[Th/Eu] ratios from the 5989 Å Thorium line in the spectra of 36 Stars: Constraints on r-process origins and galactic chemical evolution

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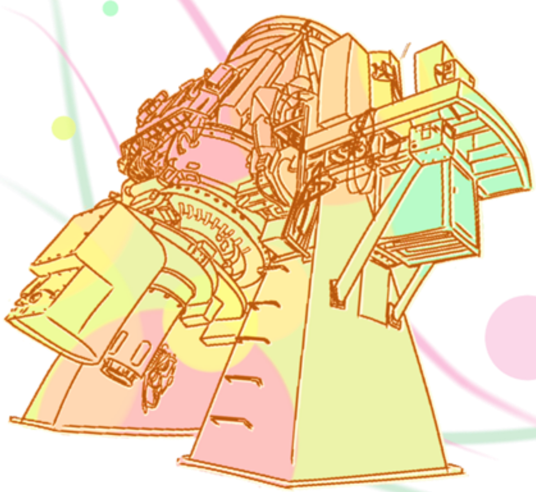


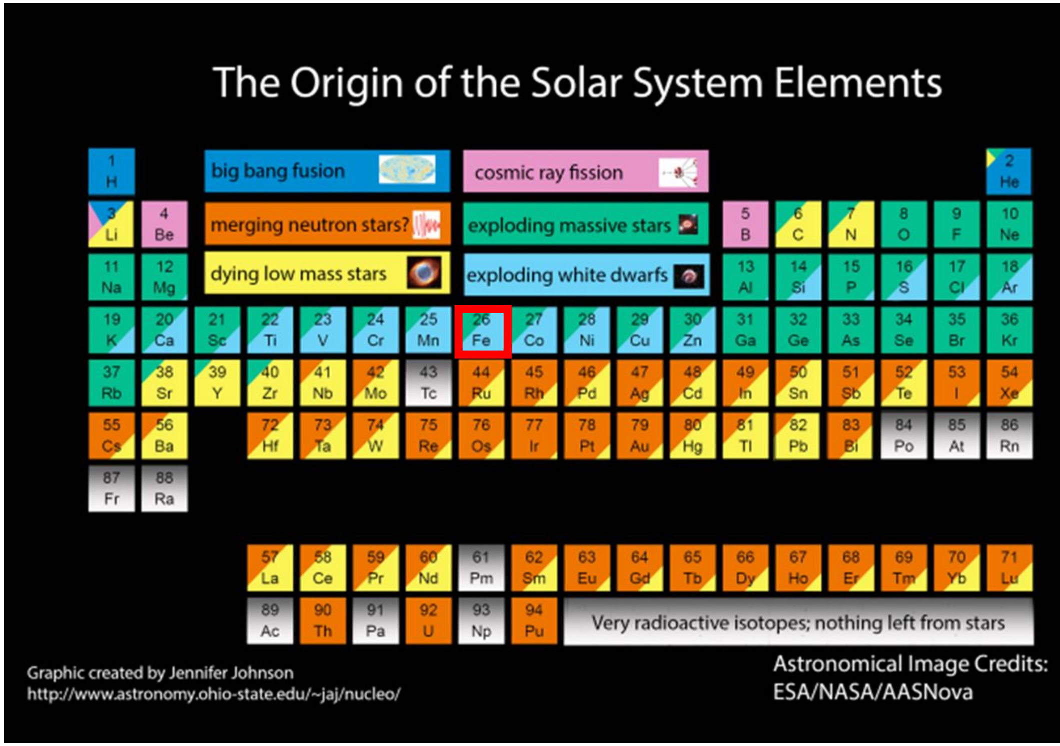
Introduction Origin of the elements

Elements have been synthesized in the universe.

H, He, Li
Big Bang

C, N, O, ~ Fe
stellar nucleosynthesis

Fe ~
neutron capture process
s (slow)-process: AGB stars
r (rapid)-process: Neutron star mergers, etc.

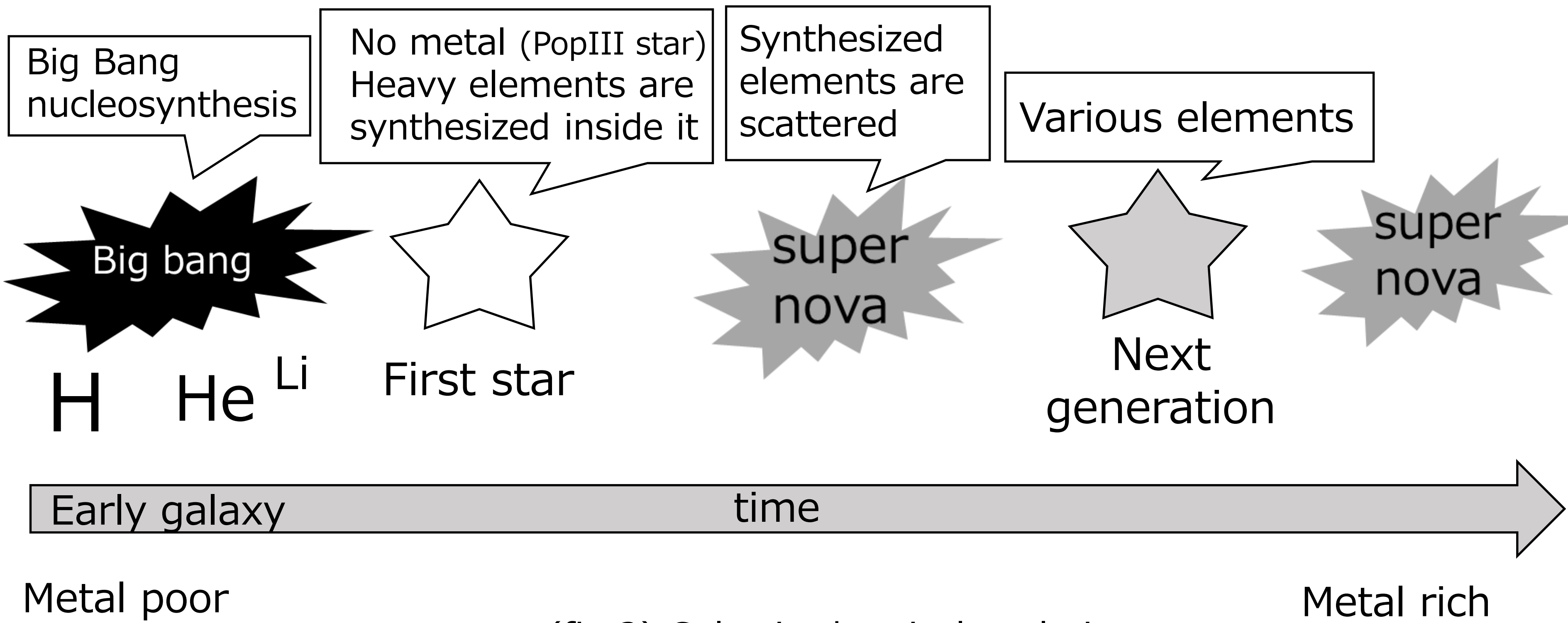


(fig.1) Periodic table

It is still a matter of debate whether the origin of the r-process is a single event or multiple events.

