銀河化学進化から迫る
中性子捕獲元素の起源

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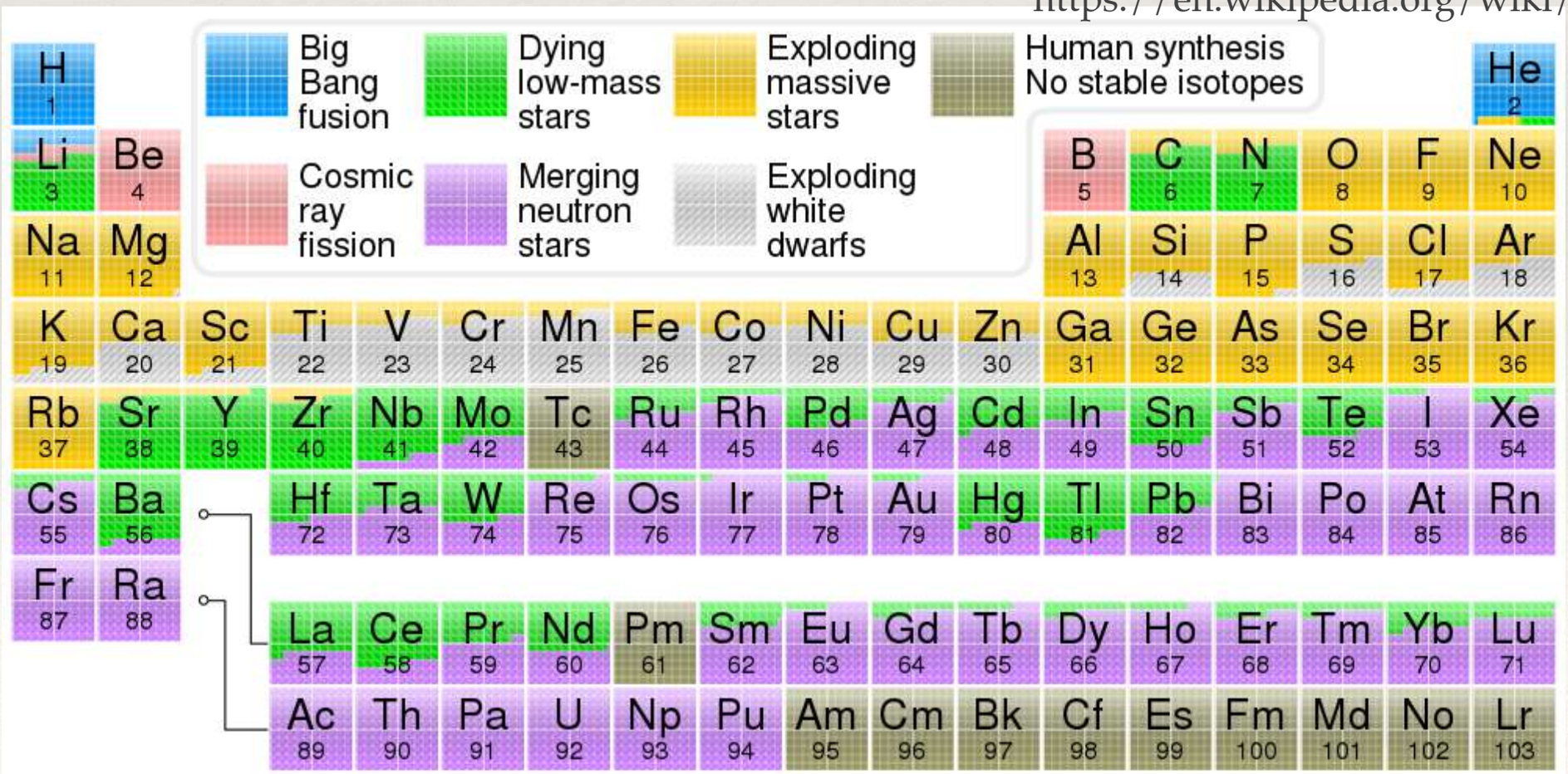
Elements in the Universe

- Elements are synthesized in high-density environment.
- Stars, compact objects, …

https://en.wikipedia.org/wiki/Nucleosynthesis



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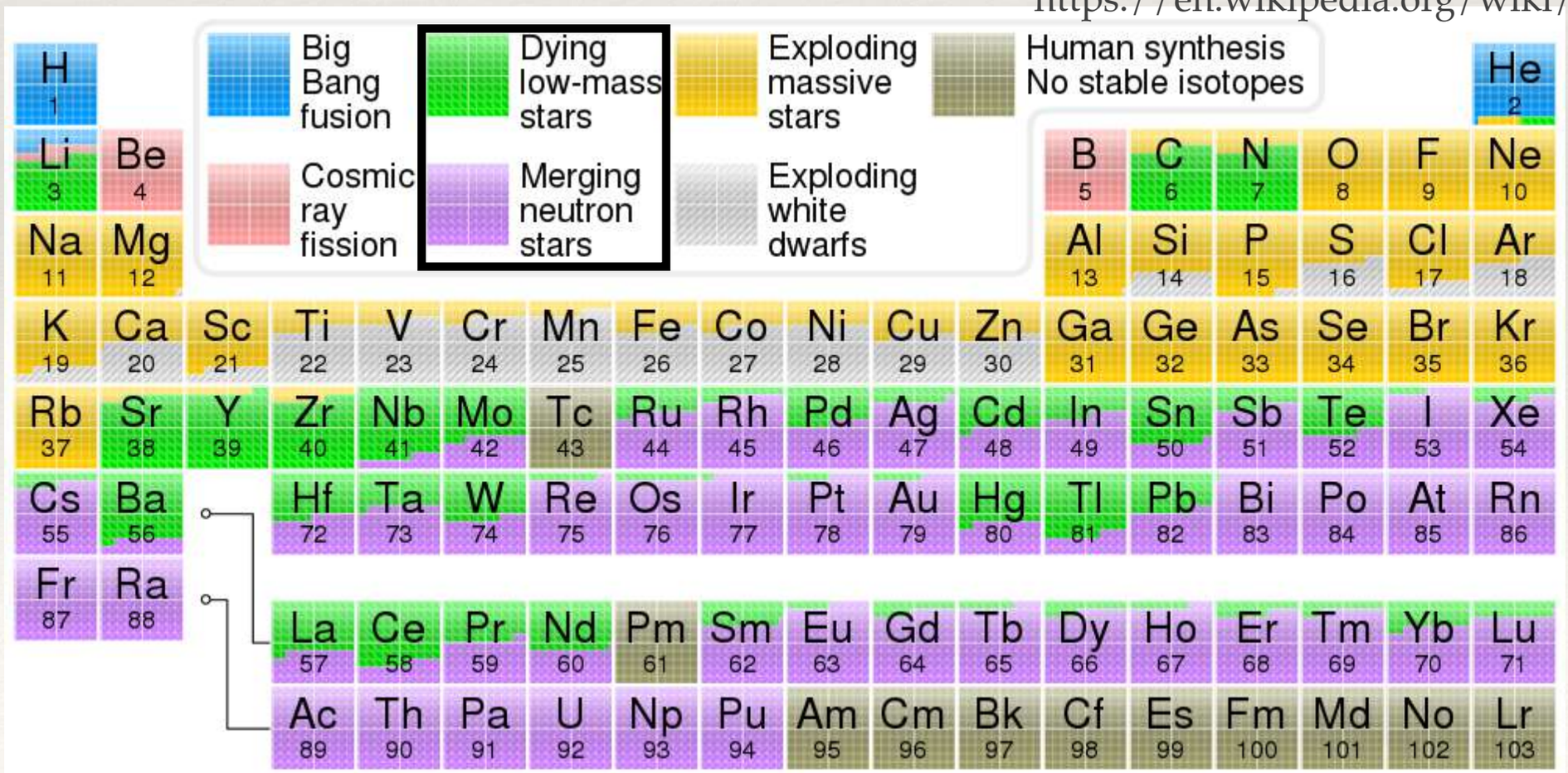
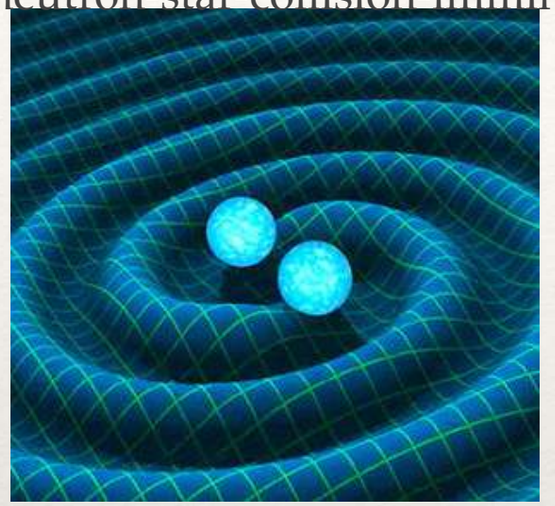
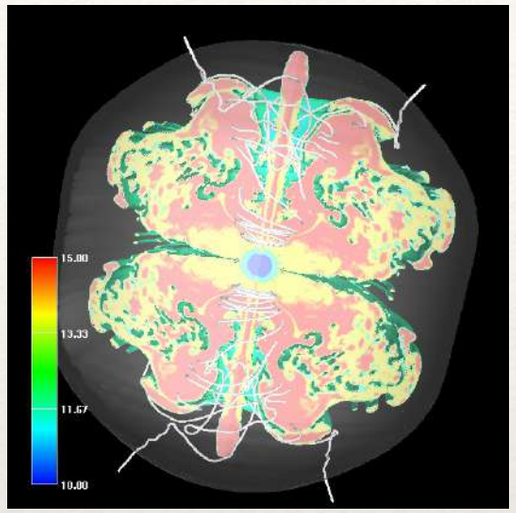


What is the origin of r-process elements?

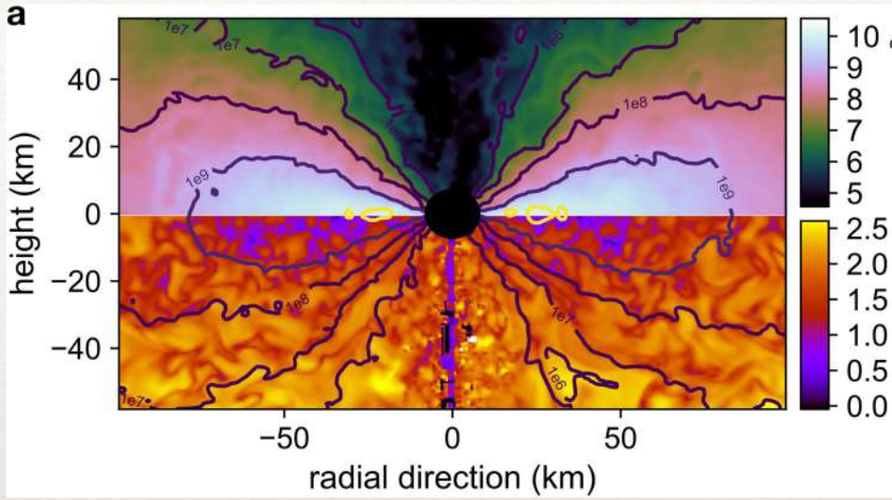
https://aasnova.org/2021/01/06/warning-neutron-star-collision-imminent/



Nishimura+17



Siegel+19



Neutron-Star Merger

- r-process is observationally confirmed
- Too long delay time?

