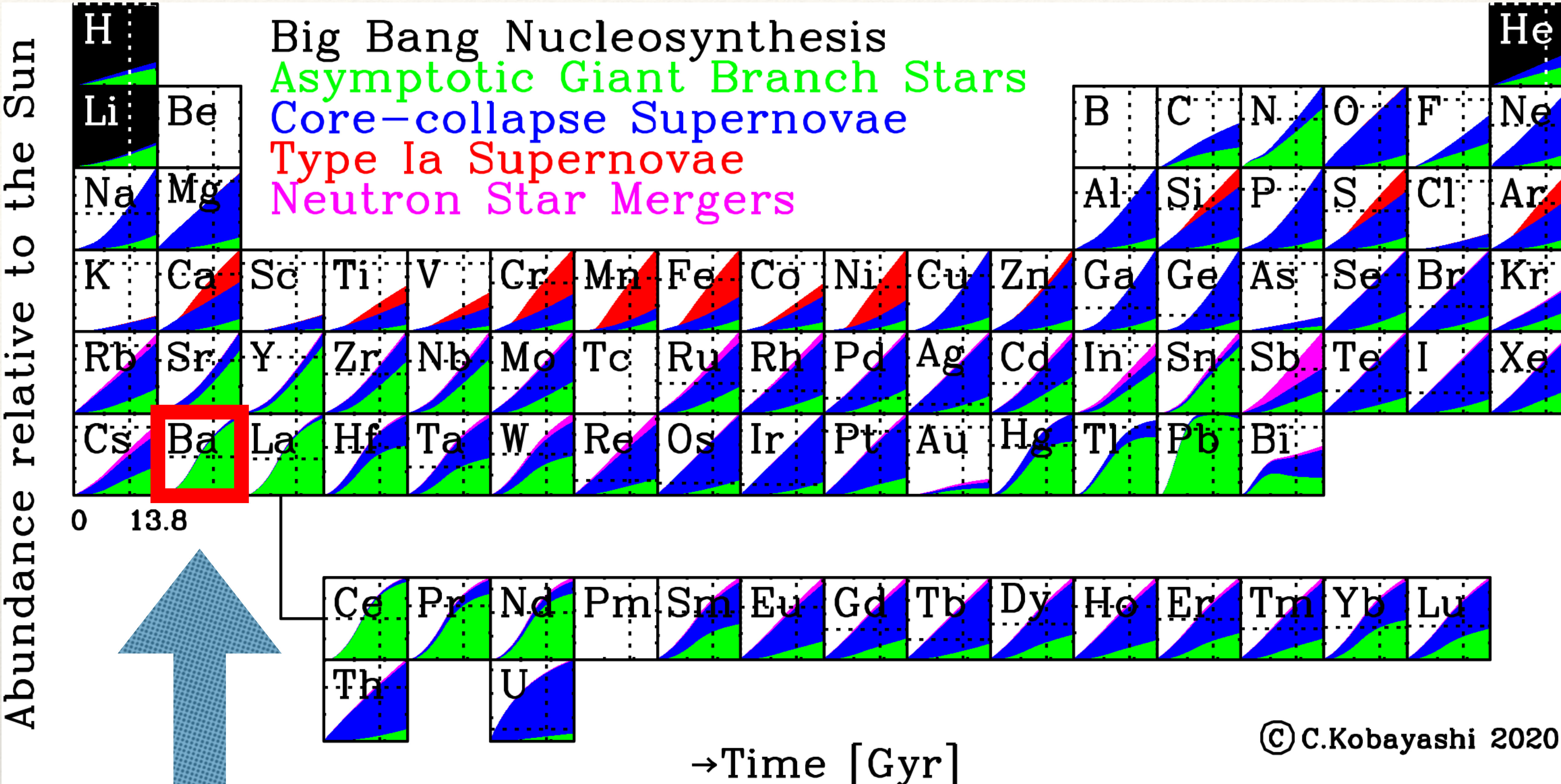


Kobayashi+20

# Barium in UFDs


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# What are / Why UFDs?