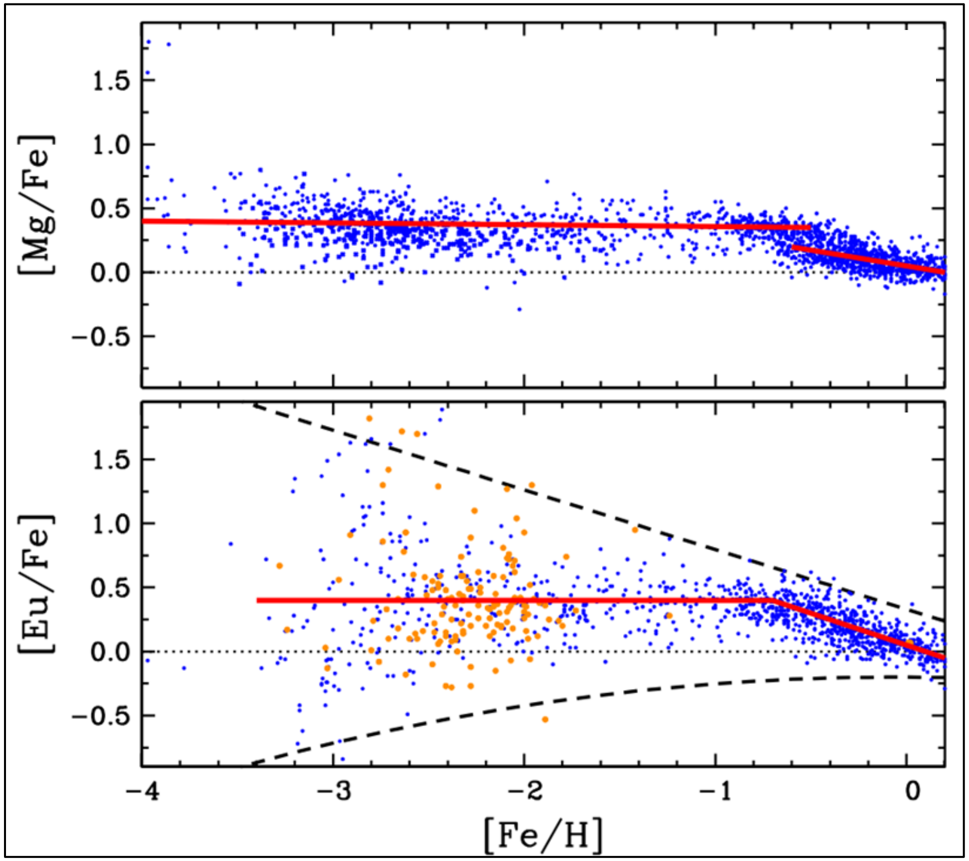
Introduction Galactic chemical evolution

One of the method of estimate the origin of elements is investigate stellar abundances.
Stellar atmosphere retains the chemical abundance of the universe when the star was born.



(fig.2) Galactic chemical evolution

Observation of stellar abundances



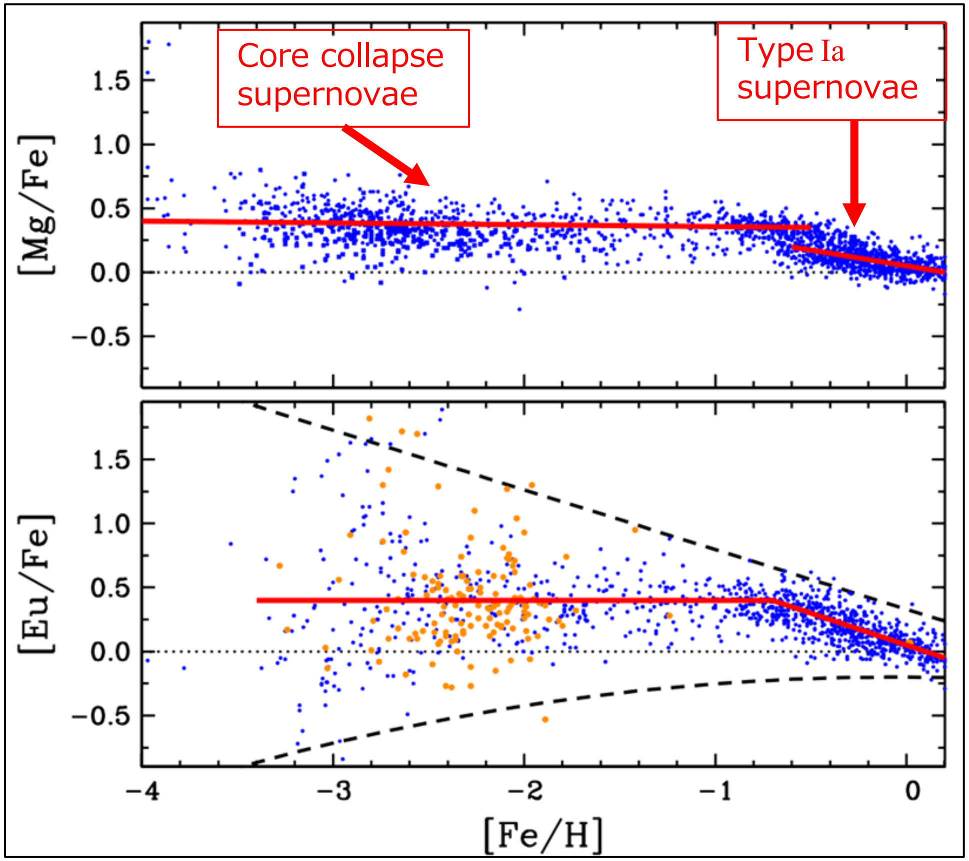
$$[X/Y] = \log_{10} \frac{(n_X/n_Y)_{star}}{(n_X/n_Y)_{\odot}}$$

(fig. 3) Observation of (a)Mg, (b)Eu in stellar atmosphere (Cowan et al., 2021)

Mg: Type II supernovae

Eu: r(rapid)- neutron capture process (e.g., Neutron star mergers)

Observation of stellar abundances



(fig. 3) Observation of (a)Mg, (b)Eu in stellar atmosphere (Cowan et al., 2021)

<u>Top panel</u>

[Fe/H] ≲ -1

[Mg/Fe] is constant and independent of the [Fe/H].