Magneto-Rotational supernova

- r-process may happen
- Short delay time, consistent with r-process trend at [Fe/H] > -1

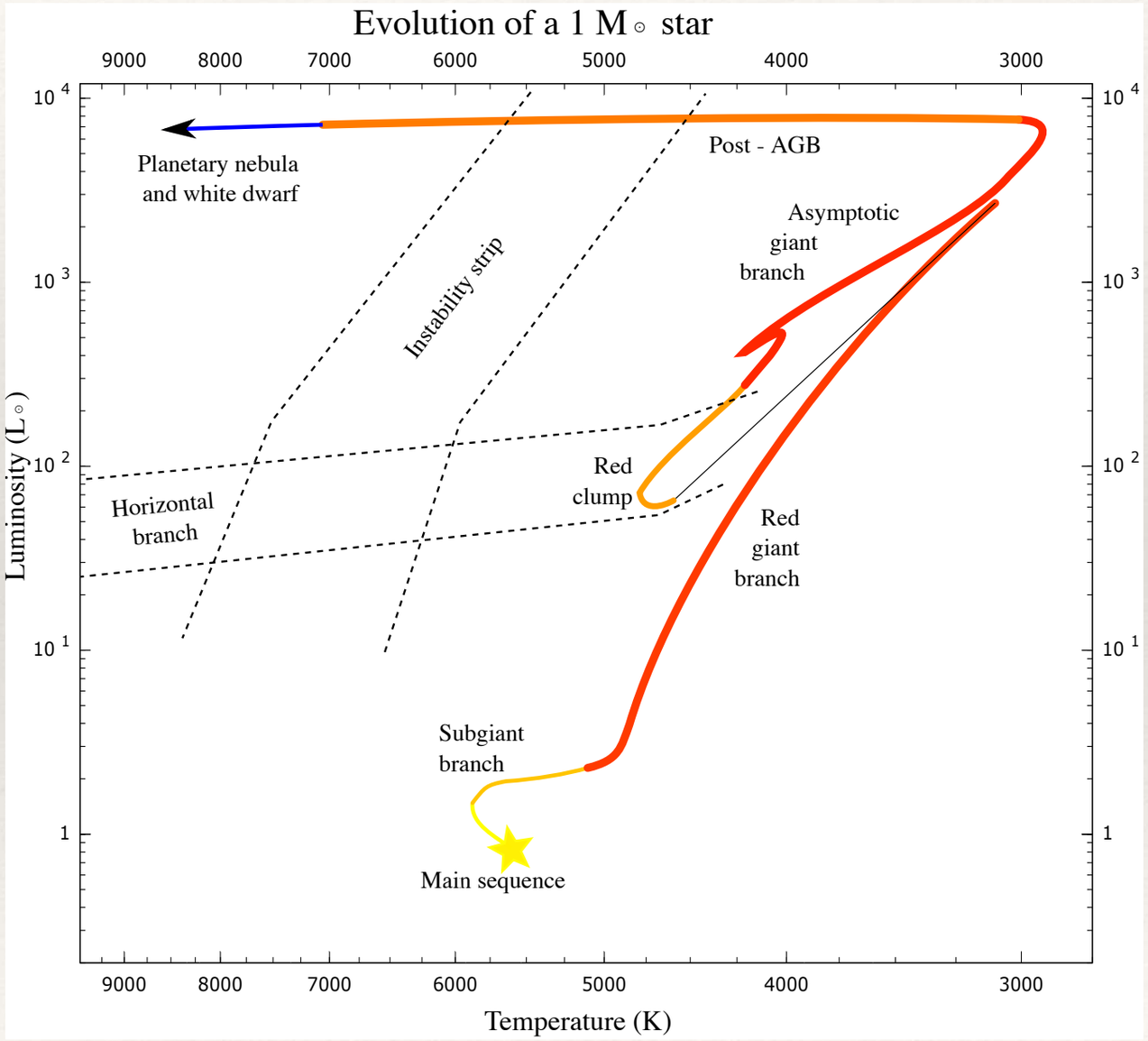
Collapsar

- r-process may happen
- Negative delay time?

S-process in AGB stars

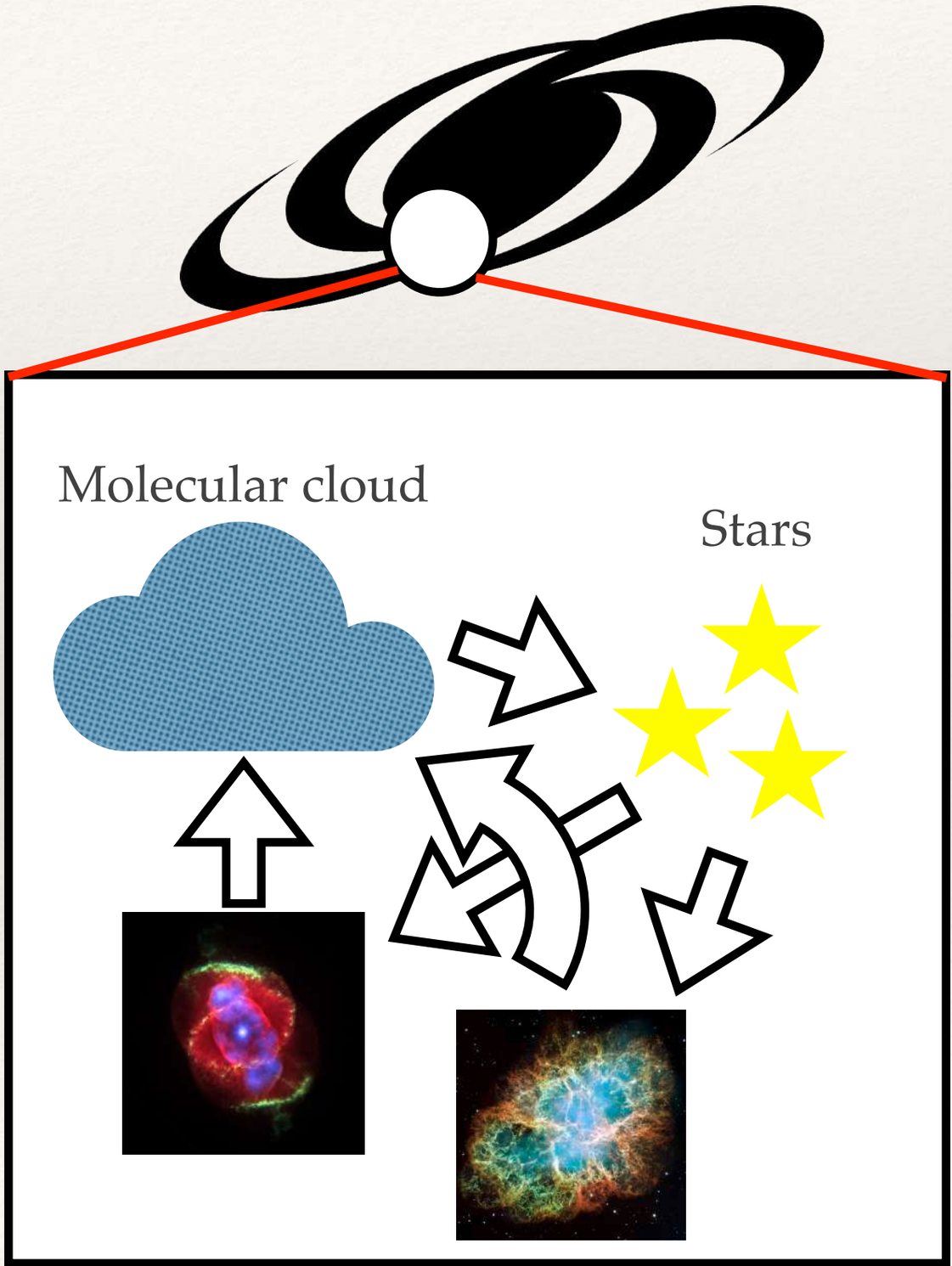
Figure from https://en.wikipedia.org/wiki/Asymptotic_giant_branch

- ^{99}Tc is observed in Ba-enhanced giants of AGB stage
- During H, He shell burning, convection mixes layers and produce ^{13}C via $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^{+}\nu)^{13}\mathrm{C}$
- $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ reaction produces neutrons



Chemical enrichment of a galaxy

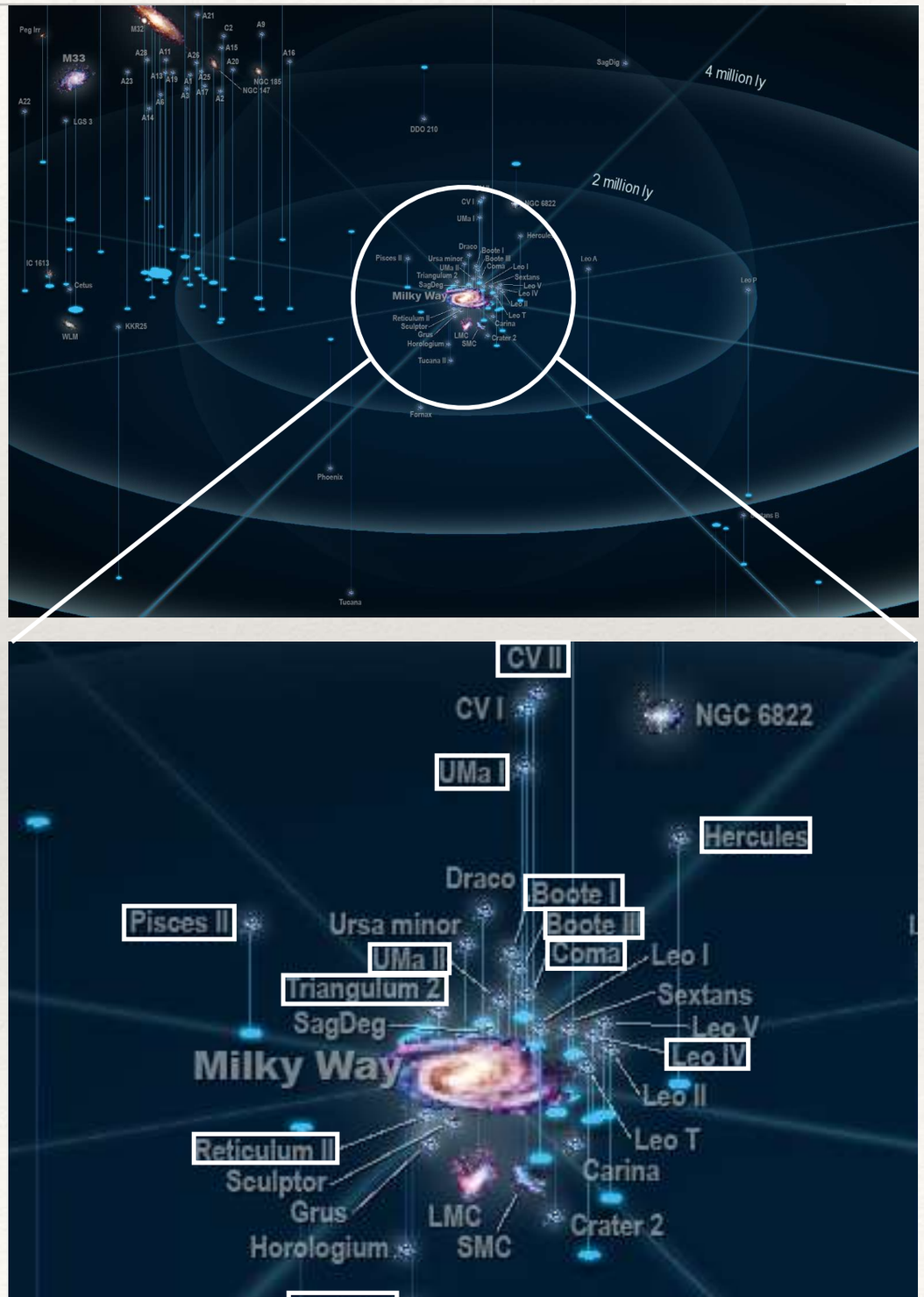
- Stars imprint the chemical abundances of the natal cloud
- Spectroscopy reveals the elemental abundances of stars
- What can we learn from them?



Local group galaxies

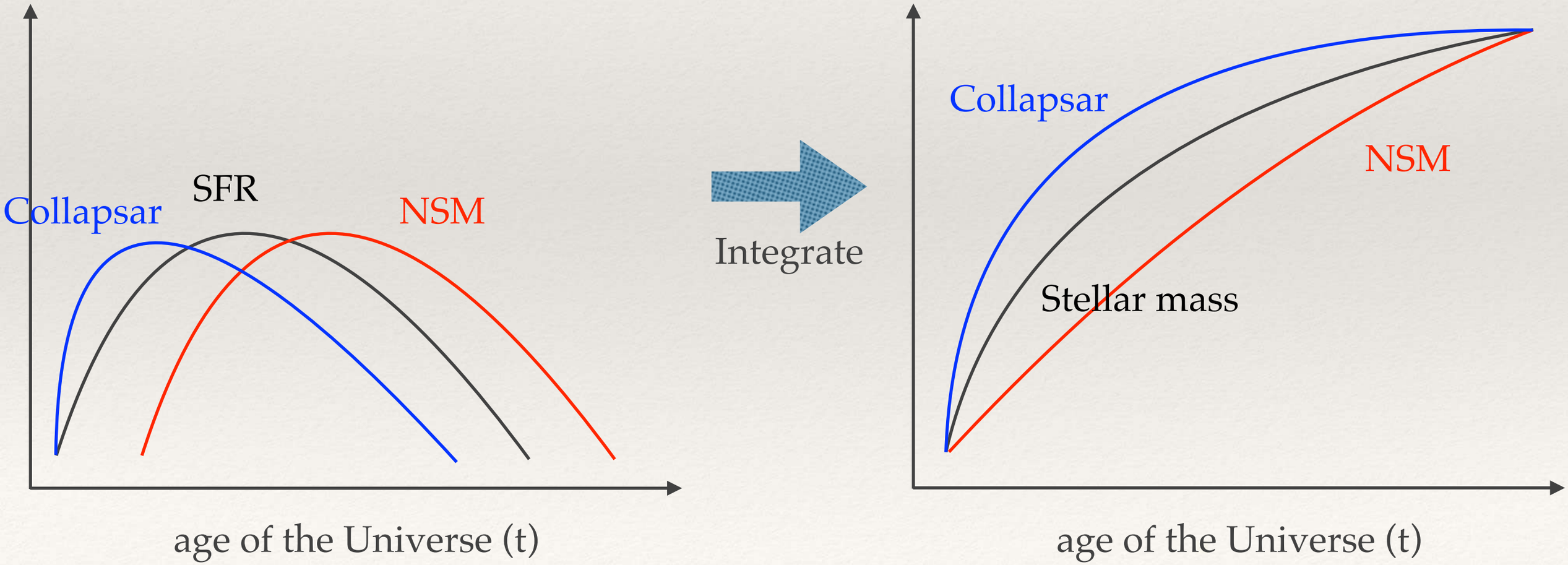
https://en.wikipedia.org/wiki/Local_Group