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

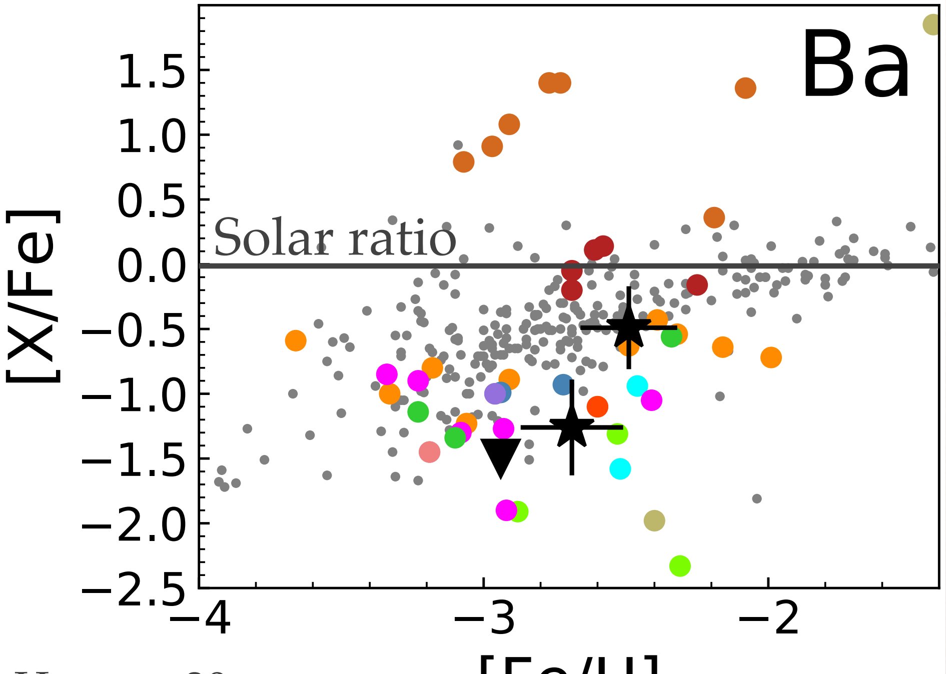

- UFDs are small (< $10^5$ Lsun) satellite galaxies.
- UFDs are old.
  - Good probe for high-z galaxy.
- Stochasticity: “0 or 1 r-process”.
- **Small but important !**

# Why Barium?

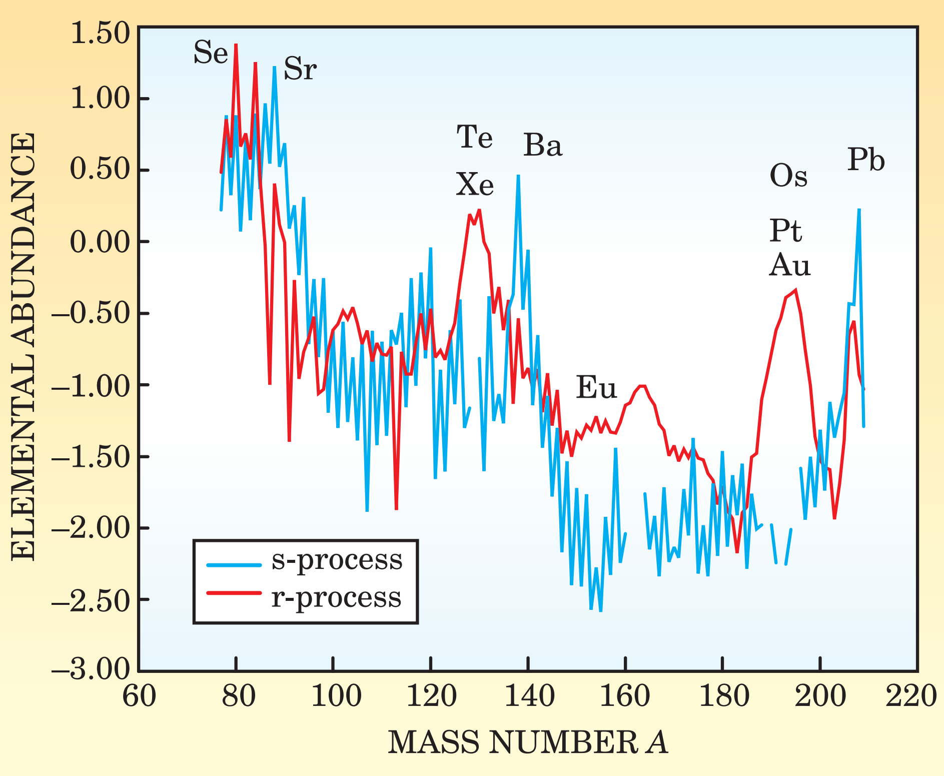
$$[X/Y] = \log_{10}\left[\frac{N_X}{N_Y}\right] + C$$