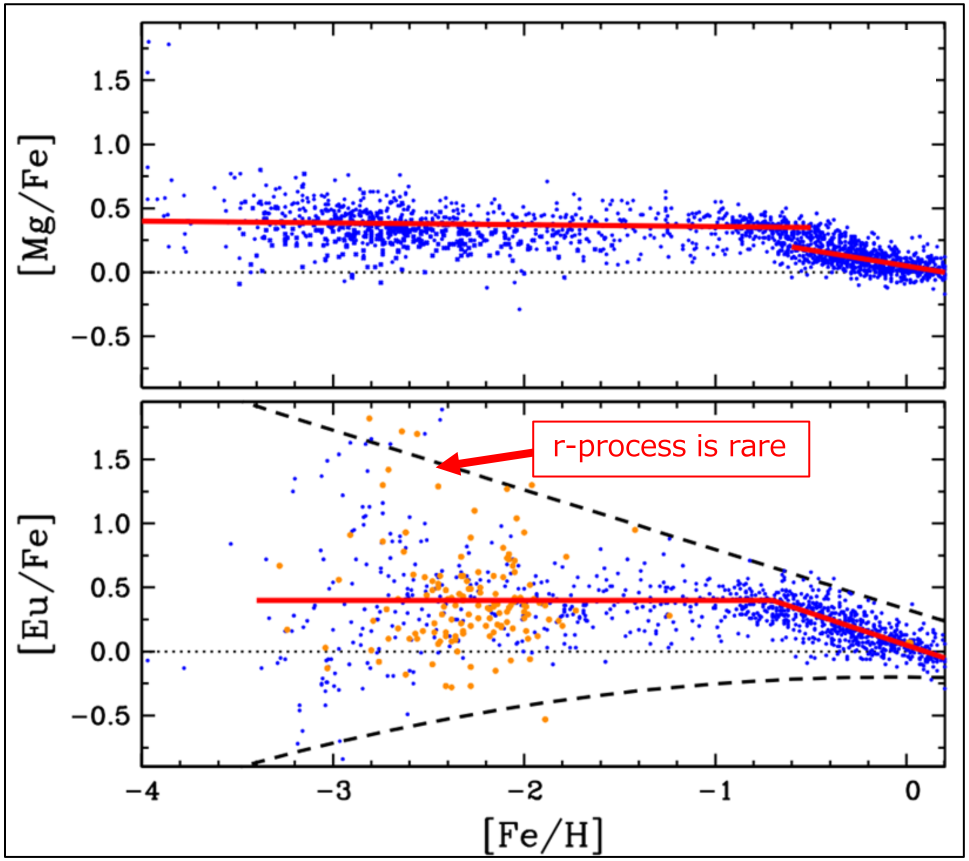
We can consider that massive stars with short lifetimes cause CCSNe, which synthesize Fe, Mg.

-1 ≲ [Fe/H]

[Mg/Fe] decreases as [Fe/H] increases.

We can consider that medium or low mass stars in a binary star system with long lifetimes cause Type Ia SNe, which synthesize a large amount of Fe.

Observation of stellar abundances



<u>Bottom panel</u>
[Fe/H] ~ -3
[Eu/Fe] have large scatter.

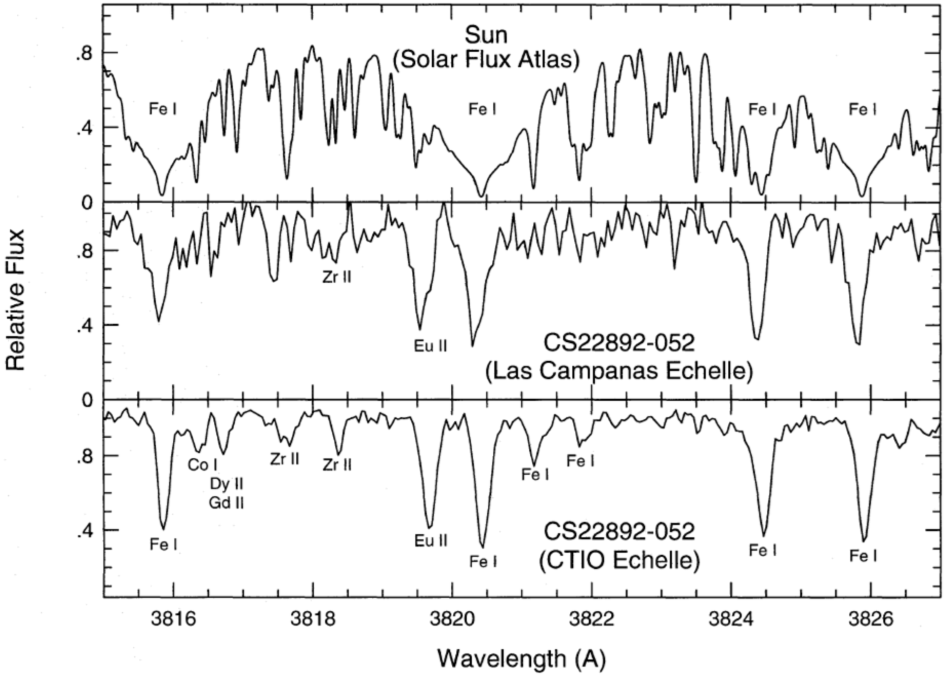
We can consider that r-process is rare event in the universe.

(fig. 3) Observation of (a)Mg, (b)Eu in stellar atmosphere (Cowan et al., 2021)

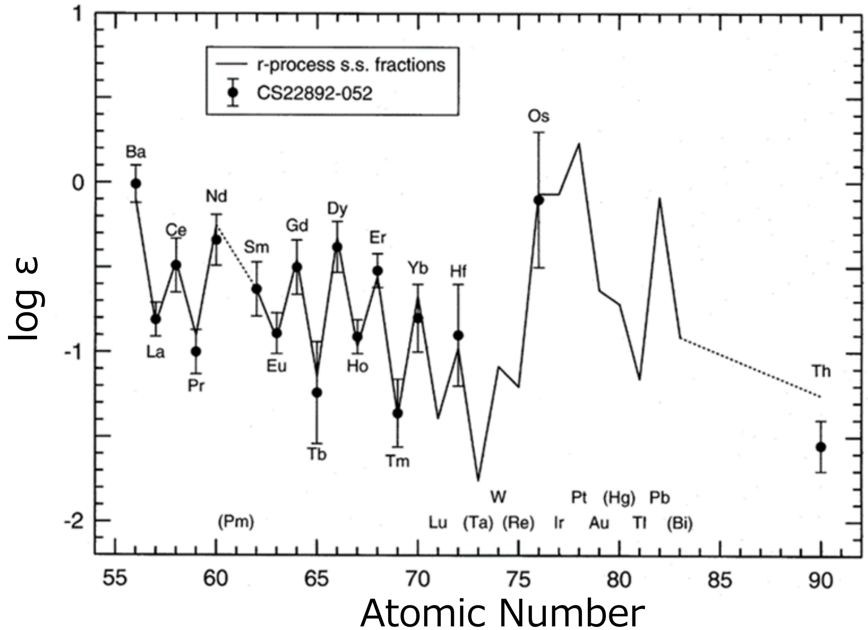
We can discuss the origin of elements by **observing various metallicity stars** and **investigating chemical abundance**.

r-process abundances in metal-poor stars

r-process rich metal-poor star ; CS22892-052 ([Fe/H] ~-3)
(Sneden et al.1996)



(fig. 4) Comparison of Sun and CS22892-052.



