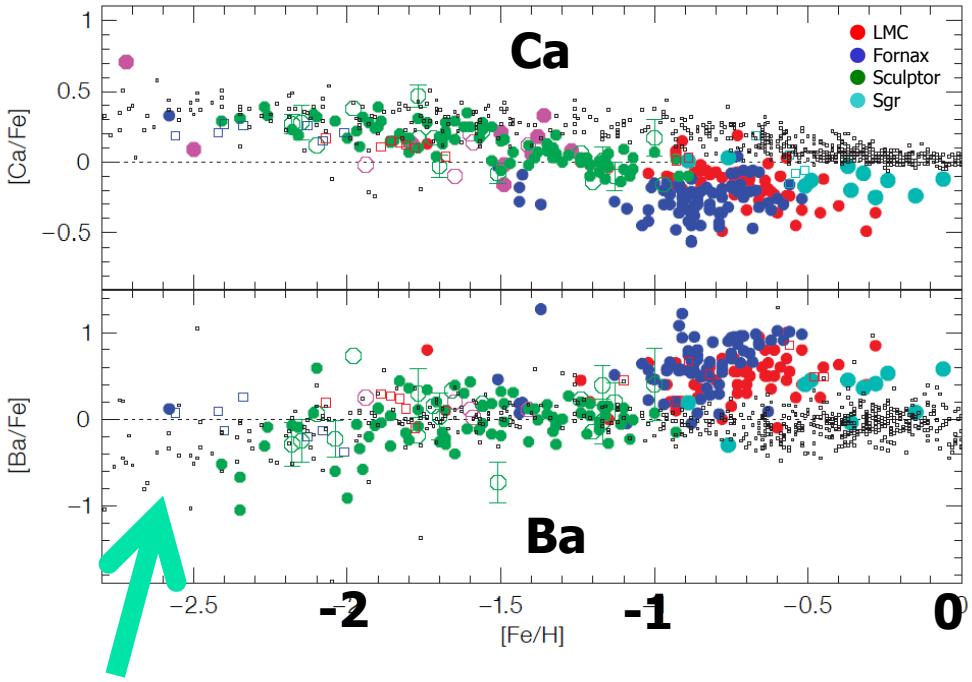
- Do metallicities and abundances of metal-poor stars in dwarf galaxies agree with MW halo's ?
  - Extremely Metal-Poor (EMP) stars in dwarf galaxies provide information of galaxy formation and chemical evolution.

Abundance studies for individual stars in dwarf galaxies

- Low α trend
  - Large contributions of Type Ia SNe at low metallicity?
- Chemical abundance trend of "luminous" ("metal-rich") dwarf spheroidal galaxies is different from MW halo.

Building blocks of galaxy ???

Venn & Hill (2007)

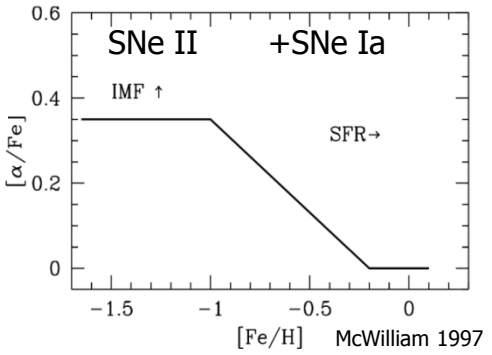


[Fe/H] < -2.5

How is the very low metallicity range ?

Many EMP stars were discovered in dwarf galaxies by SDSS, DART program.

The DART program found many EMP stars in Sextans.



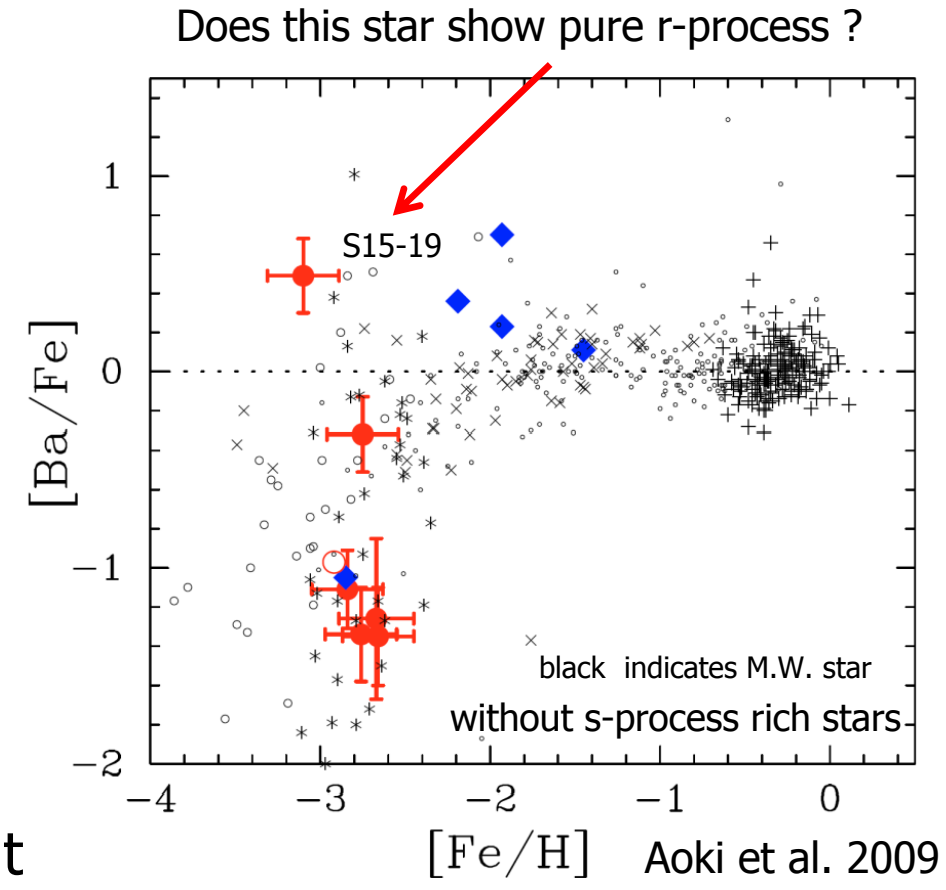
Chemical abundance analysis of Sextans stars with Subaru/HDS