	Stellar Mass
MW	$10^{10.5}$
Classical dwarf	$10^{5} – 10^{9}$
Ultra-faint dwarf	$10^{2.5} – 10^{5}$
Globular cluster	$10^{5} – 10^{7}$



Delay time

- Time difference between formation of progenitor and production of r-process elements



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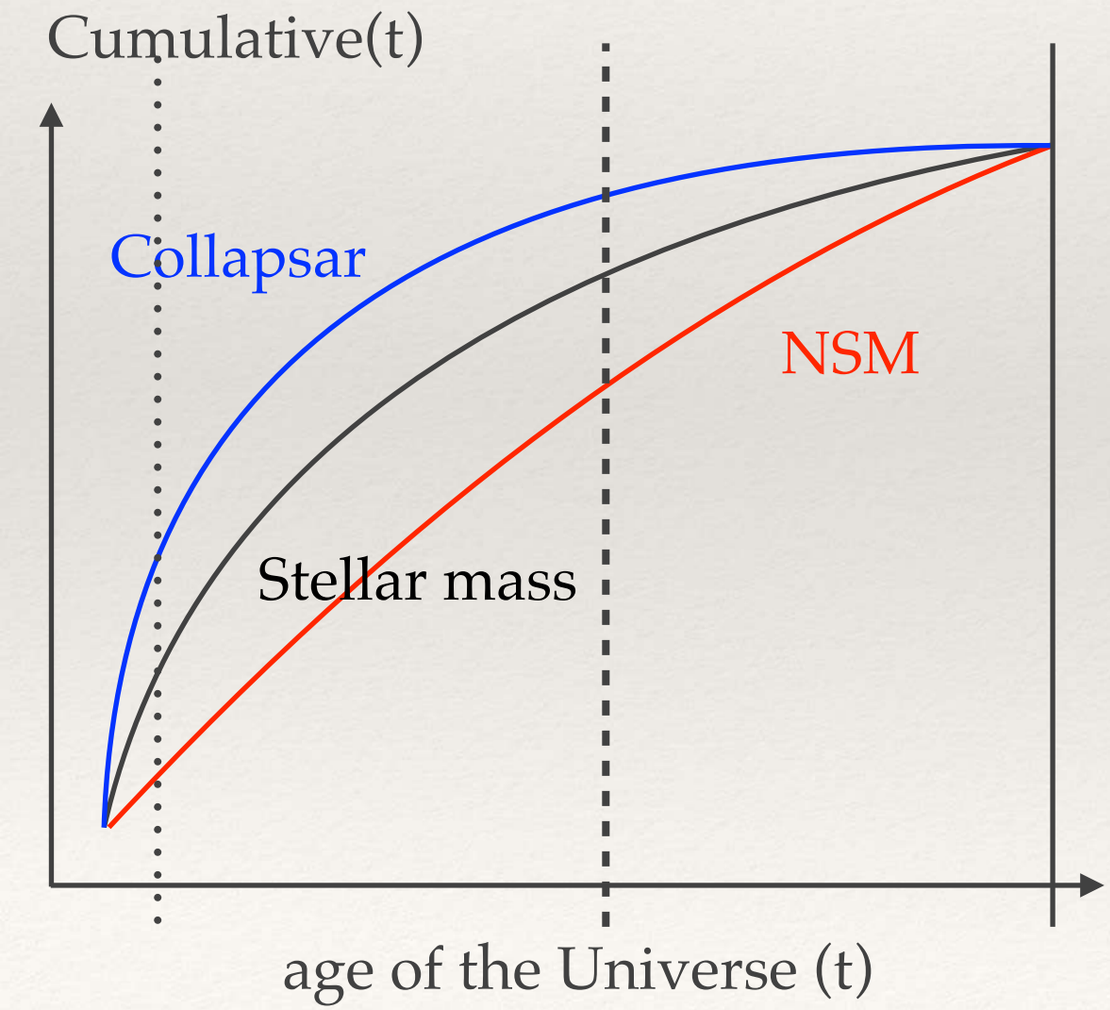
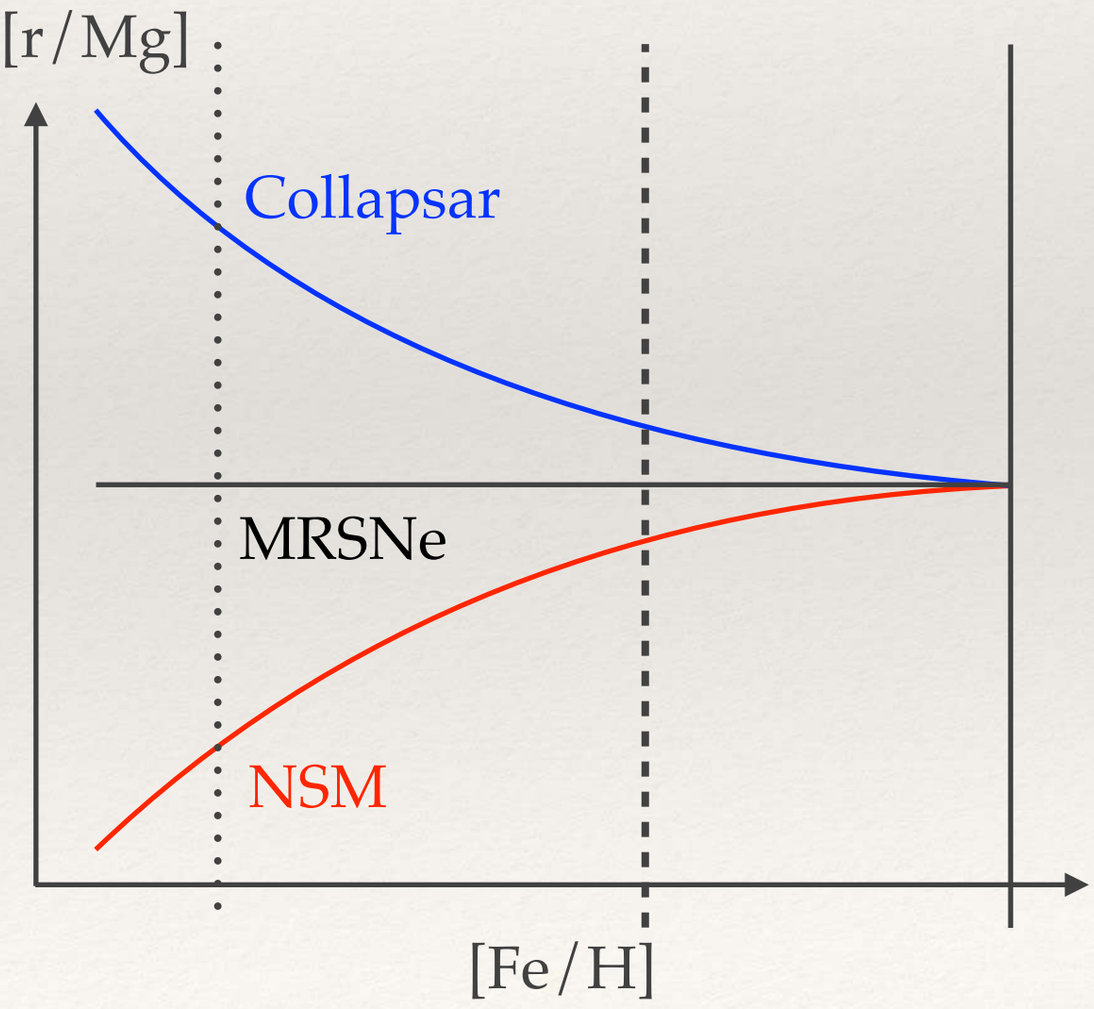
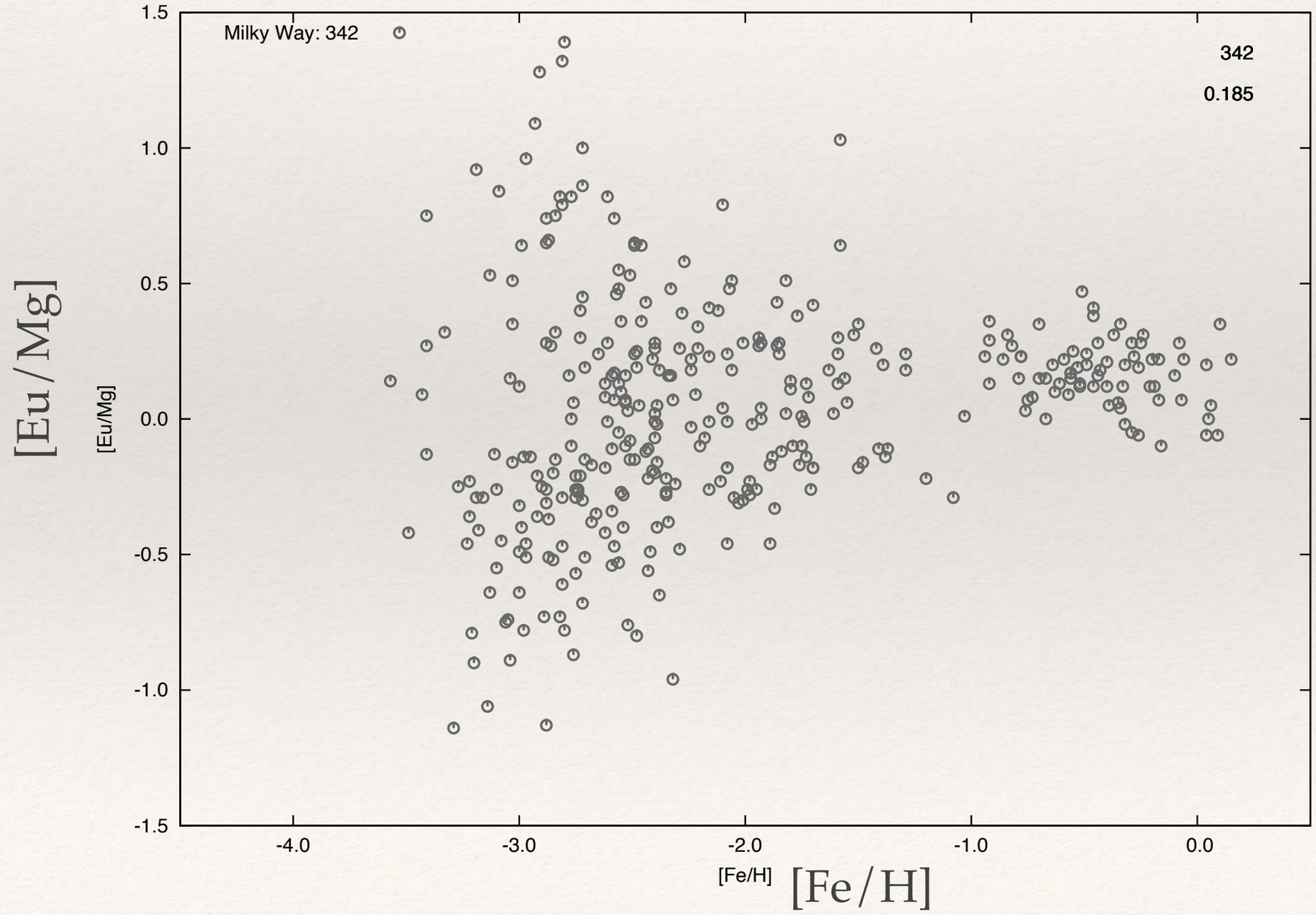




r-process in MW

- Flat and diverging?