(fig. 5) abundance pattern of Sun and CS22892-052.

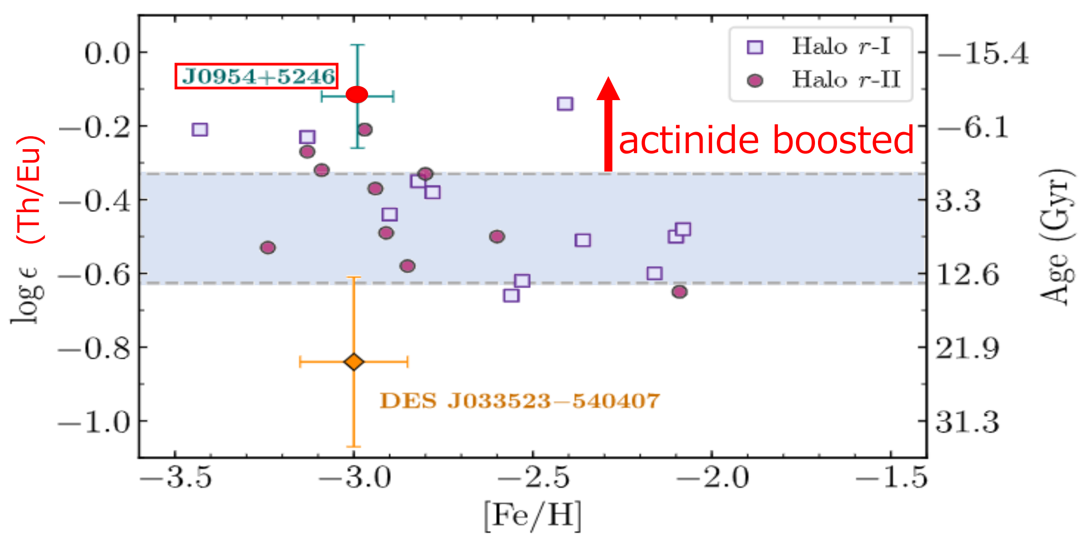
The abundance pattern is the same in Sun (relatively young) and CS22892-052 (old).

Other r-rich metal-poor stars show the same pattern, which indicates that r-process elements are synthesized with the same ratio in the progenitor event (r-process universality).

The actinide-boost star

On the other hand, there is the possibility of multiple events for the origin of the r-process.

Thorium (Th) is synthesized only by the r-process.
About <u>30 % of metal-poor r-process-rich stars</u>, high [Th/Eu] stars (actinide-boost stars) have been found (e.g., Holmbeck et al., 2018).



log ε(Th/Eu)=

log (n_{Th}/n_H)- log (n_{Eu}/n_H)

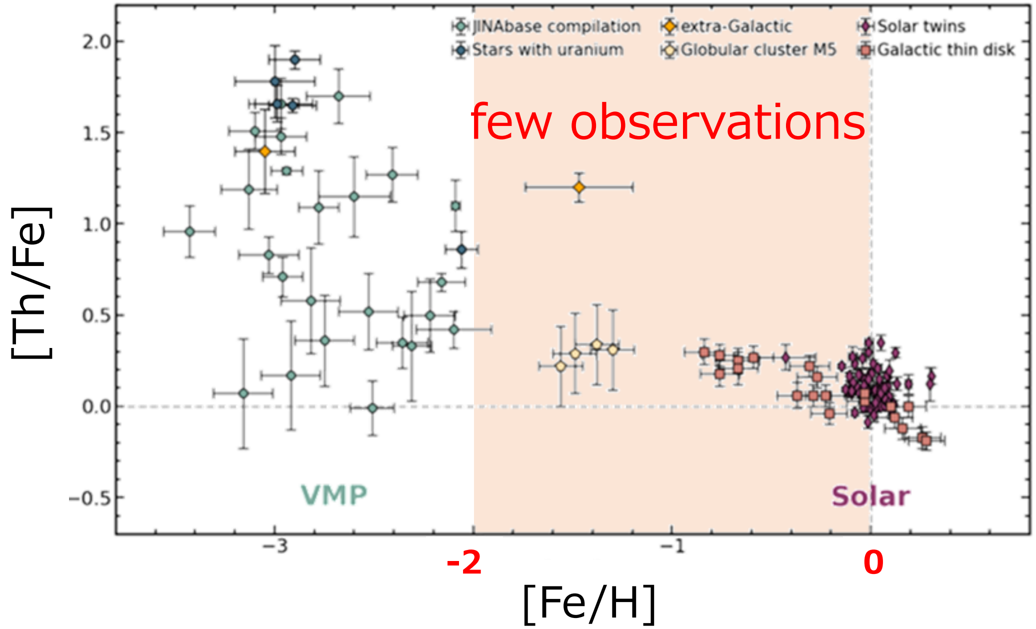
(fig. 6) log ε(Th/Eu) as a function of [Fe/H](Holmbeck et al., 2018)

A few Thorium observations

Th abundances have been observed in metal-poor stars and solar metallicity.

There are a few observations in -2 ≲ [Fe/H] ≲ 0.

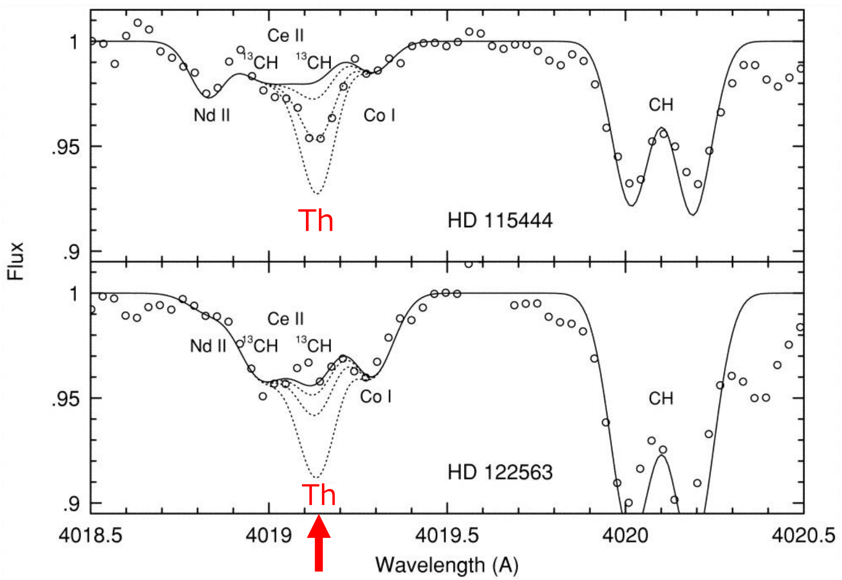
To **constrain the origin of the r-process**, we have to investigate Th abundances in a wide range of metallicity.