- High resolution follow-up for candidate EMP stars discovered with VLT/FLAMES (DART).
  (Helmi et al. 2006)

- Subaru/HDS observations (P.I.: N. Arimoto)
  - Jan. 2007 + May 2005
  - R=40,000
  - λ 4400-7200 A
  - S/N ~ 17-46 @5180A
  - Exp. time 60-390 min

Neutron-capture elements in dwarf galaxy Sextans

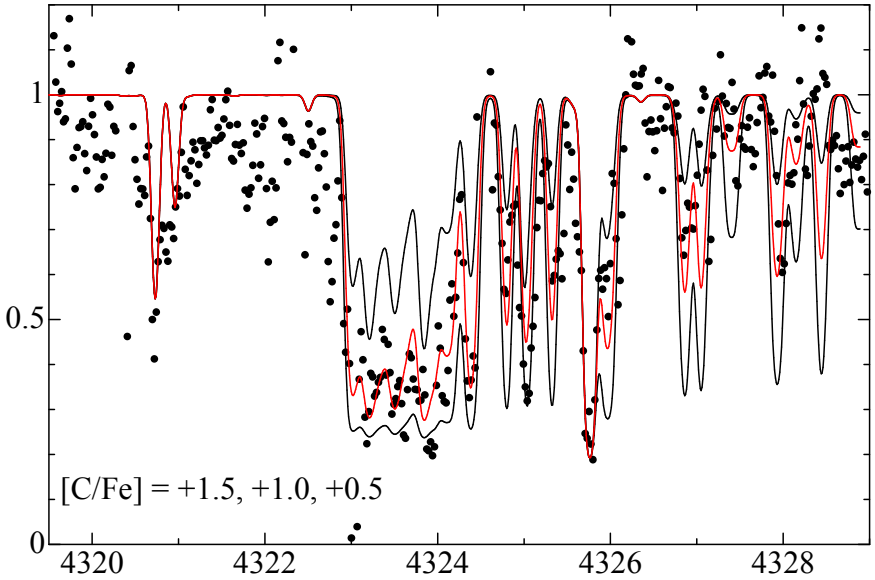
- Low metallicity is confirmed
- Under-abundant in five EMP stars.
- Two EMP stars show large and moderate excess of Ba.
- Ba in Sextans shows large scatter as in MW halo.
  - Is the behavior of neutron-capture element similar to that of Our Galaxy ?

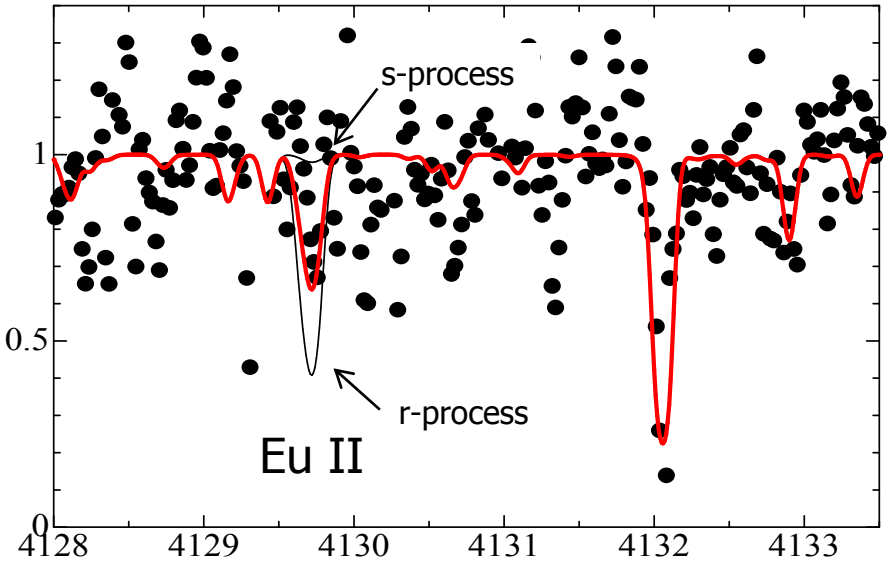


High resolution spectroscopy of the Ba-rich EMP star S15-19 with Subaru/HDS

- V=17.5
- $T_{\rm eff}$: 4600K, logg: 1.2, [Fe/H]=-3.1
- Obs. Date : 2010 Feb. 9
- R=40,000, λ 3760 ~ 5490 A (Sr, Eu, CH)
  - 4400 ~ 7200 A (previous obs.)
- Exp. time 8h
- S/N = 25 @ 4500 A