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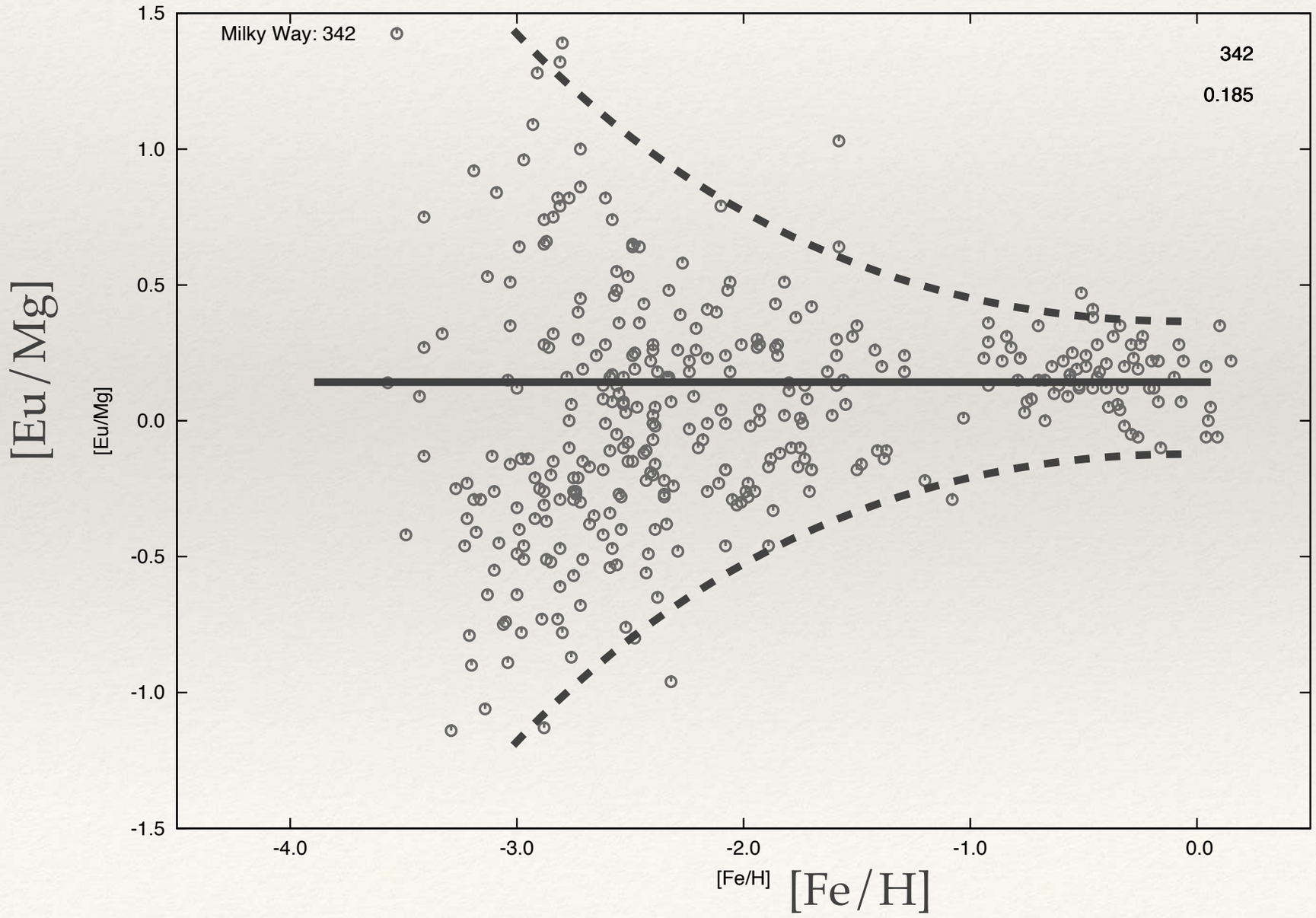
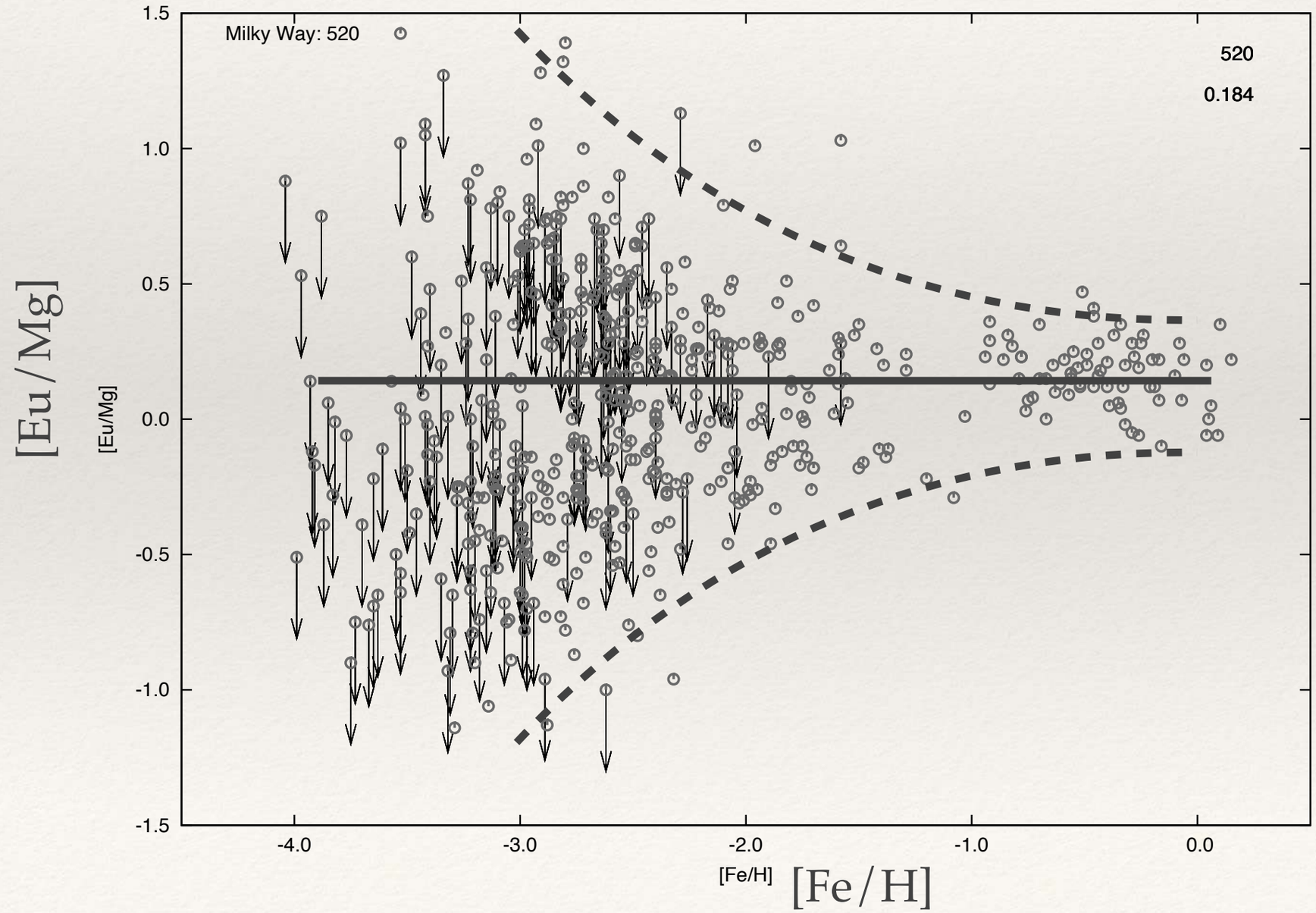


r-process in MW

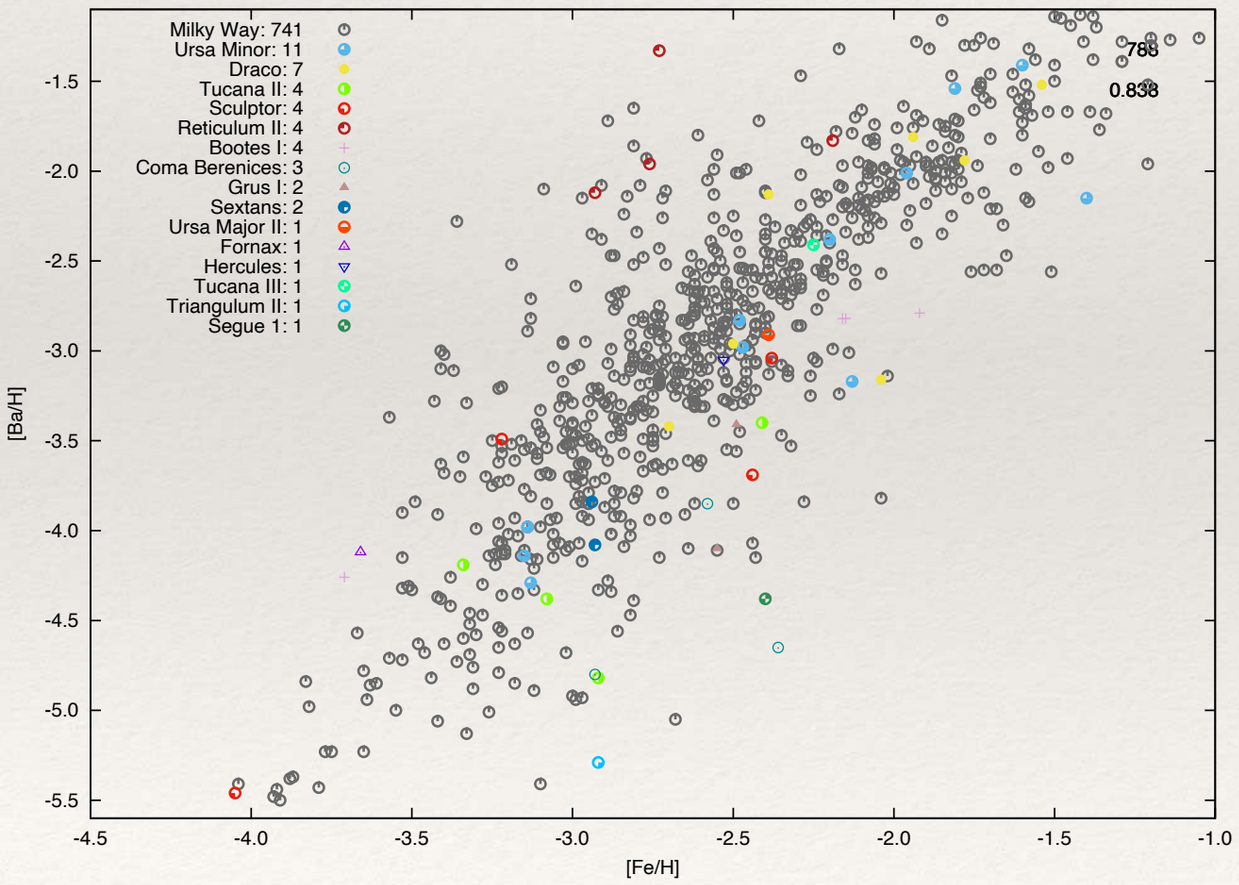
- Flat and diverging, but too many upper limits



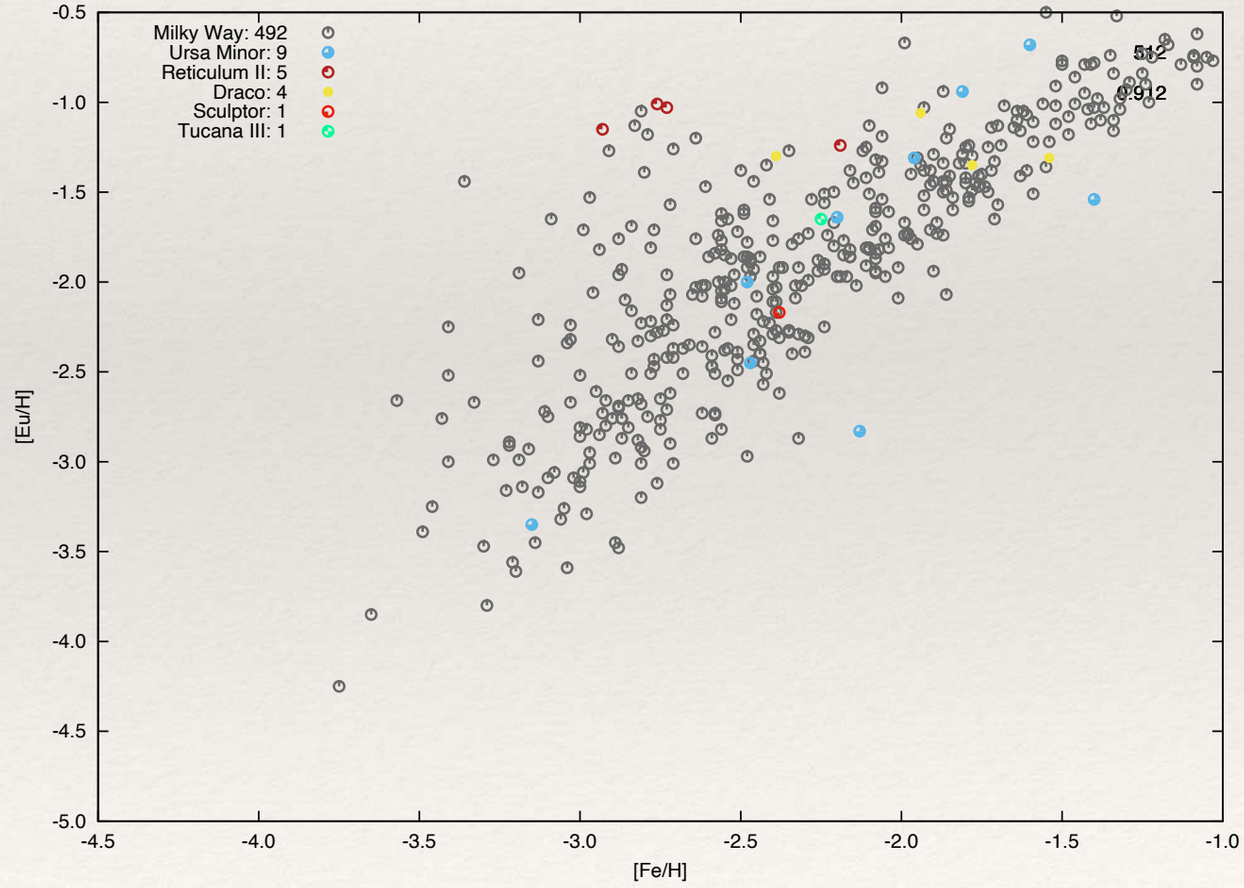
Ba as the r-process tracer

- Is Ba appropriate as the r-process tracer?