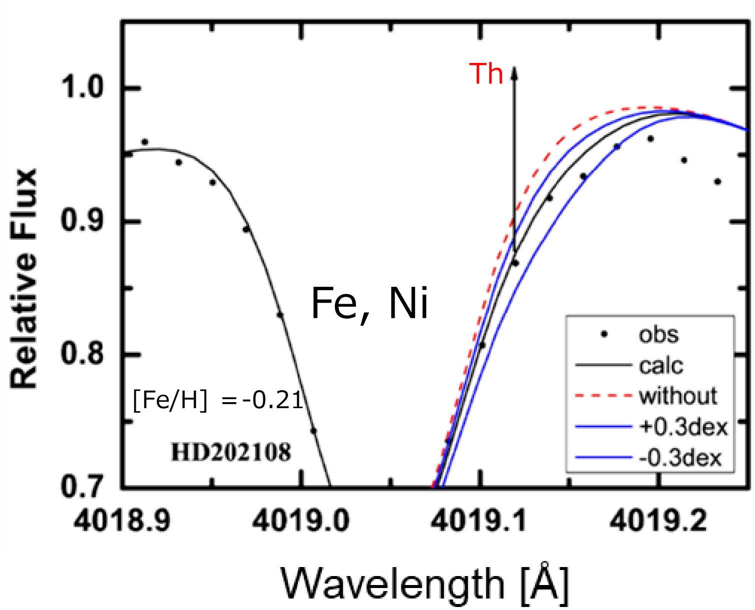
(fig.7) [Th/Fe] as a function of [Fe/H] in previous studies (Holmbeck et al., 2023)

Absorption line of Thorium①

<u>4019 Å</u>
This line is useful and has been used so far, especially **in metal-poor and r-process enhanced stars**.
On the other hand, it is difficult to observe in **high metallicity** because the line blends with other absorption lines (e.g. Fe, Ni).



(fig. 8) 4019 Å absorption line in metal-poor star (Westin et al., 2000).

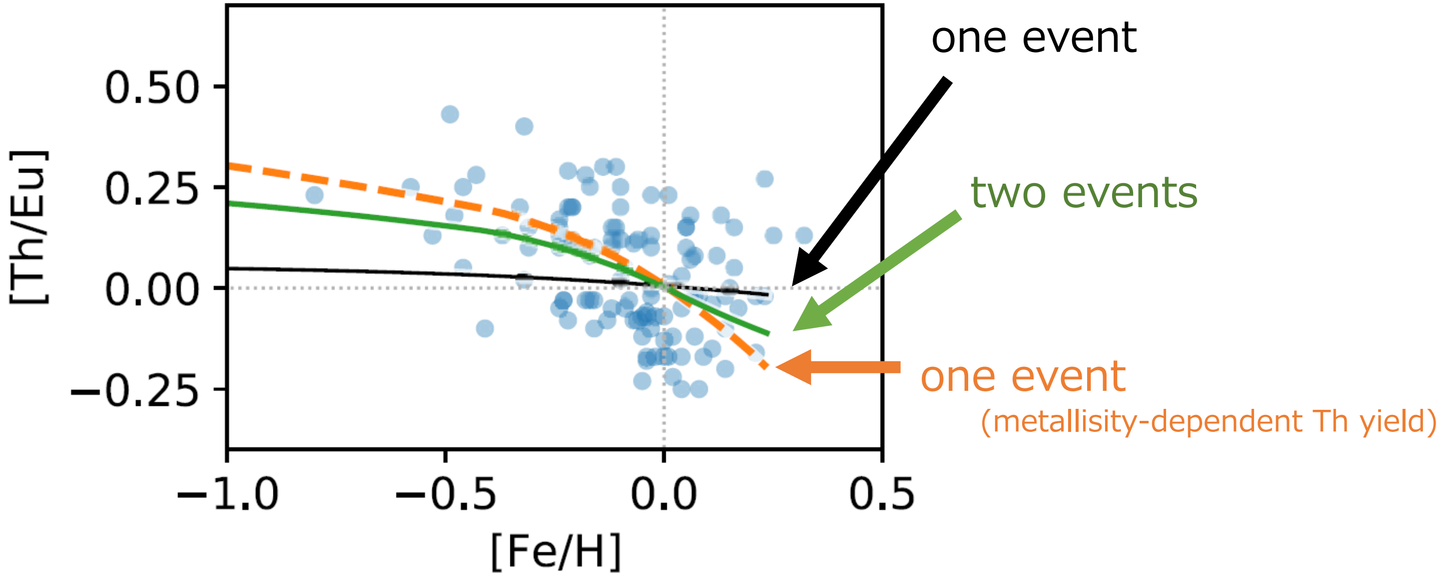


(fig. 9) 4019 Å absorption line in higher metallicity stars (Mishenina et al., 2022).

Observations of Thorium abundance

Th abundances were investigated for <u>main-sequence (metal-rich) stars</u> by using 4019 Å line.

[Th/Eu] shows a decrease as a function of [Fe/H] in solar metallicity.



(fig.10) Observation of [Th/Eu] (Mishenina et al., 2022)

This study suggests that the r-process has **more than one origin** (Mishenina et al., 2022).
It is necessary to observe at middle and lower metallicity with high accuracy.