Abundances of S15-19





- No detection of Eu II line ([Eu/Fe] < +0.9)
- Carbon-rich ([C/Fe] = +1.0, C^{12}/C^{13} =4±1)
- Low Sr/Ba (= -1.9)

This result shows that the abundance of this star is reflects **s-process in low metallicity.** (e.g., Gallino et al. 1998)

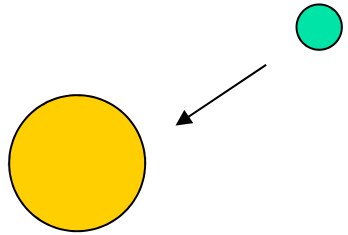
S15-19 is not r-process enhanced star

- Variation of radial velocity is found.

  226.05±0.11 km/s (2005) → 223.5±0.6 (2010)

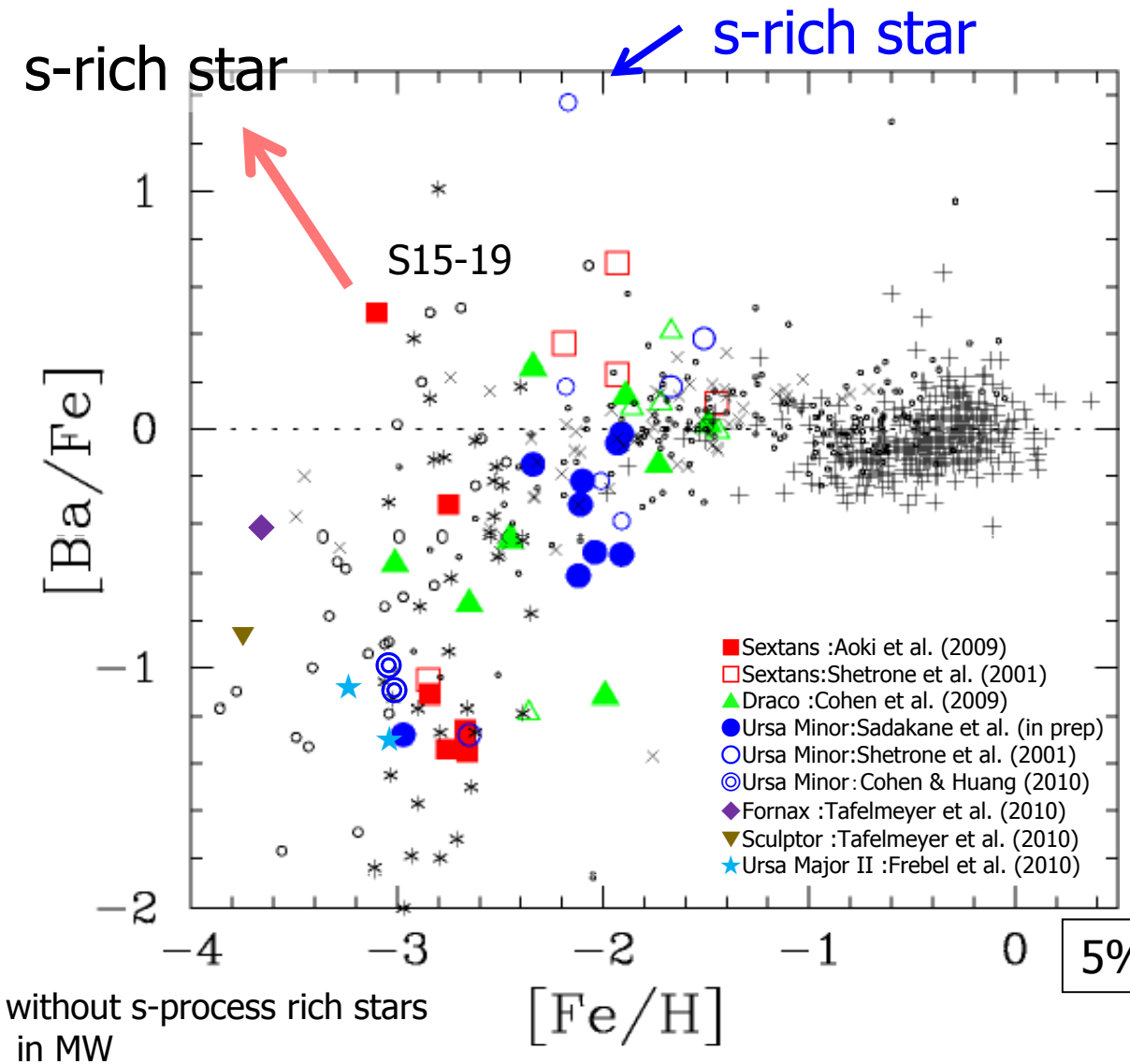
  → binary system

- S15-19 probably belongs to binary system and is affected by an AGB star.
  - High Ba is the result of the mass transfer from AGB star.



The chemical composition of this star does not show initial composition.

neutron-capture elements in EMP stars in faint dwarf galaxies



without s-process rich stars in MW

In spite of many observations in recent years, **no r-process enhanced EMP star** is found in dwarf galaxies and ultra-faint dwarf galaxies, yet.