Ba



Eu



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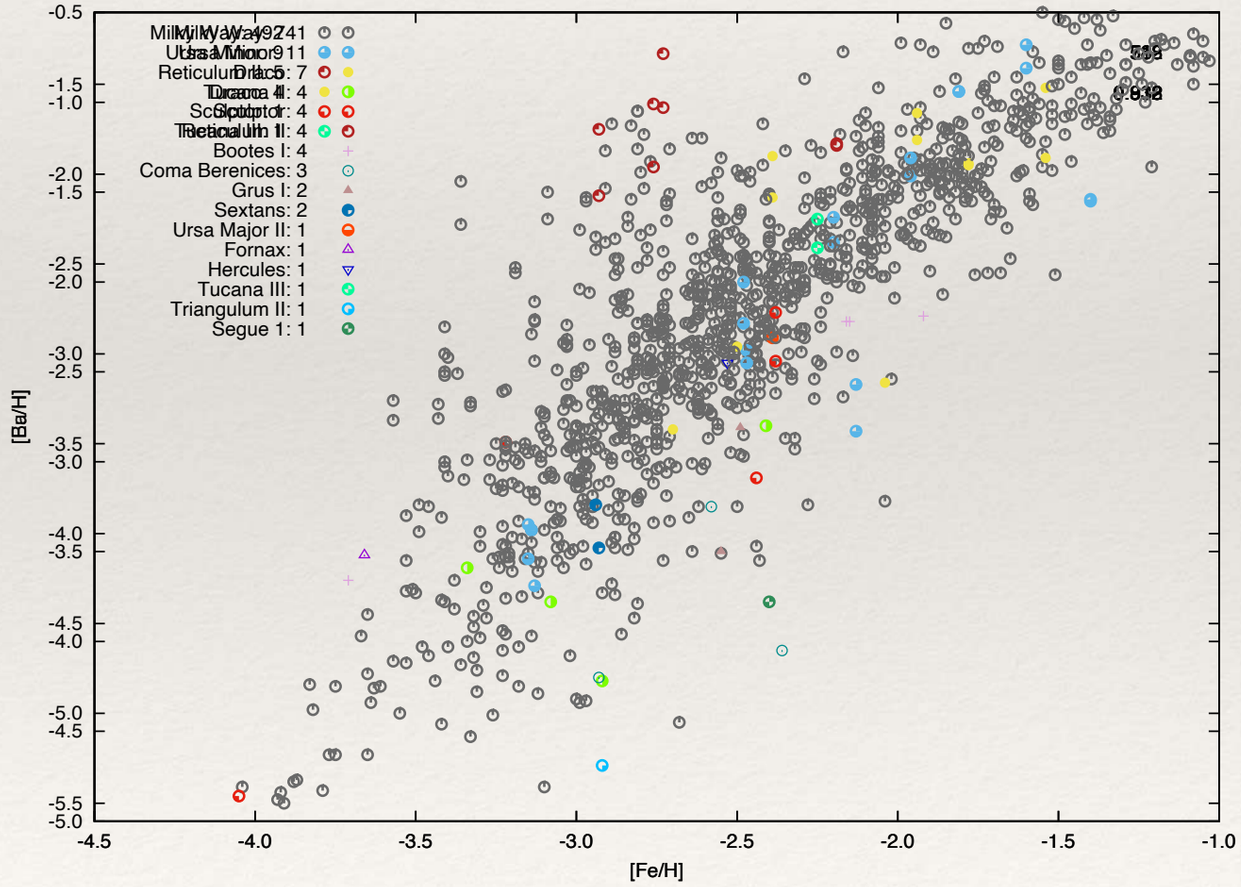
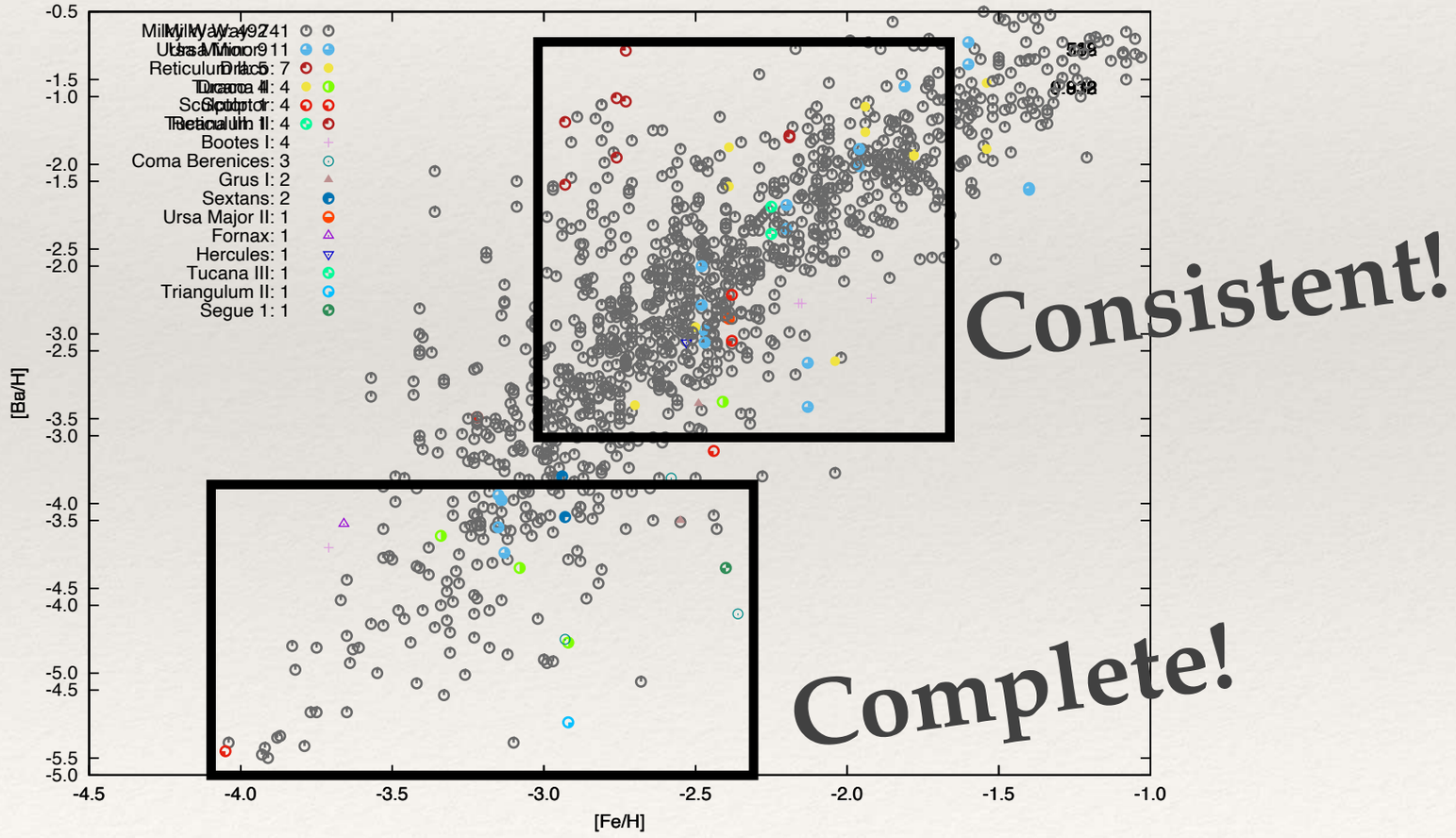


Ba as the r-process tracer

- Is Ba appropriate as the r-process tracer? → **Yes!**

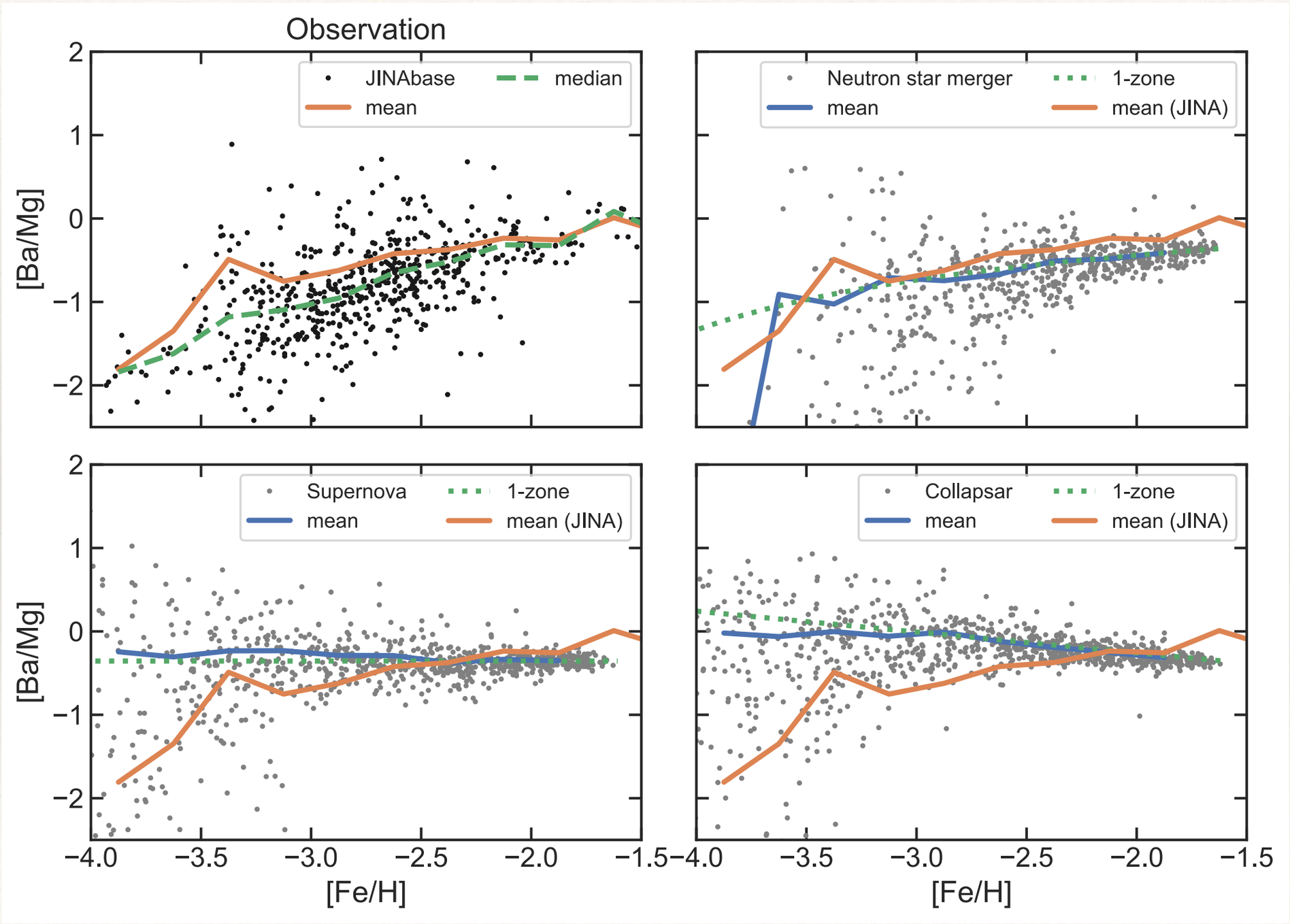
Ba Eu



Consistent!

Complete!