Normalized to solar

- **A Neutron-capture element** that is **Easy to observe**.
  - Ba is detected in 16/16 UFDs.
  - A solid theoretical framework: r/s process
- Caveat: ~10% from r-process, ~90% from s-process.
  - We need to take into account the contribution from both r-process and s-process




Hansen+20



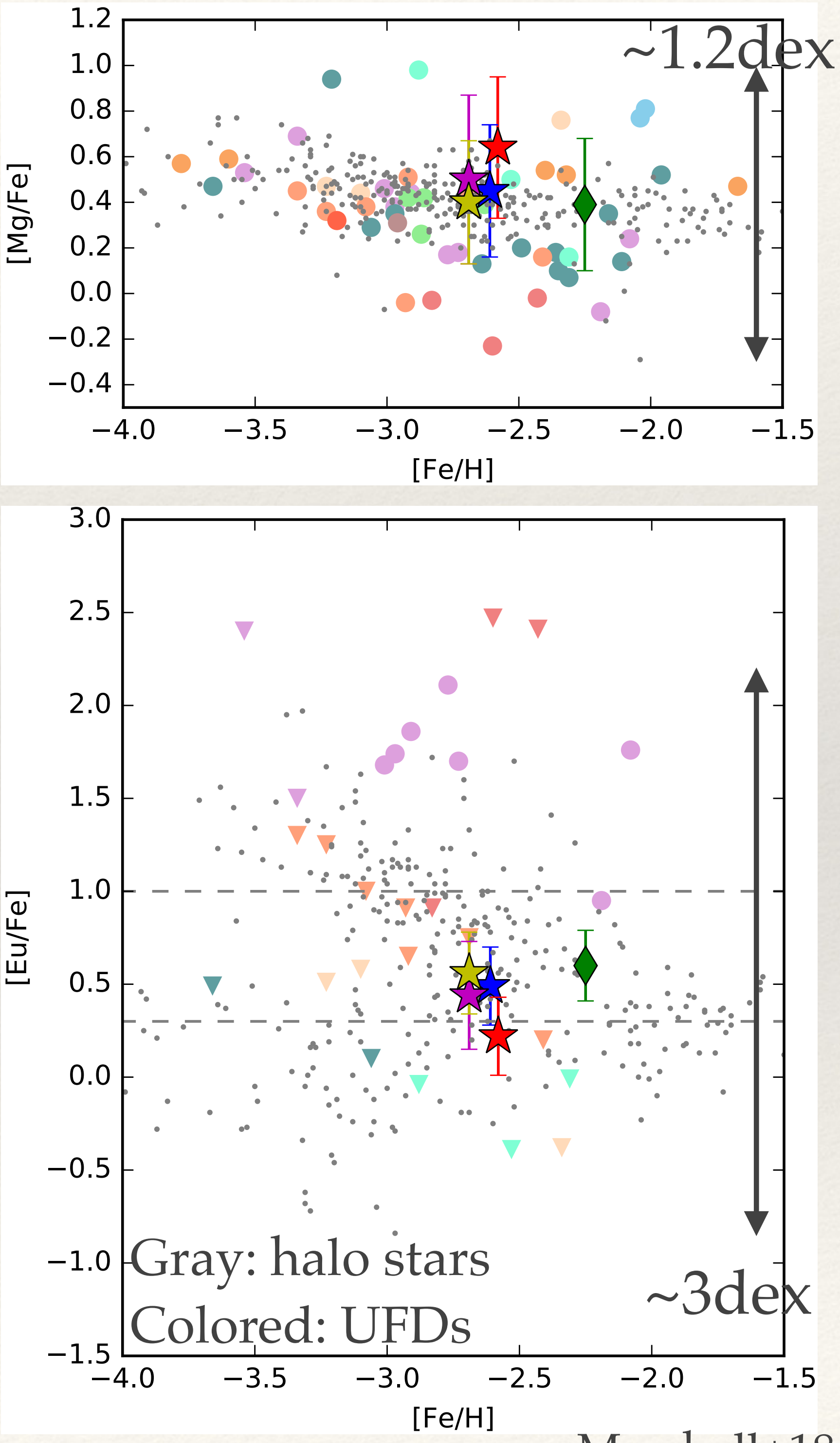

Cowan&Thielemann04

# Rarity of r-process

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

Normalized to solar

- The scatter of [Eu/Fe] among halo stars is quite large compared to other elements.
- Only 3/16 UFDs have Eu detection.
- → r-process event should be **rare and prolific.**