Dwarf galaxies may have a history of chemical evolution different from that of MW.

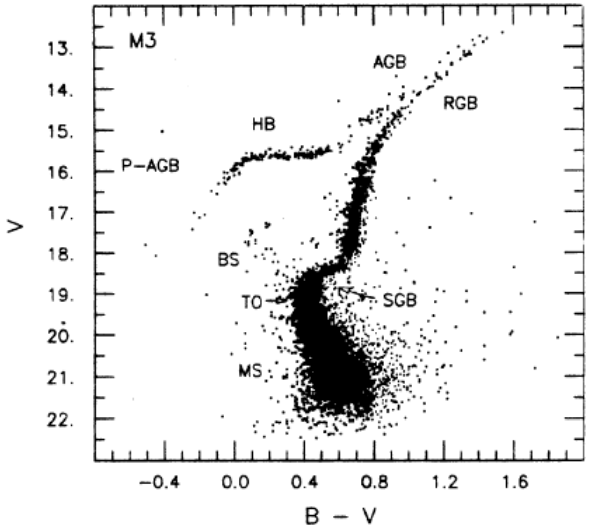
5% ~ r-rich star in MW

Barklem et al. 2005

Globular Clusters

- Oldest objects in our Galaxy
  - ≒ Age of Galaxy

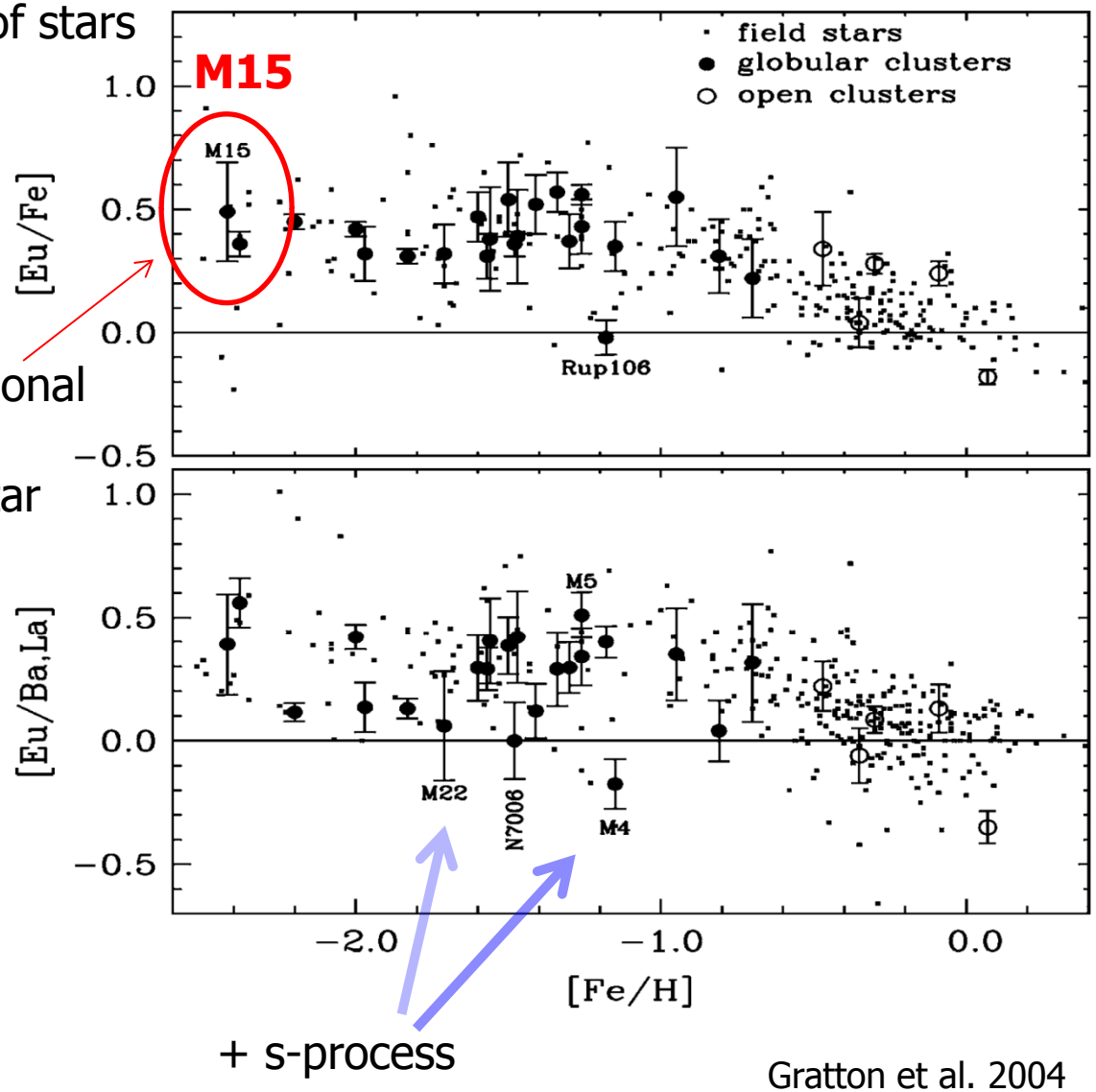
- Single stellar population
  - Homogeneous metallicity
    - Formed at same time
      c.f., Exceptions are ω Cen, NGC2808, etc.
  - No EMP star



- Formation history is still unclear
  - Building blocks of Galaxy ?
  - Remnant of core in dwarf galaxies ?
  - ???