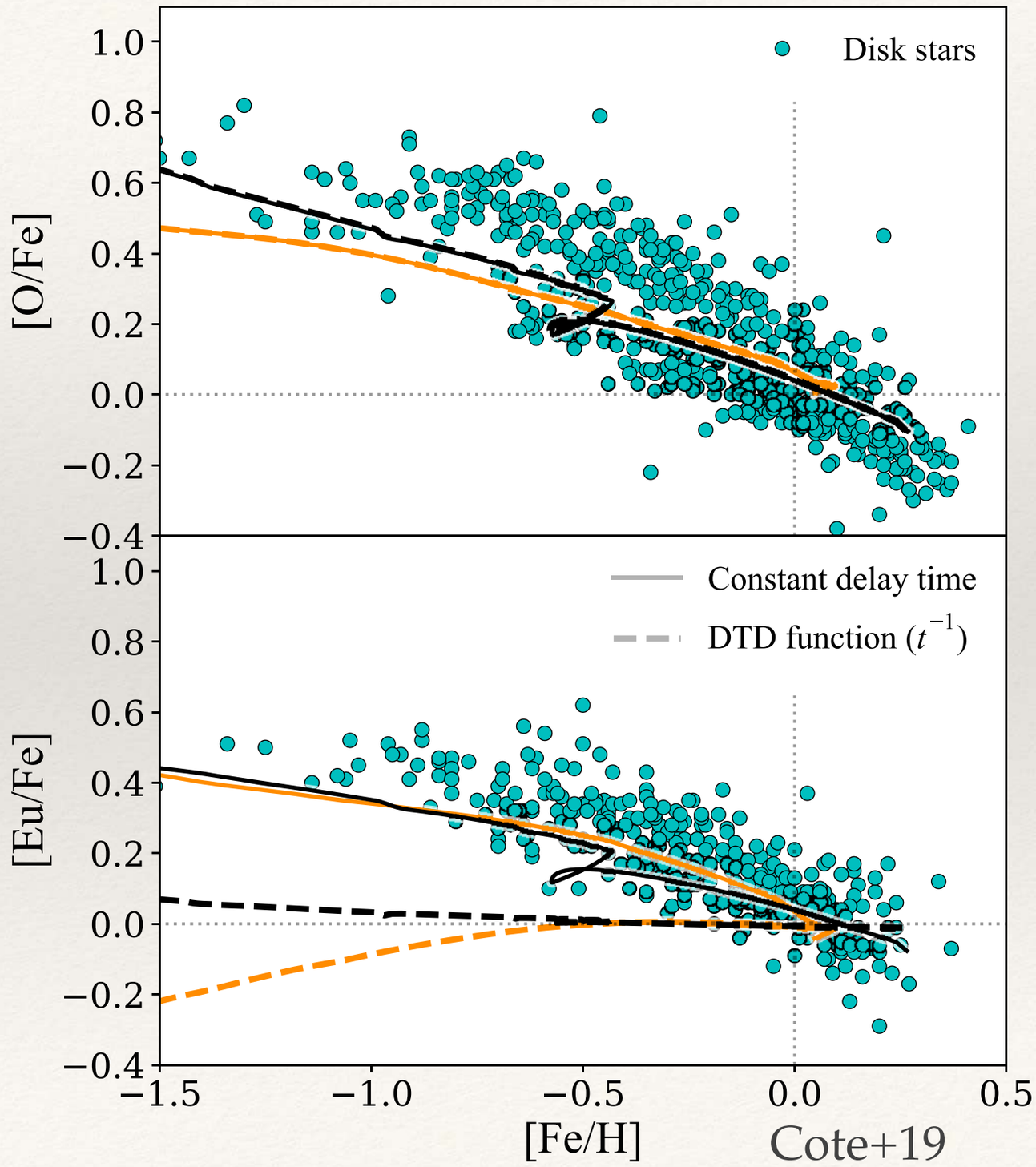
r-process in MW (metal-poor)



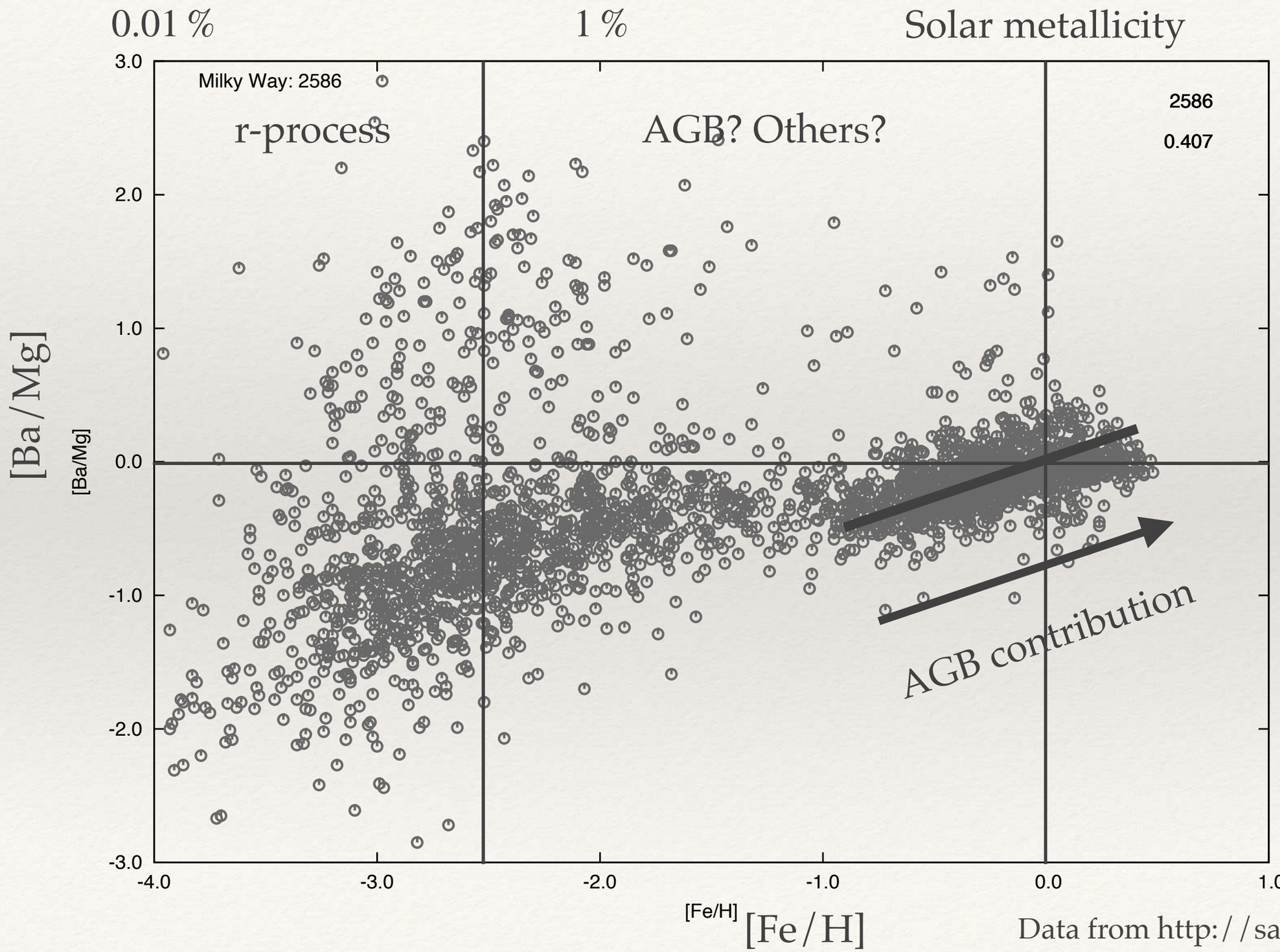
Tarumi+21

r-process in MW (metal-rich)

- Metal-rich regime shows no delay
- "2-phase ISM model" (Schoenrich+19), "natal kick" (Banerjee+20), …