Marshall+18

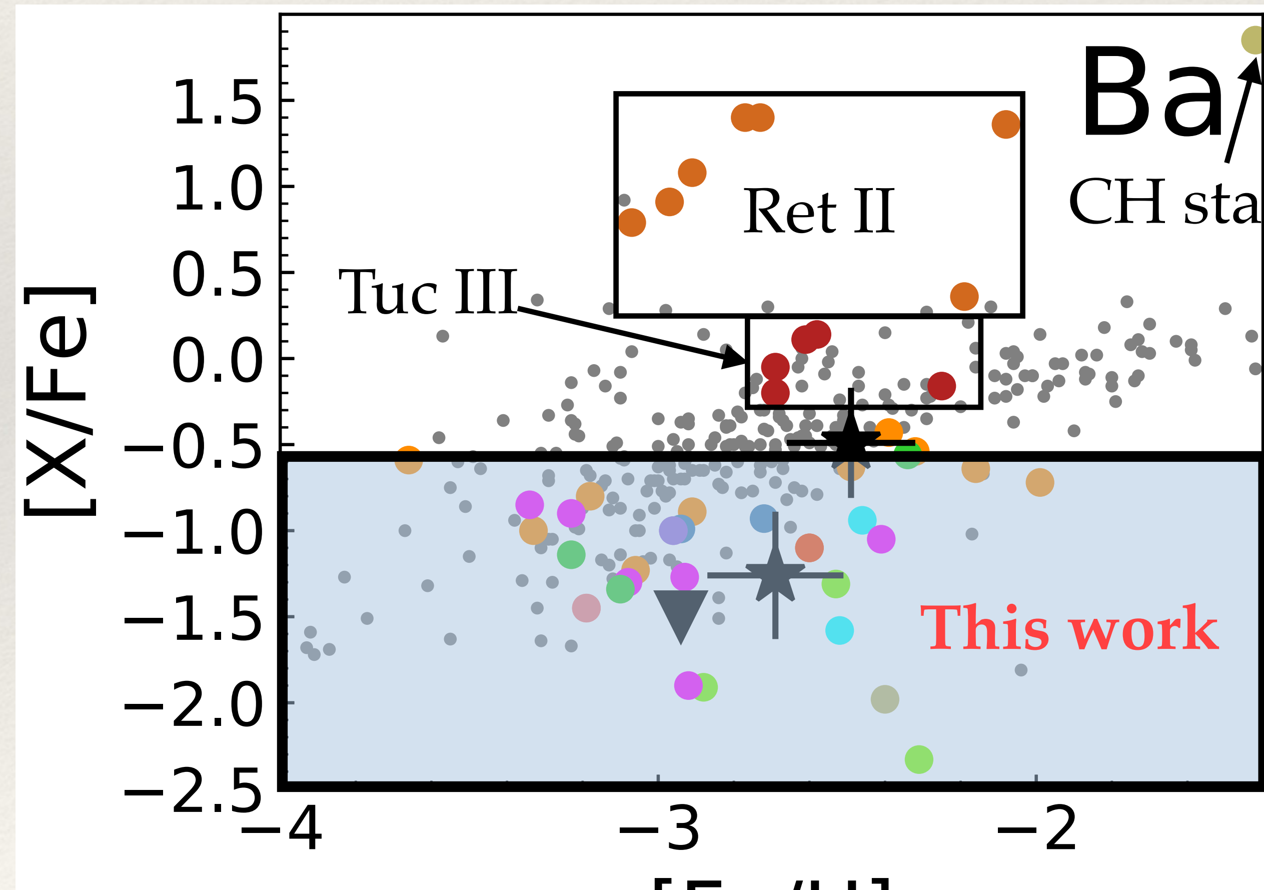
# Ba in UFDs

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

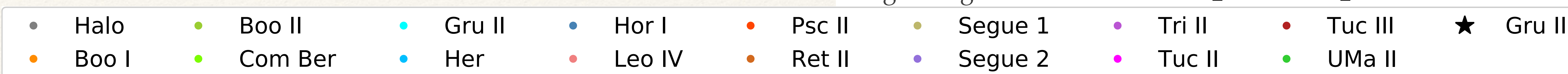
Normalized to solar

- Stars with Eu detection have high Ba. Abundance is consistent with the “rare, prolific r-process event”.
- **What is the origin of Ba in “no r-process” UFDs?**
  - <u>Can AGB stars explain the Ba abundance?</u>