Neutron-capture elements in GCs

average of stars in GCs



Observational error ?
Star-to-star scatter ?

+ s-process

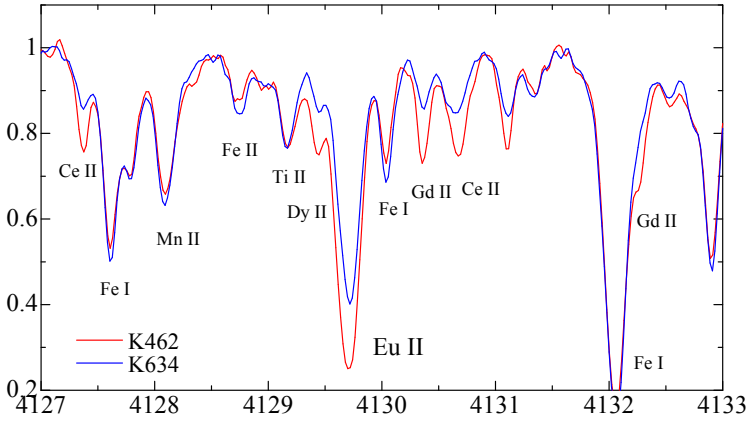
r-process is dominant source in metal-poor GCs.

r-process

s-process

Gratton et al. 2004

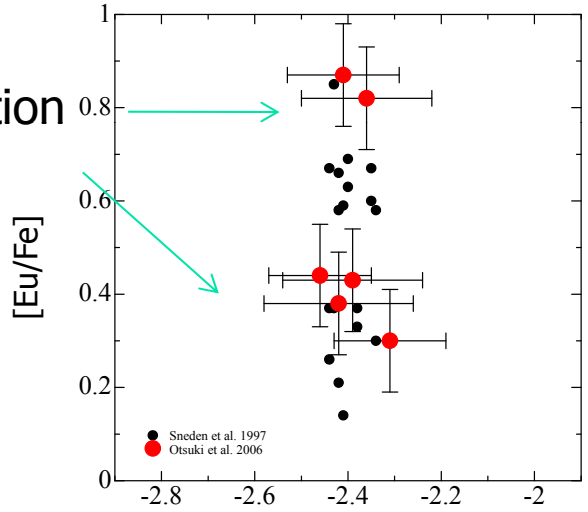
Star-to-star abundance variations in M15



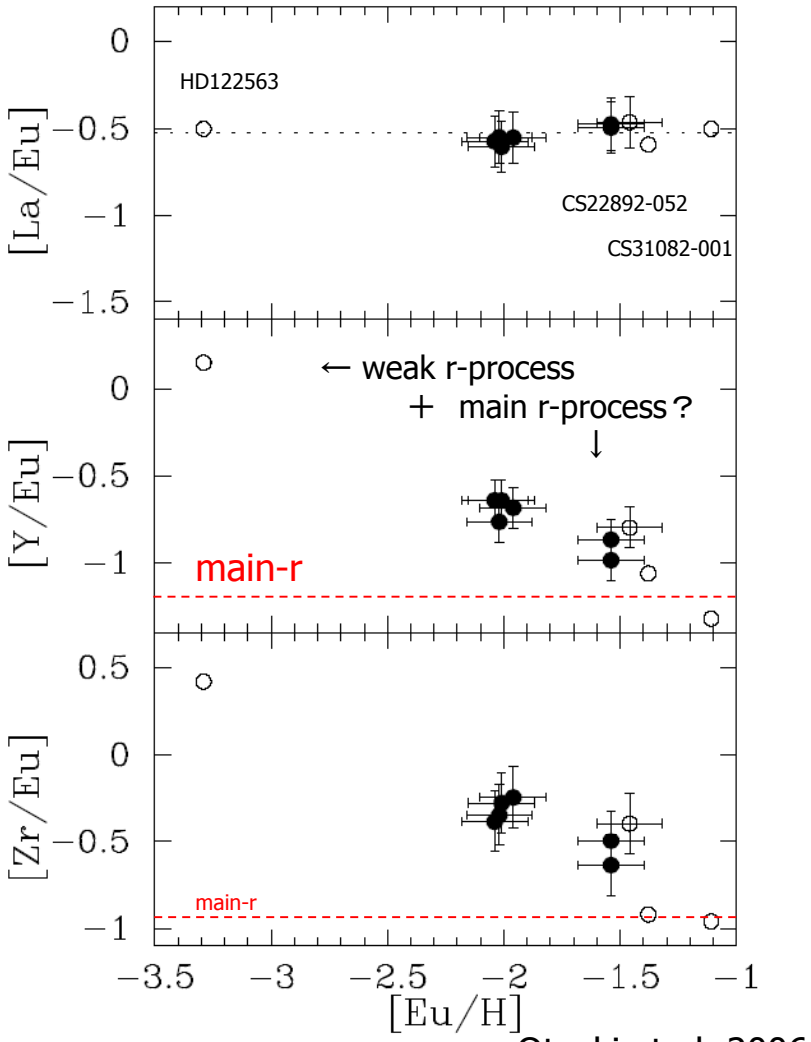
star-to-star scatter !

inhomogeneous r-process ?