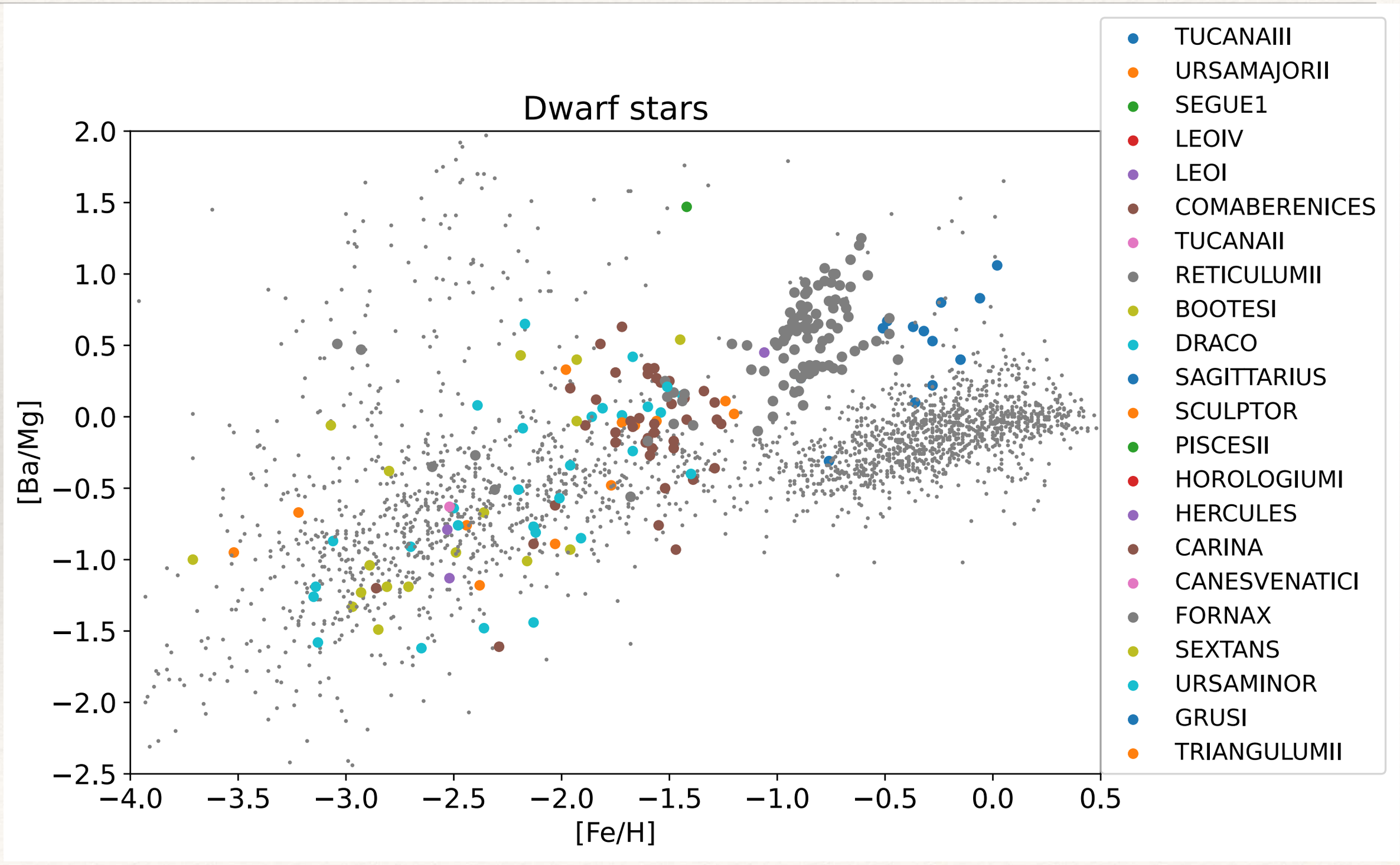


Barium in Milky Way



Data from http://sagadatabase.jp/

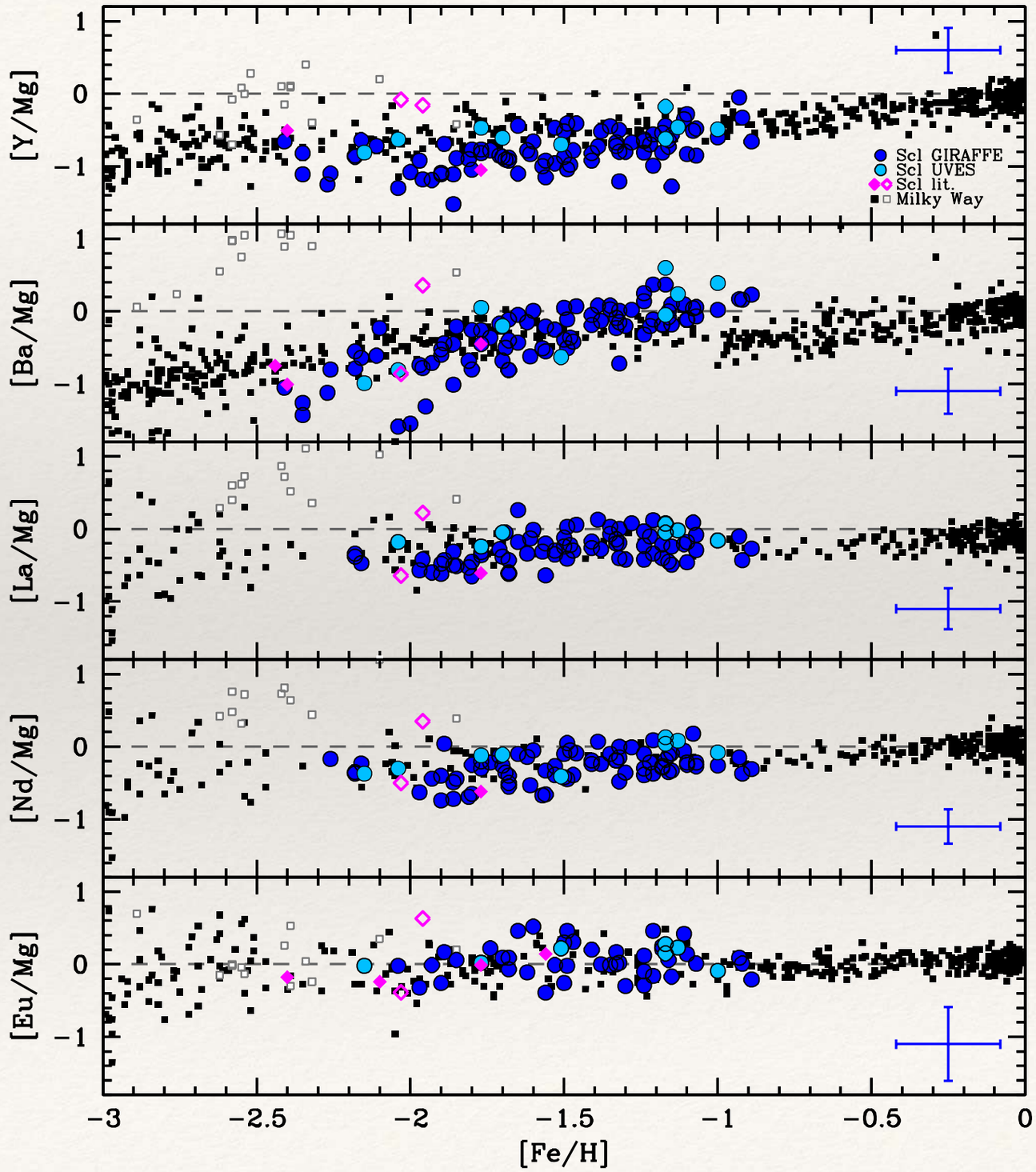
Classical dwarfs



Classical dwarf: Sculptor

Skuladottir+19

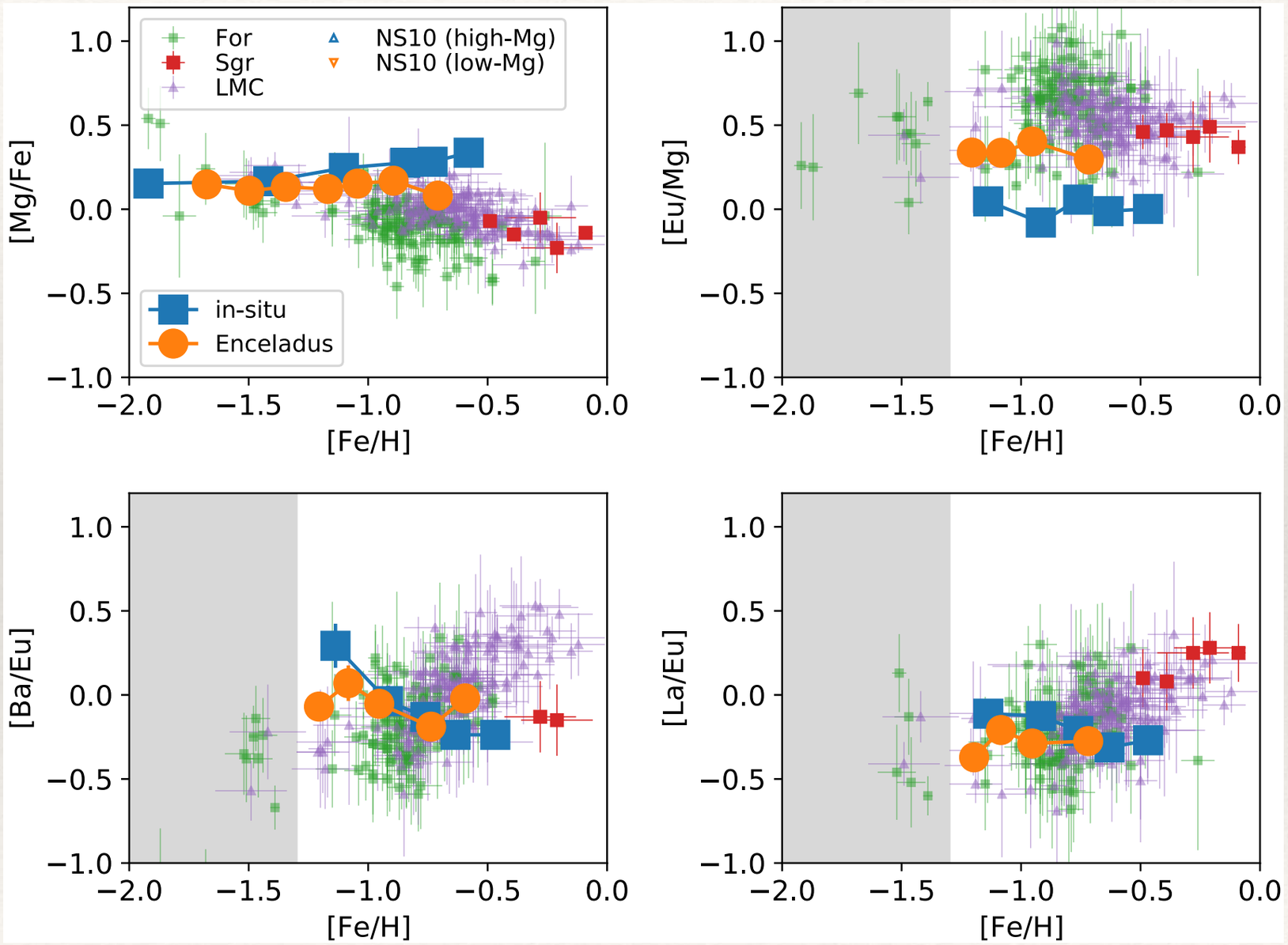
- [Ba/Mg] increase: s-process delay
- [Eu/Mg] flat: no r-process delay



Disrupted classical dwarf: Gaia Enceladus

Matsuno+21

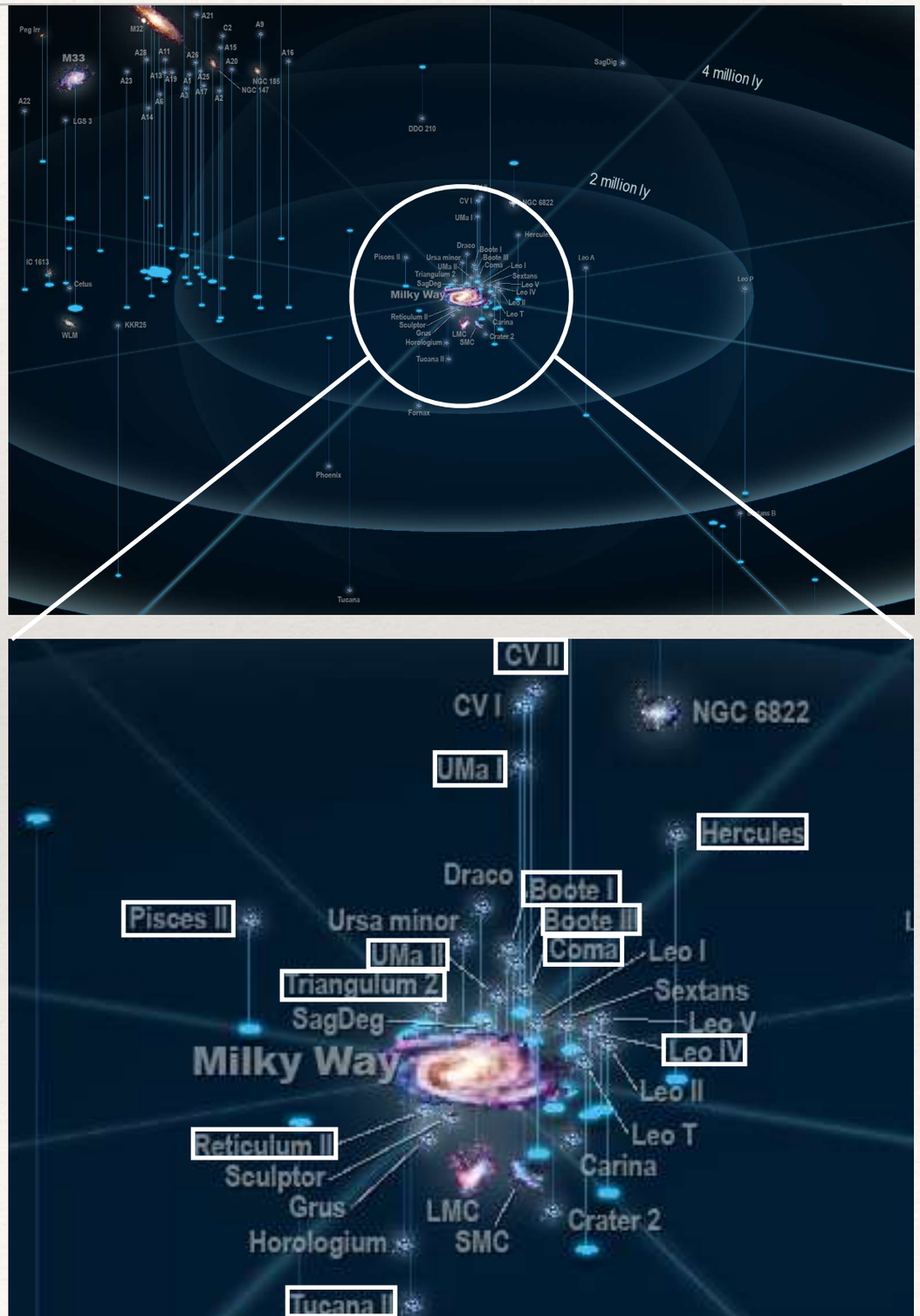
- Gaia-Enceladus is r-rich, could be similar to some classical dwarfs



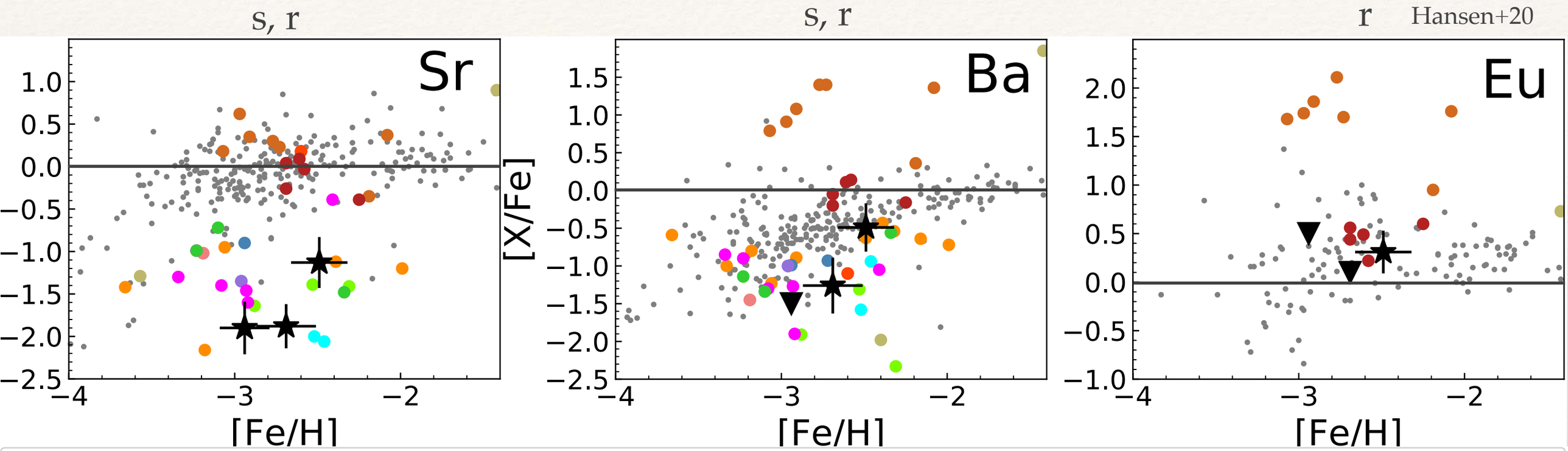
What are / Why UFDs?

https://en.wikipedia.org/wiki/Local_Group

- UFDs are small (< 10^5 Lsun) satellite galaxies.
- UFDs are old.
  - Good probe for high-z galaxy.
- Small stellar mass: “0 or 1 rare&prolific r-process”.
- **Small but important !**



r-process elements in UFDs



$$[X/Y] = \log_{10}\left[\frac{N_X}{N_Y}\right] + C$$

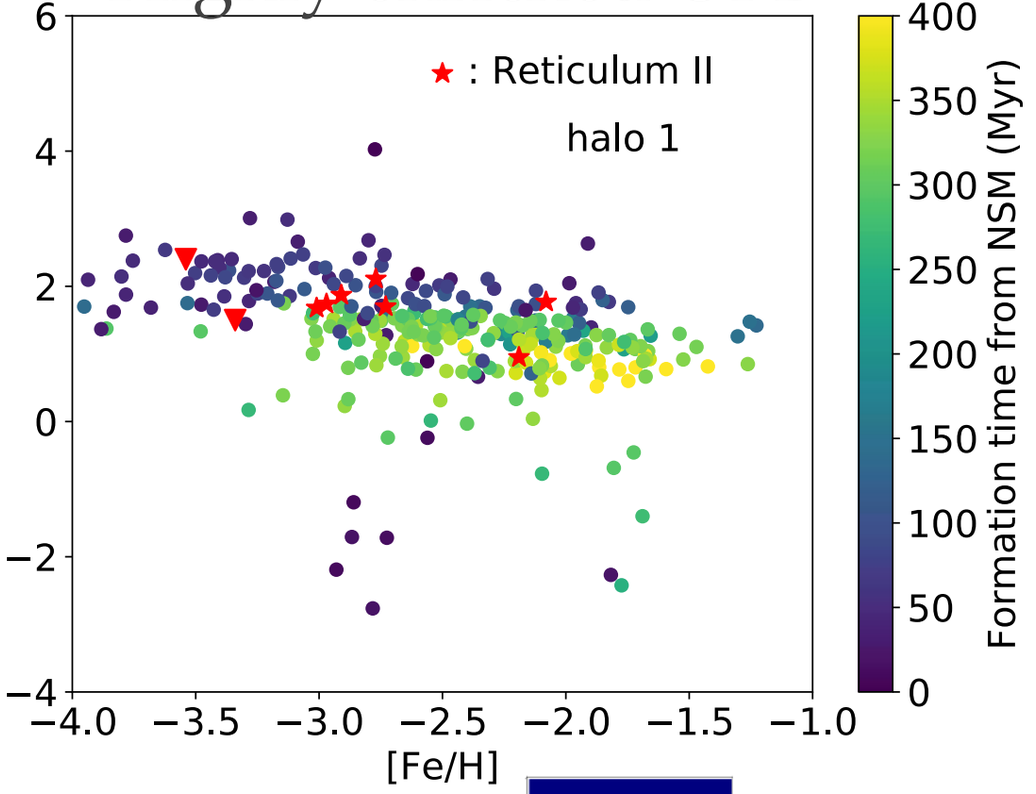
- 3/16 UFD are enriched with Eu.
- [Eu/Fe] ~ 2: highly enriched, consistent with $\sim 0.01\ M_\odot$ of r-process enrichment, NSM?
- [Eu/Fe] ~ 0.5: moderately enriched, NSM in the outskirt or used to be a larger galaxy?