Ret II, Tuc III, and Gru II have Eu-detected stars




Original figure: Hansen+20

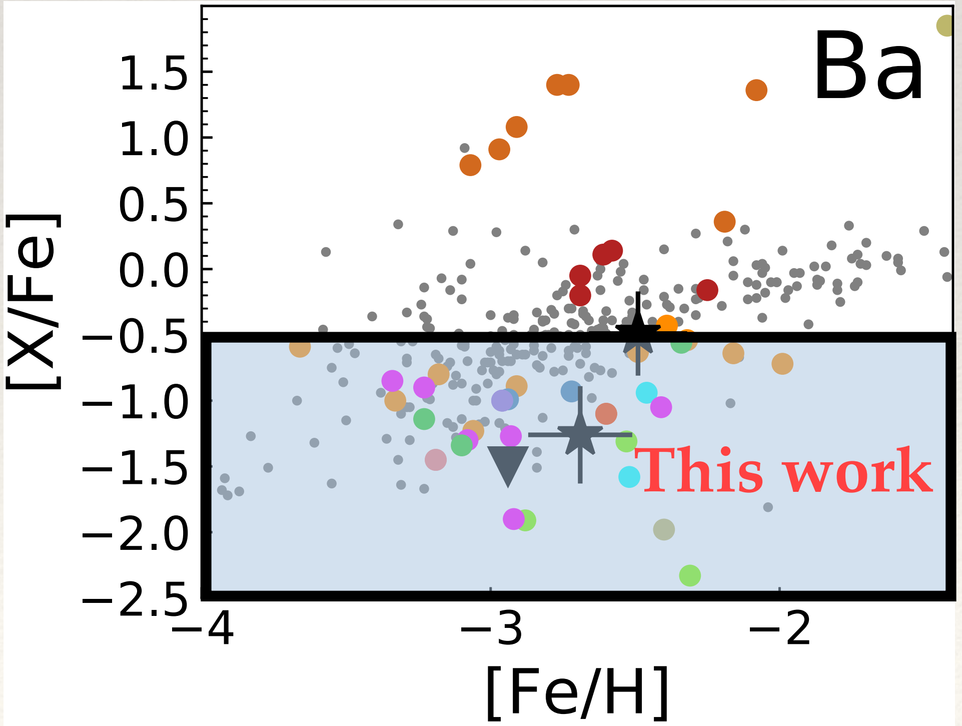


# Motivation

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

Normalized to solar

- **What is the origin of Ba in "no r-process" UFDs?**
  - UFDs quench within the first 1 Gyr, **weaker AGB contribution** than Milky-Way.
  - Can AGB stars contribute to the chemical enrichment of UFDs?