Selection bias ?



Sneden et al. 1997
Otsuki et al. 2006



Otsuki et al. 2006

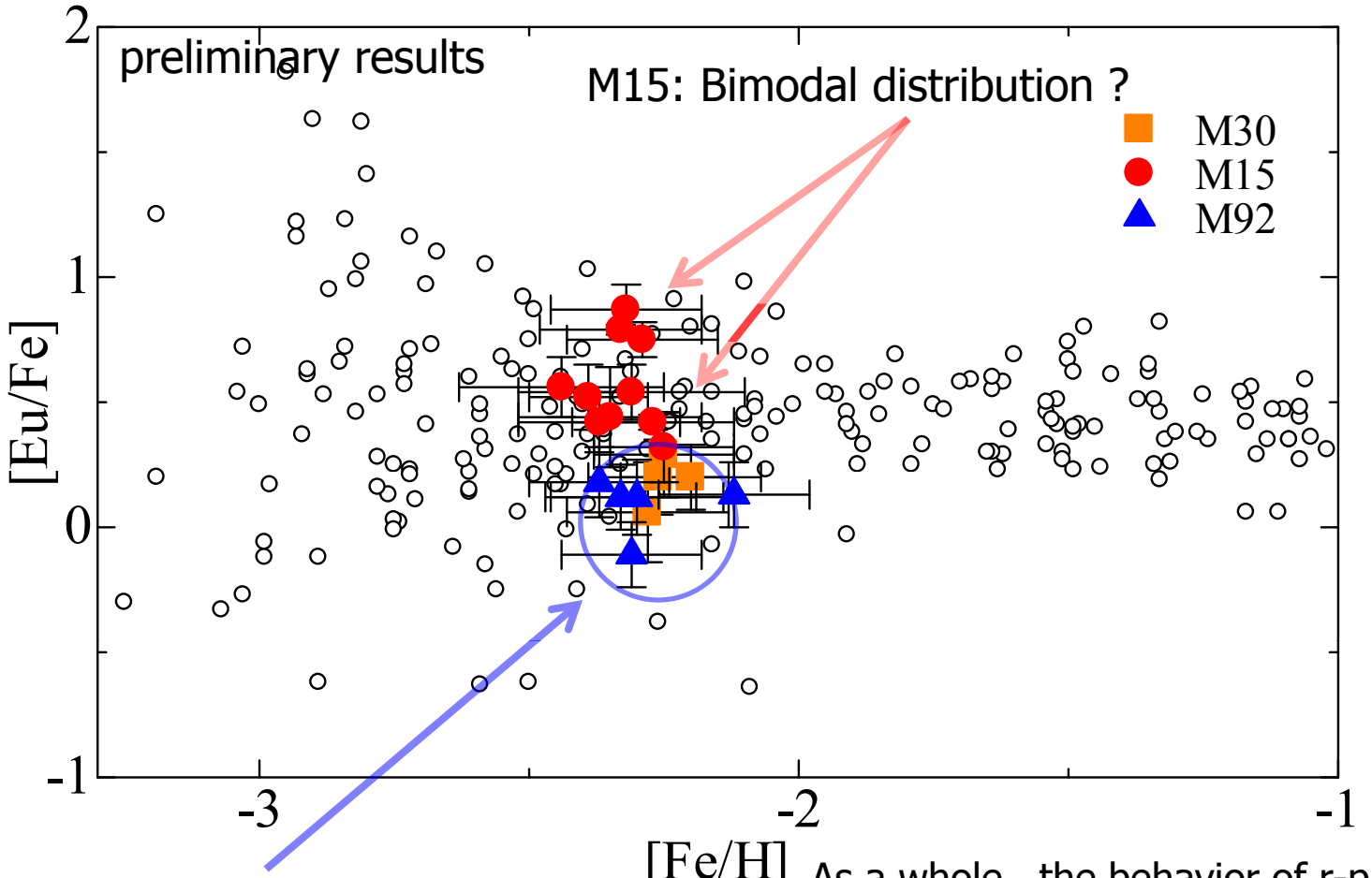
Need more sample of other clusters!

HDS observations of GCs stars

	GC	star	V	$V-K$	Obs. Date(UT)	Exp.(sec)	S/N(4000)	S/N(5000)
M15	M15	K144	13.06	2.78	2011. 6.9-10	7200	55	110
	M15	K146	13.57	2.50	2004. 7.25	9000	79	146
	M15	K386	12.80	2.86	2004. 7.26	5400	74	158
	M15	K431	13.03	2.65	2011. 6.10	3600	63	122
	M15	K462	12.90	2.84	2004. 7.25	5400	77	158
	M15	K490	12.84	2.67	2004. 7.26	5400	87	158
	M15	K634	12.81	2.86	2004. 7.25	5400	83	163
	M15	K825	12.79	3.02	2011. 6. 9	3600	57	122
	M15	K853	12.88	2.81	2011. 6.8-9	6598	51	107
	M15	K1040	13.40	2.62	2004. 7.26	9000	76	152
M30	M30	155	12.03	3.01	2007. 8. 6	4000	81	179
	M30	156	13.03	2.58	2007. 9.19	5400	72	128
	M30	157	13.99	2.58	2005.10.21	5400	72	124
	M30	D	12.83	2.65	2005.10.21	5400	85	149
M92	M92	II-53	12.50	2.68	2008. 6.15	3600	41	75
	M92	III-13	12.11	3.05	2004. 7.26	3600	75	161
	M92	III-65	12.47	2.85	2008. 6.15	5400	47	87
	M92	VII-18	12.18	2.99	2011.6.8-9	12428	67	144
	M92	B-107	12.42	2.85	2004. 7.26	3600	80	151