r-process enrichment

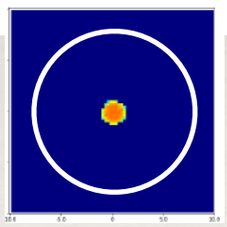
$$[X/Y] = \log_{10}\left[\frac{N_X}{N_Y}\right] + C$$

Normalized to solar

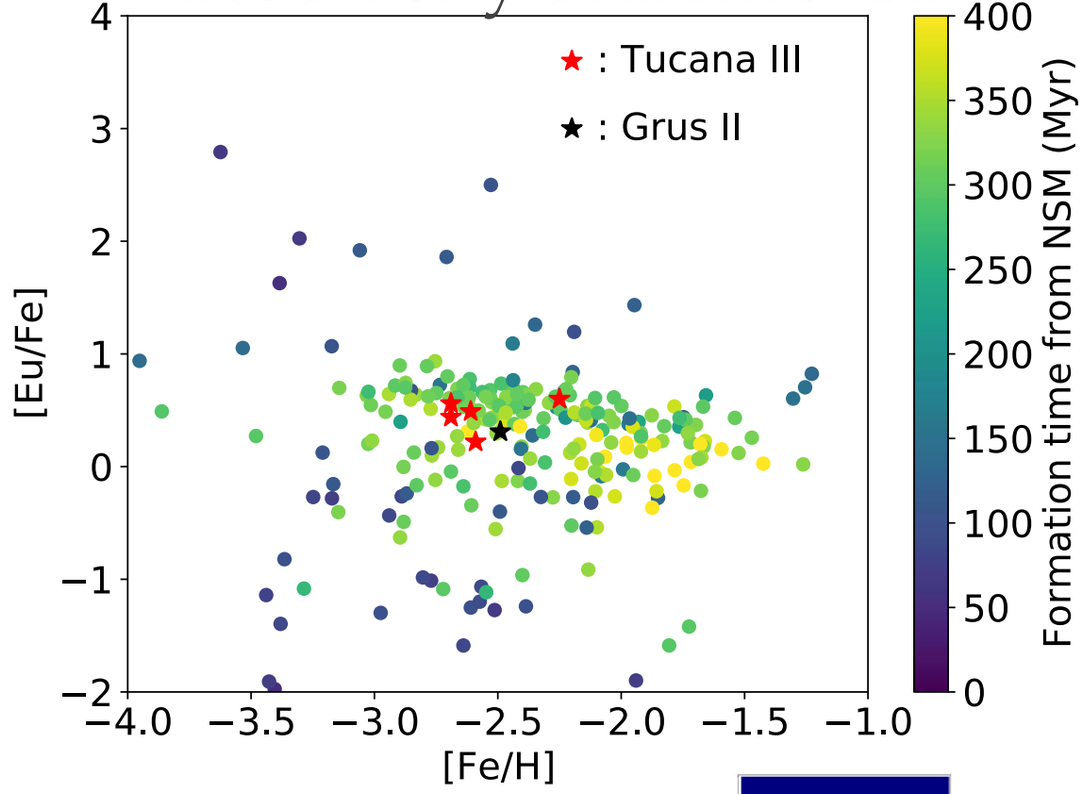
Highly enriched UFD



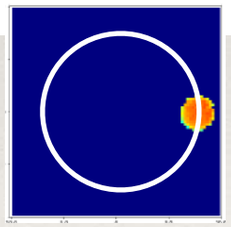
Central explosion



Moderately enriched UFD

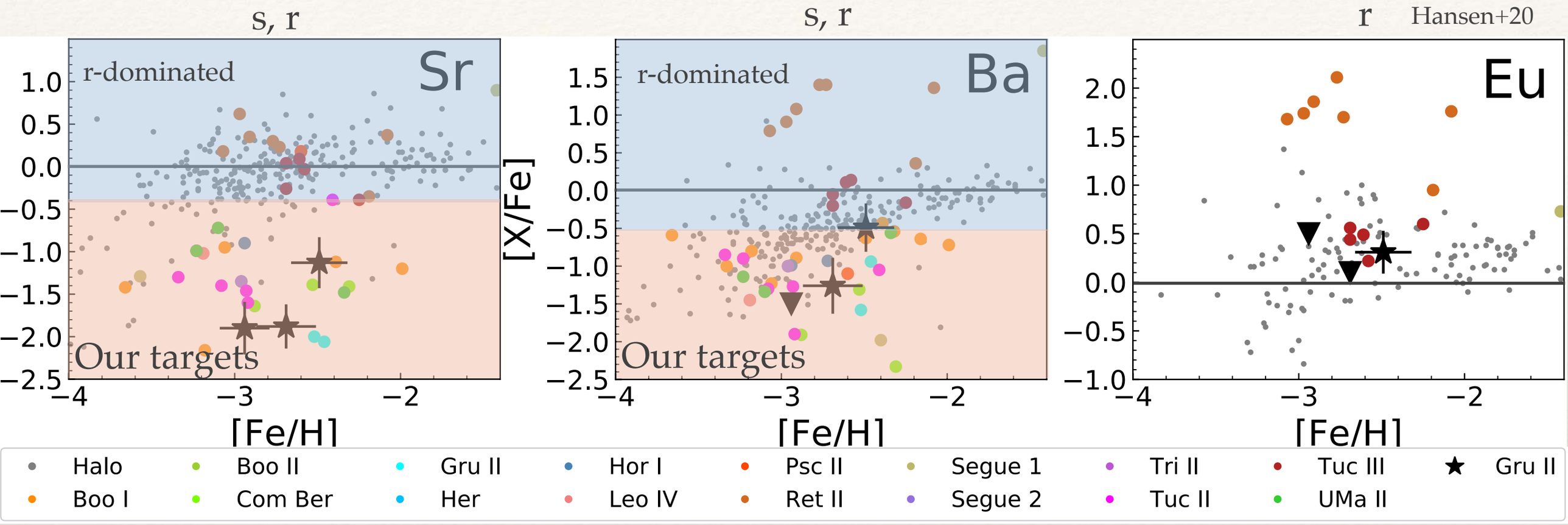


explosion at 100% of radius



- Inside explosion is favored for highly enriched UFD (Ret II).
- Outside explosion is favored for Moderately enriched UFD (Tuc III, Gru II).

s-process elements in UFDs



- Sr, Ba: deficit. Eu: Not enough data.
- 3/16 UFD are enriched with Eu.
- **What is the origin of Ba, Sr in "no r-process" UFDs?**
  - Can AGB stars explain the Ba, Sr abundances in UFDs?

$$[X/Y] = \log_{10}\left[\frac{N_X}{N_Y}\right] + C$$

Normalized to solar

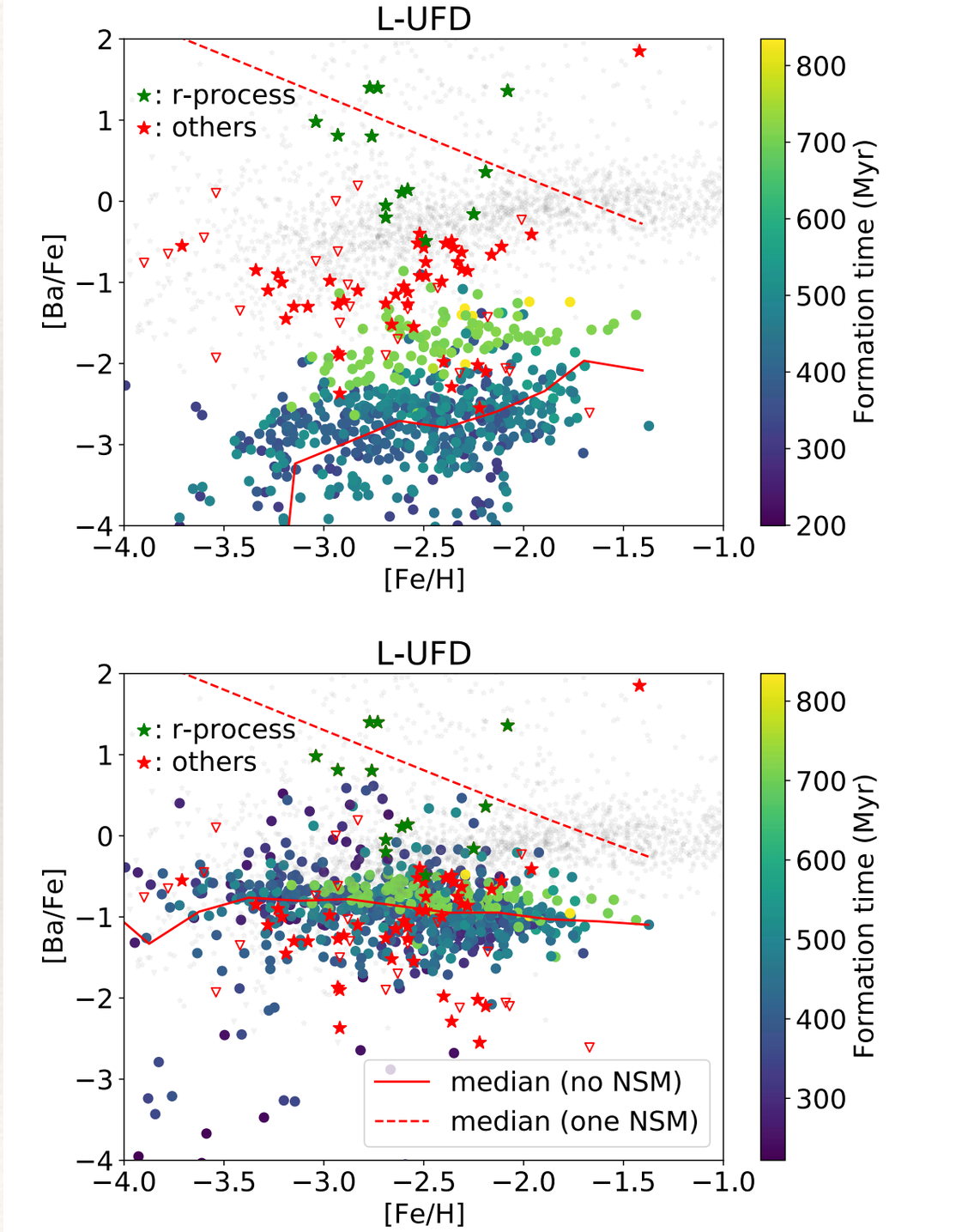
AGB enrichment

$$[X/Y] = \log_{10}\left[\frac{N_X}{N_Y}\right] + C$$

Normalized to solar

- **AGB alone cannot explain Ba abundances.**
- Additional source (e.g. rotating massive stars) should be working

- In UFDs,
  - R: rare and prolific
  - S: AGB+<u>something</u>



What can we infer?

	Timescale	Signature	Interpretation
MW, [Fe/H] > -1	A few Gyr	r ↘ s ↗	R: no delay S: delay or metallicity dependence
MW, [Fe/H] < -2	A few 100Myr	r ↗ s ×	R: delay S: no information
Classical dwarf (-3 < [Fe/H] < -1)	A few Gyr?	r ↗ s ↗	R: no delay? S: delay or metallicity dependence
Ultrafaint dwarf (-3 < [Fe/H] < -2)	A few 100Myr	R: 1 or 0? S: AGB+α	R: Rare&prolific S: additional source (e.g. RMS)
Globular clusters (-3 < [Fe/H] < 0)	Depends on formation process	R: M15? S: ?	R: abundance spread in the natal cloud? S: measurement error?

Unsolved problems

- [Fe/H] > -1 stars have flat [Eu/Mg] - [Fe/H] trend: delay shorter than ~Gyr?
- Do rotating massive stars really produce s-process elements?
- How should we interpret the Ba abundances of classical dwarfs?