Hansen+20

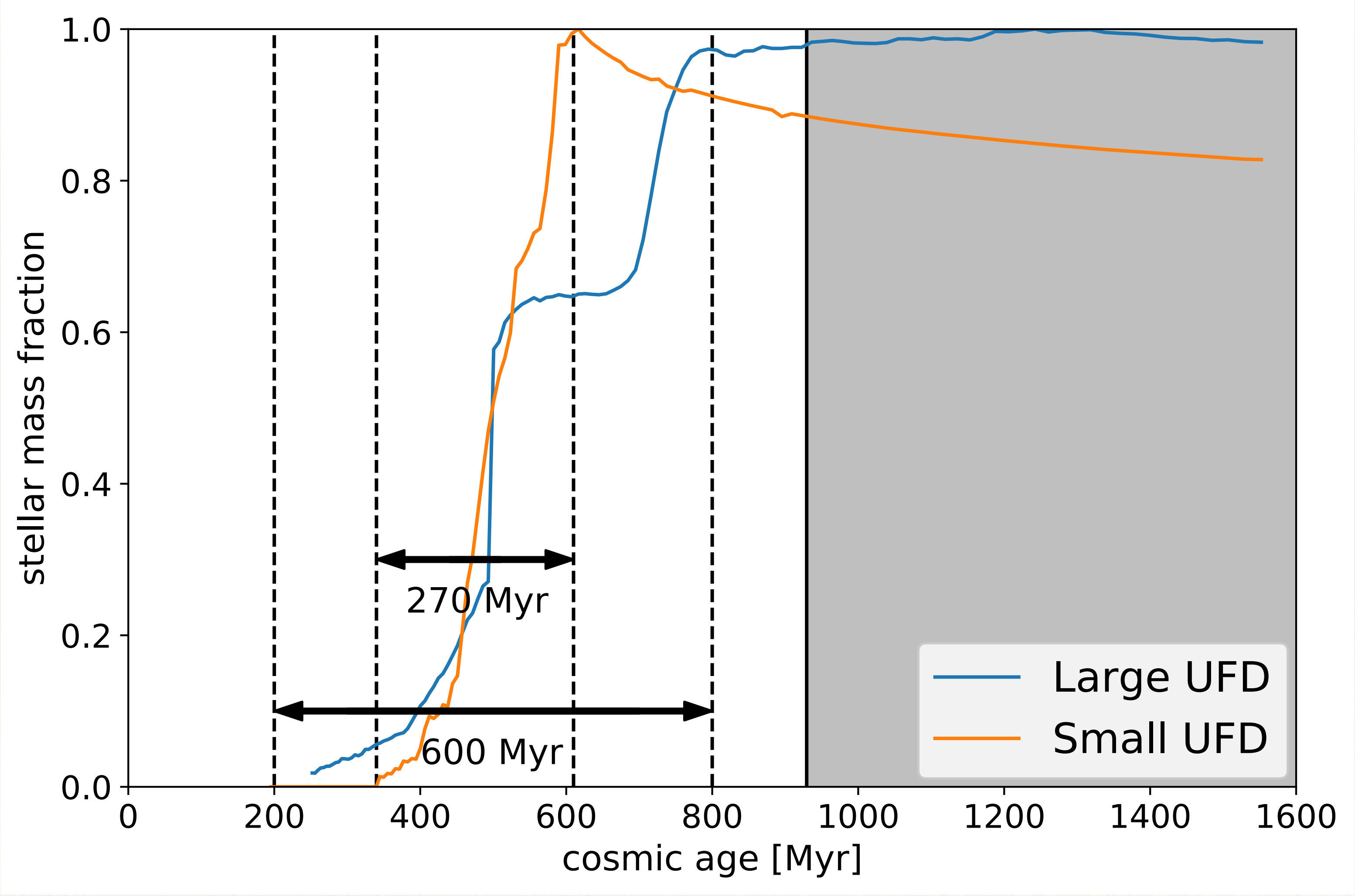
# Method: simulation

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

Normalized to solar

- Code: AREPO
- Auriga galaxy formation model
- **Ba only from AGB stars**
- Prepare two UFD progenitors with different star formation history: “large” ($2\times10^4$ Msun) and “small” ($3\times10^3$ Msun).