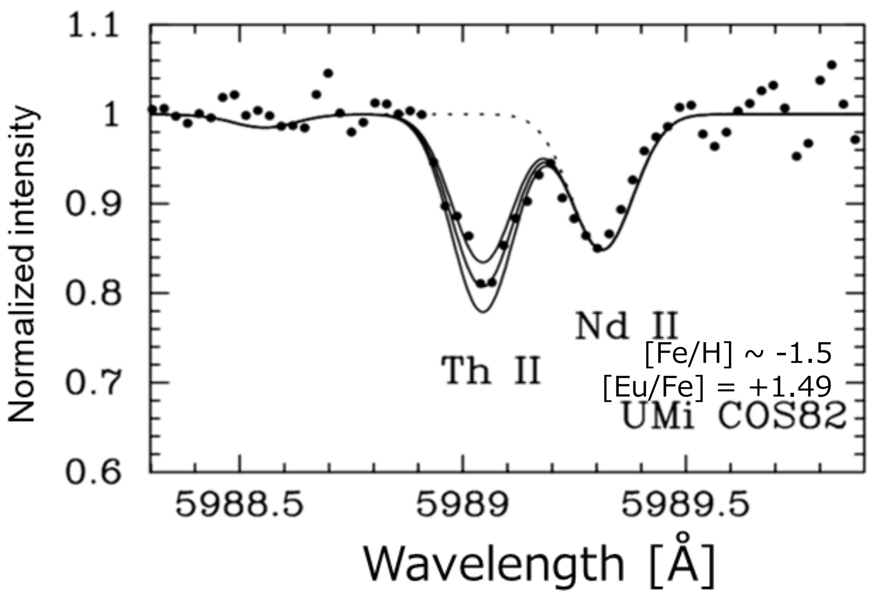
Absorption line of Thorium②

<u>5989 Å</u>

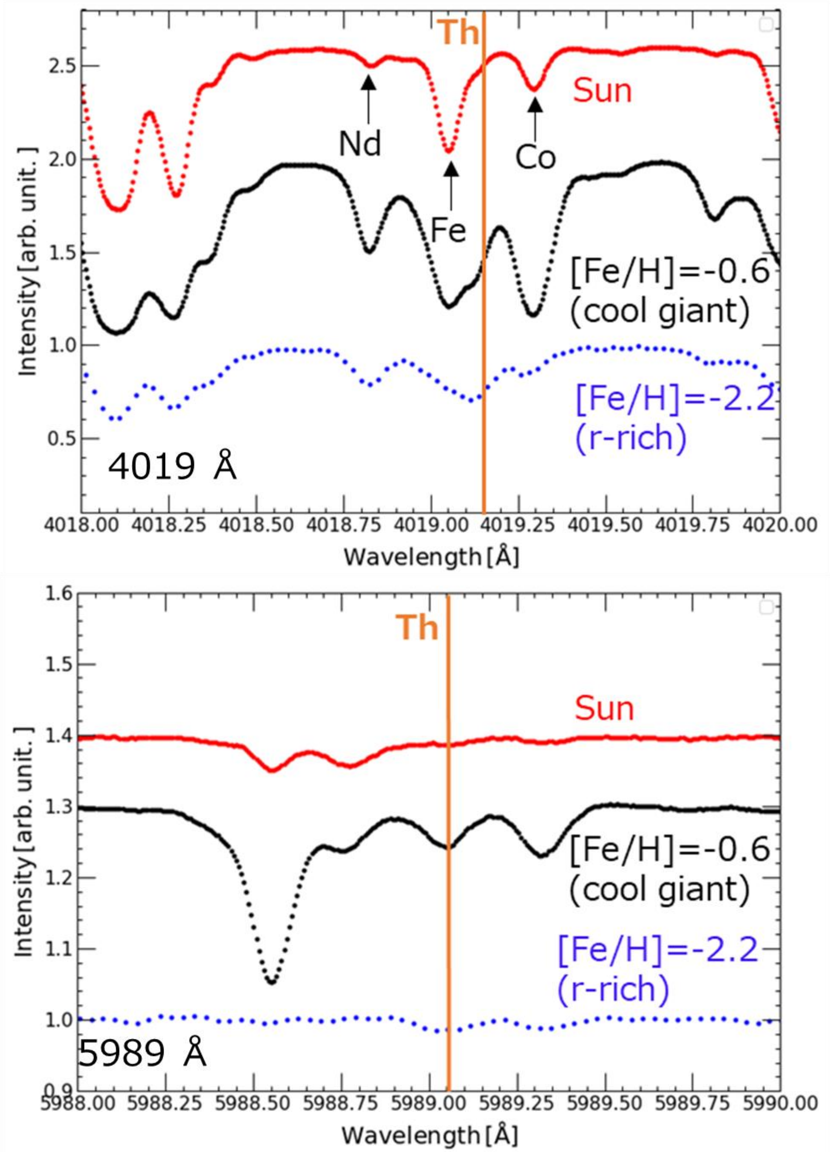
This line will not blend with any other absorption lines.

We might **detect** Th in <u>high metallicity stars</u> by using this line. (Azhari et al., 2025)

We used this line.



(fig. 11) Th absorption line of 5989 Å (Aoki et al., 2007).



(fig. 12) Comparison of 4019 Å and 5989 Å lines.

Aim and Observations

Aim

To approach the origin of the r-process, we aim to detect Th at -2 ≲ [Fe/H] stars by using 5989 Å line.

Observations

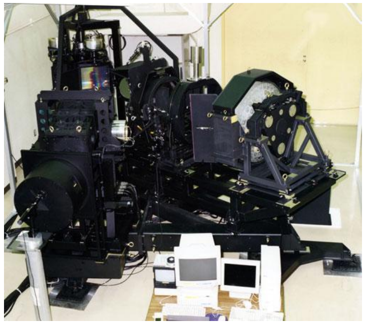
・2 m Nayuta telescope
・MALLS (R~35000)

(fig. 13) Nayuta/MALLS

・150 cm telescope/ Gunma
・GAOES (R~70000)

(fig. 14) Gunma 150 cm/GAOES

・Archived data of Subaru telescope (SMOKA)
・HDS (R~70000)



(fig. 15) Subaru/HDS

We analyzed 36 stars. S/N is 100 – 200, wavelength is 5000 - 7000 Å.