R～50,000　　3500 Å ～5200 Å

New observations of Eu in GCs



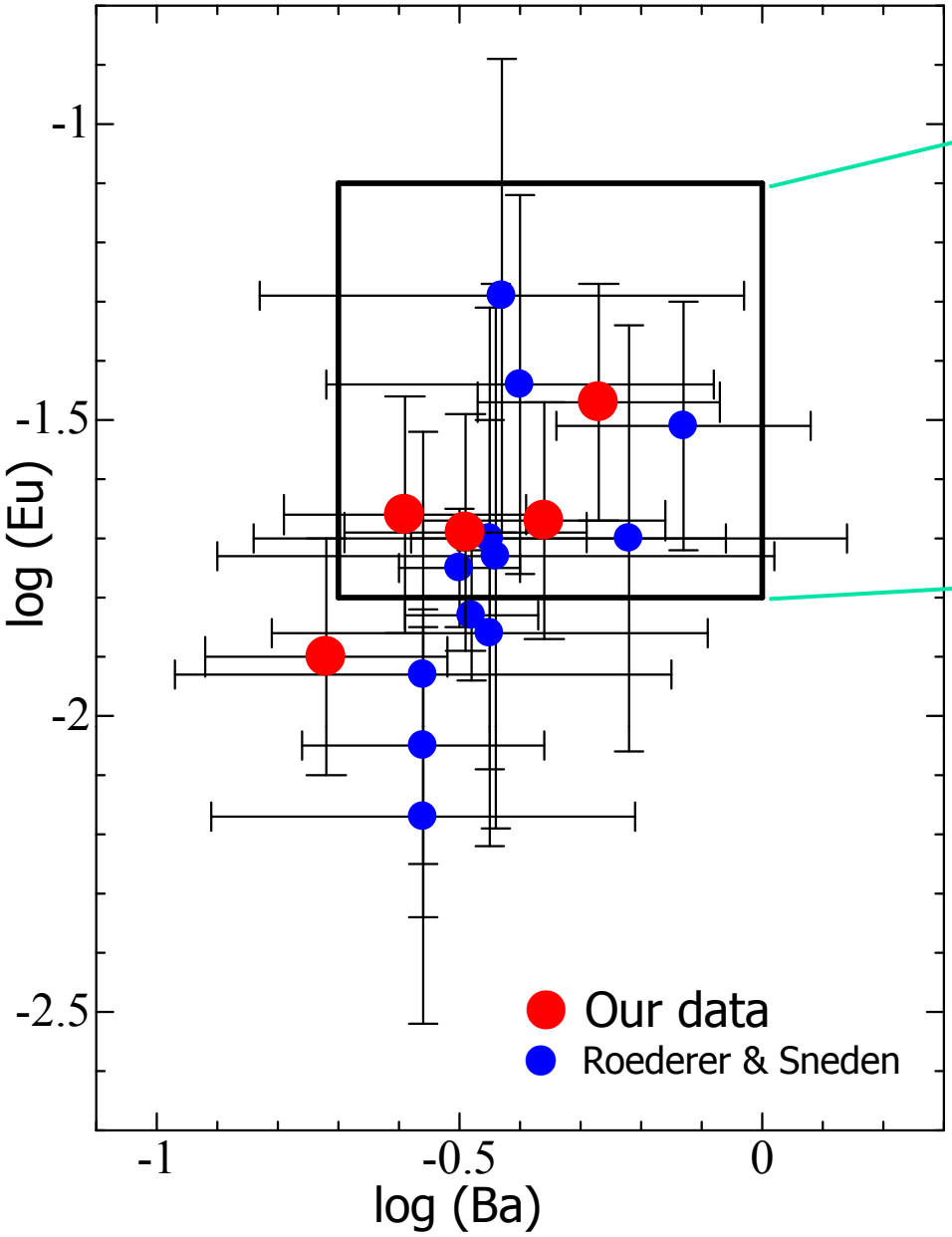
M92 also show dispersion ?

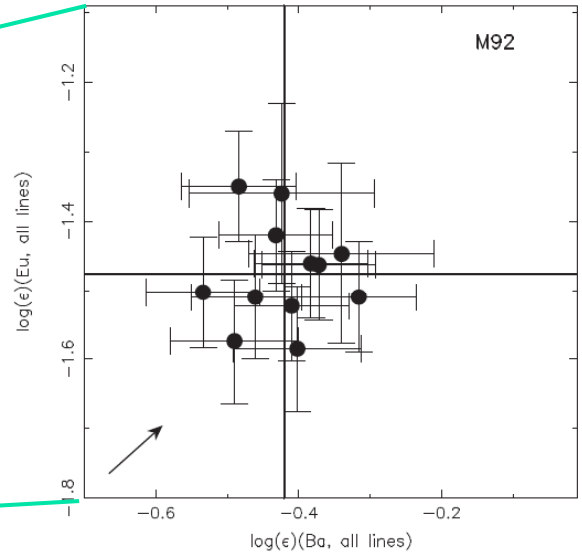
Dispersion exists (Roederer & Sneden 2010)
No dispersion (Cohen 2011)

As a whole, the behavior of r-process abundances are similar to that of our Galaxy.