(table.1) Atmospheric parameters for objects

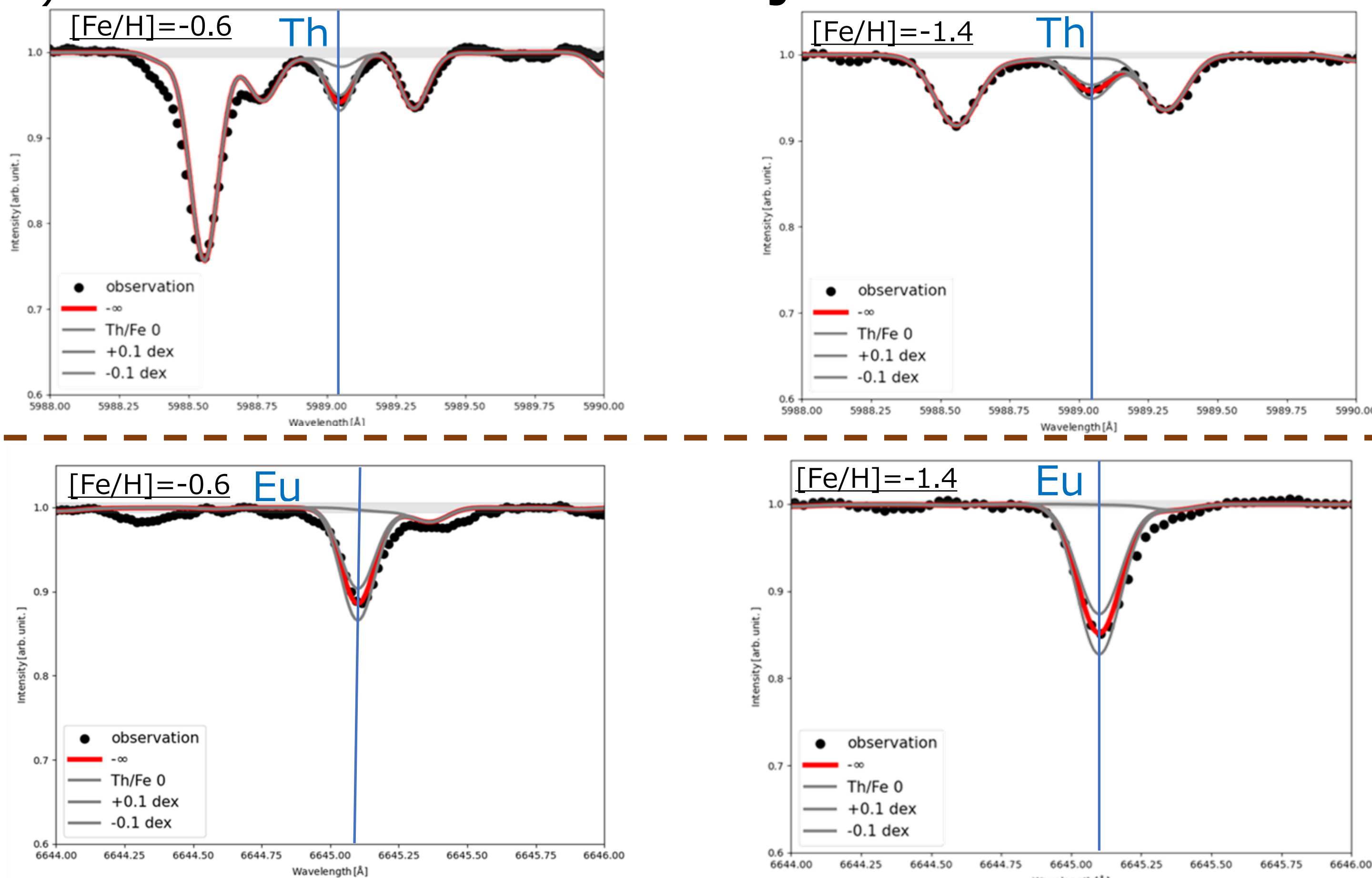
Effective temperature [K]	4000 – 5000
Surface gravity (log g)	1.0 – 3.8
Micro turbulence (V_t) [km/s]	0.7 – 1.8
[Fe/H]	-2.2 – 0.4

Abundance analysis

Atmospheric parameters is obtained from observational spectrum (TGVIT ;Takeda et al., 2005).
Abundances were estimated by comparing observed spectra with synthetic spectra from model atmospheres (SPTOOL; Kurucz 1993, Takeda et al. 2002). **Th was detected in 24 objects.**

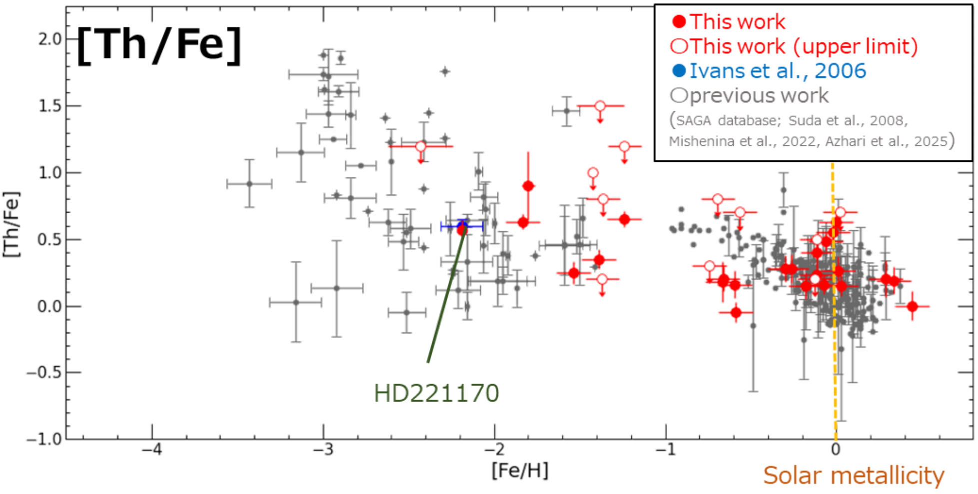
Th
5989 Å

Eu
6645 Å



(fig. 16) Th and Eu observation

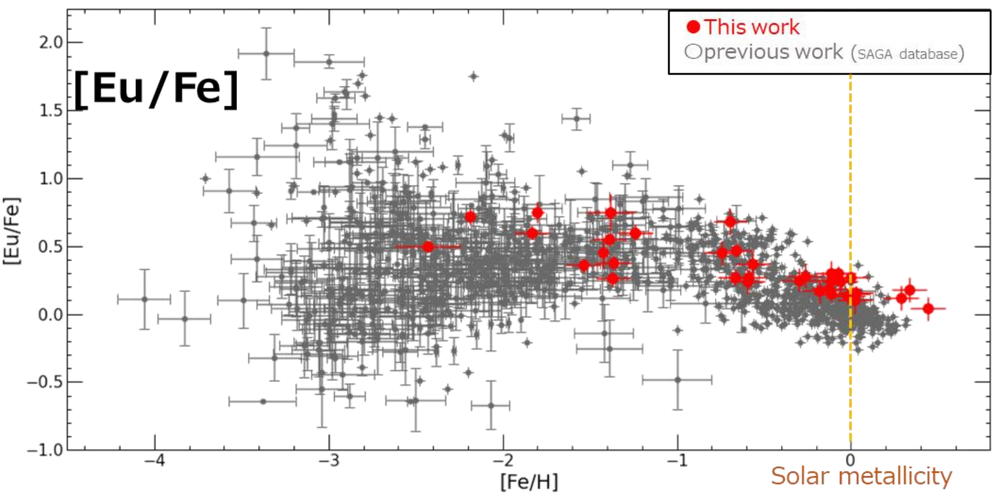
Result abundances of Th and Eu



(fig. 17) [Th/Fe] as a function of [Fe/H]

[Th/Fe] is less than the previous studies in [Fe/H] ~ -0.7 and larger than the previous study in [Fe/H]~0.

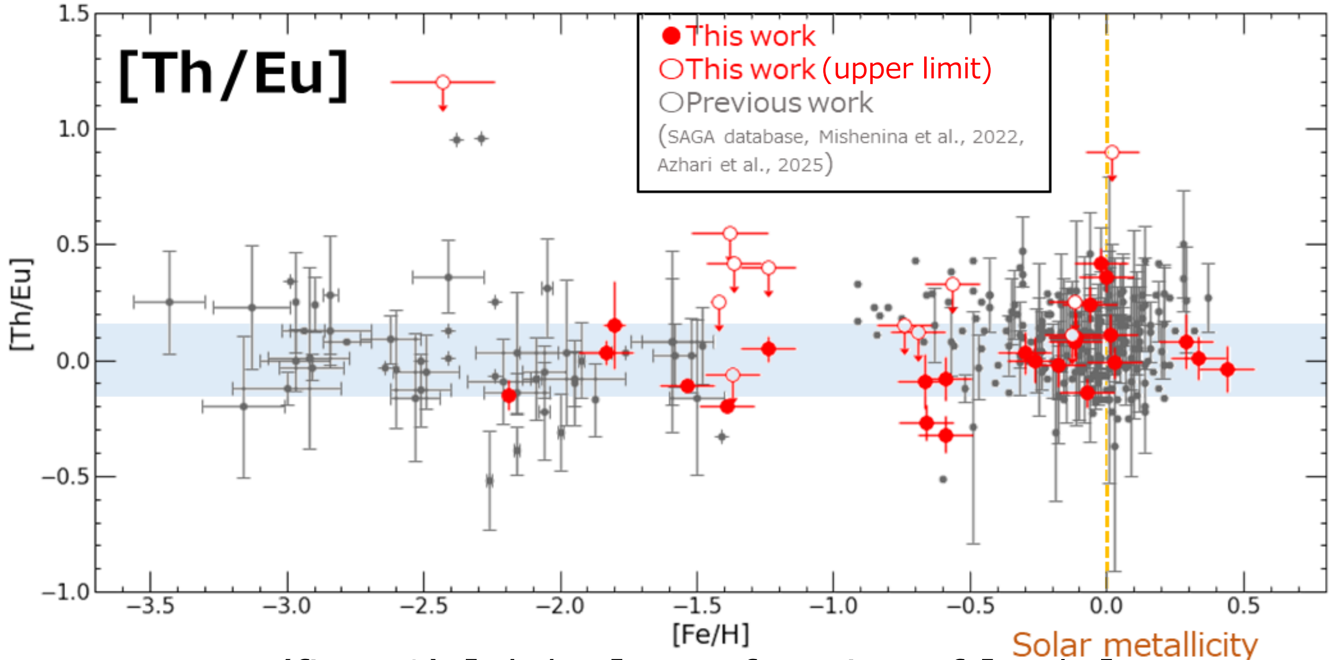
For HD221170,
we confirmed the same [Th/Fe] obtained mainly by using the 4019 Å line (Ivans et al., 2006).



(fig. 18) [Eu/Fe] as a function of [Fe/H]

[Eu/Fe] trend is consistent with previous studies.

Discussion Th/Eu



(fig. 19) [Th/Eu] as a function of [Fe/H].

[Fe/H]<0

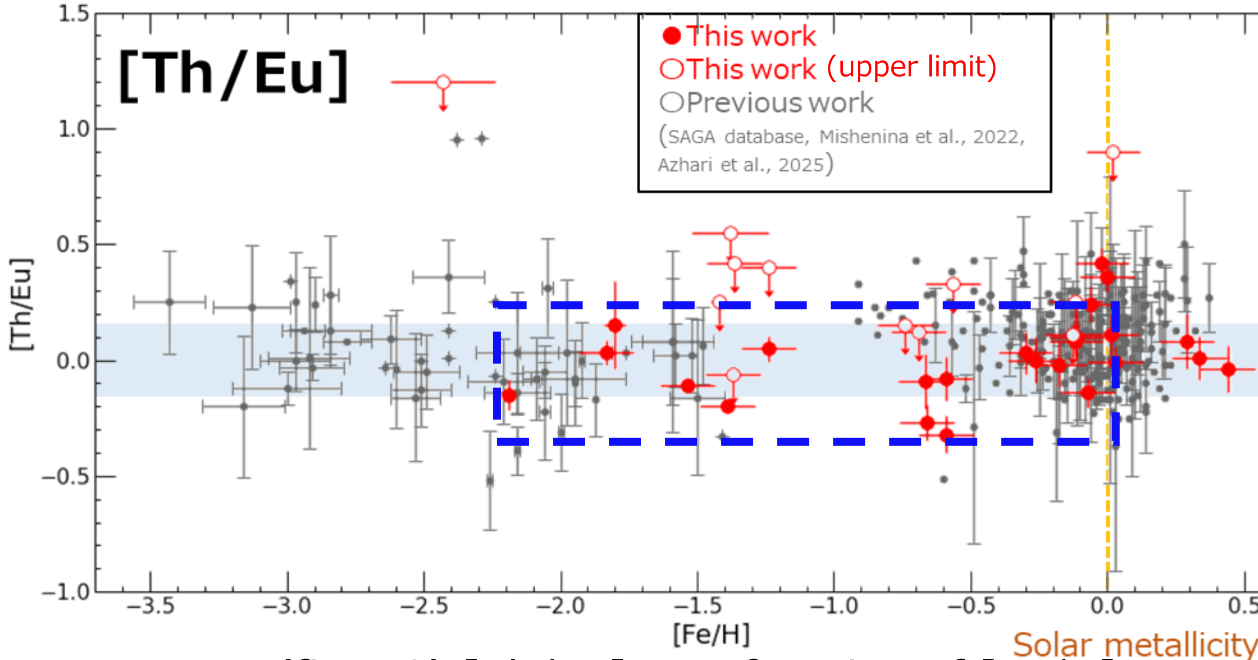
- <u>19 samples are not actinide boost stars.</u>

<u>The fraction of actinide boost stars is less than 30%.</u>

- <u>[Th/Eu] is almost constant.</u>

It suggests that Thorium and Europium are mainly synthesized in a single origin in these stars.

Discussion Th/Eu



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Summary

Problems

It is still a matter of debate whether the origin of the r-process is a single event or multiple events.

Aim

To approach the origin of the r-process, we aim to detect Th at -2 ≲ [Fe/H] stars by using 5989 Å line.

Result

We analyzed 36 objects. Th was detected in 24 objects.

[Fe/H]<0

- **19 samples are not actinide boost stars.**

  The fraction of actinide boost stars is less than 30%.
- **[Th/Eu] is almost constant.**

Discussion

Thorium and Europium are mainly synthesized in a single origin in these stars.

Future work

To investigate the contribution of other processes, we'll investigate other elements.
We want to detect Th, especially [Fe/H] ~ -1.

Thank you for your attention.