Is the behavior different for every GCs ?

Heavy-element dispersion in the GC M92 ?





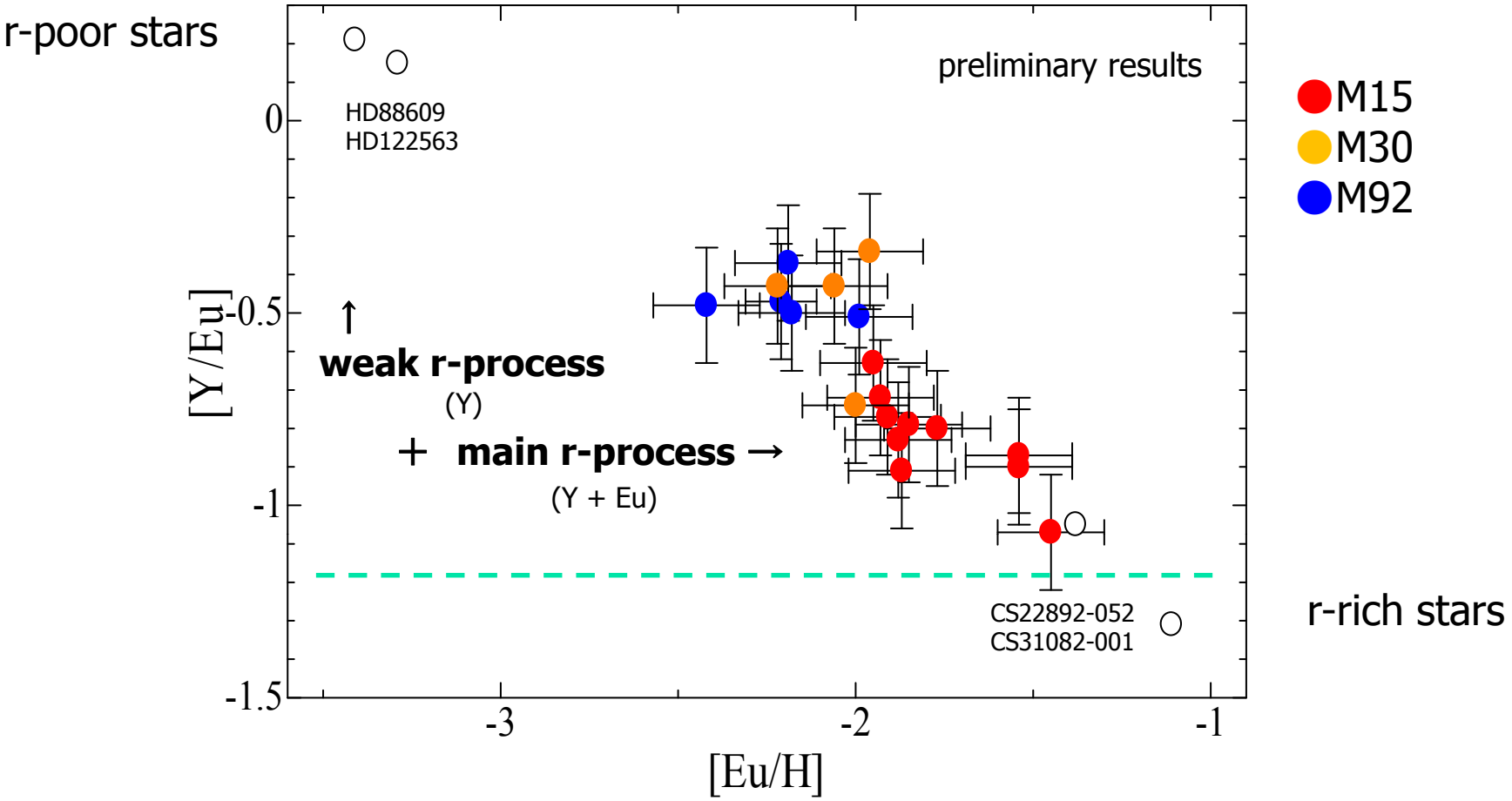
Cohen 2011

No dispersion (<0.07dex)

Roederer & Sneden 2011

Large dispersion also exists in M92 (0.5-0.8dex)

Weak r-process in GCs



Light neutron-capture elements (Y) are commonly enhanced
Heavy neutron-capture elements (Eu) show scatter.

Summary

- EMP stars show large dispersion in MW halo.
  - Existence of r-rich stars and r-poor stars
- No r-process enhanced EMP star is found in dwarf galaxies yet.
  - S15-19 is CEMP-s star.
- We confirm the dispersions in very metal-poor GCs (M15, M92 ?).
  - No dispersion in M30
  - Bimodal distribution M15 ?
  - Weak r-process is common in metal-poor GCs ?
- We need r-process chemical evolution models that can explain neutron-capture elements in MW halo, globular clusters and dwarf galaxies.
- **Further research on EMP stars in MW, dwarf galaxies, and GCs would clarify the r-process.**

  e.g. → **Subaru/PFS + Keck/ESI + Subaru/HDS(+MOS)**

  → **TMT/HROS**