Time evolution of stellar mass

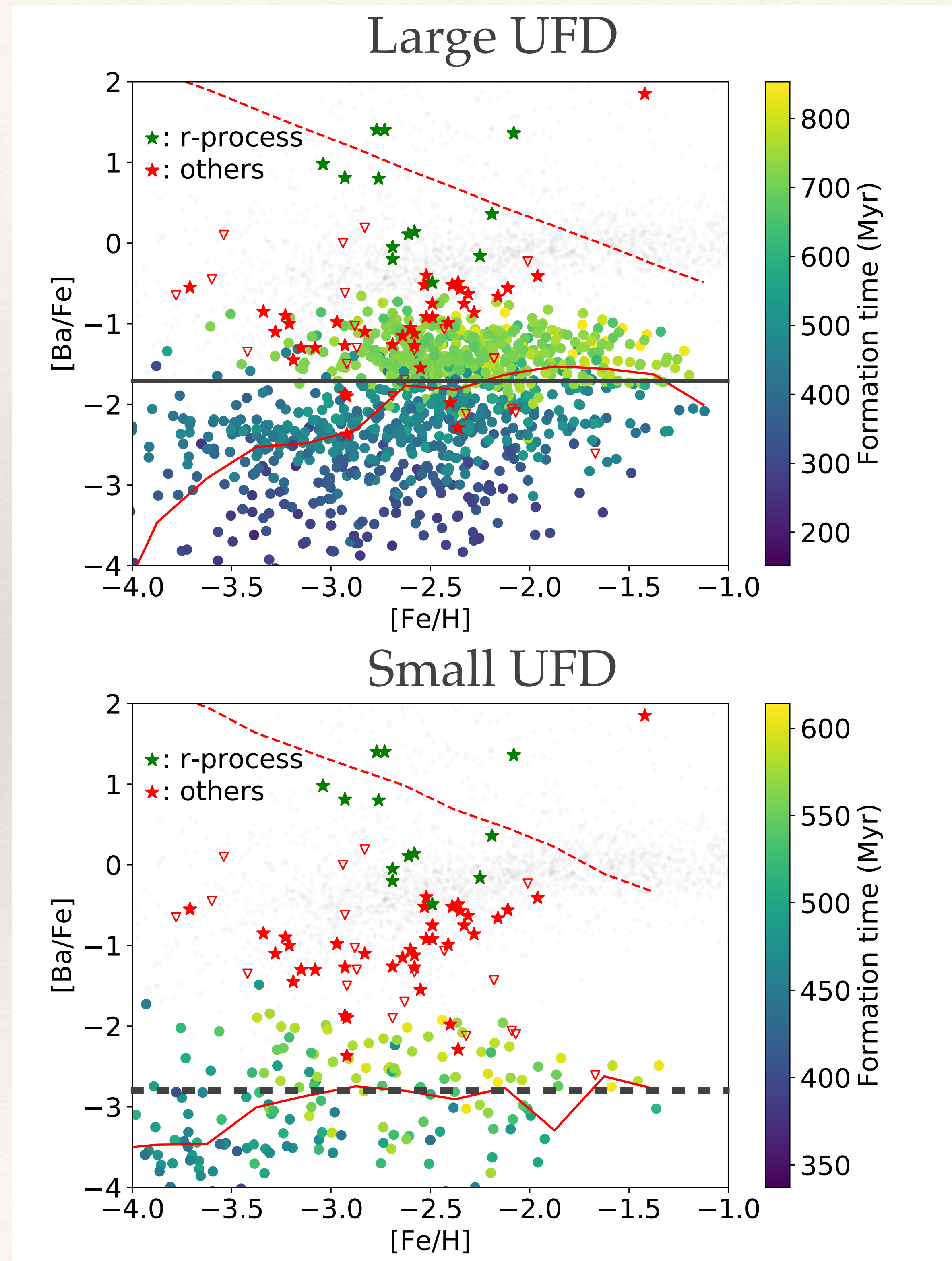


# Results: [Ba/Fe] value

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

Normalized to solar

- [Ba/Fe] is too low.
- Keep forming stars for a long time?
- However, the star formation duration of "Large UFD" is at the longest end of UFDs.

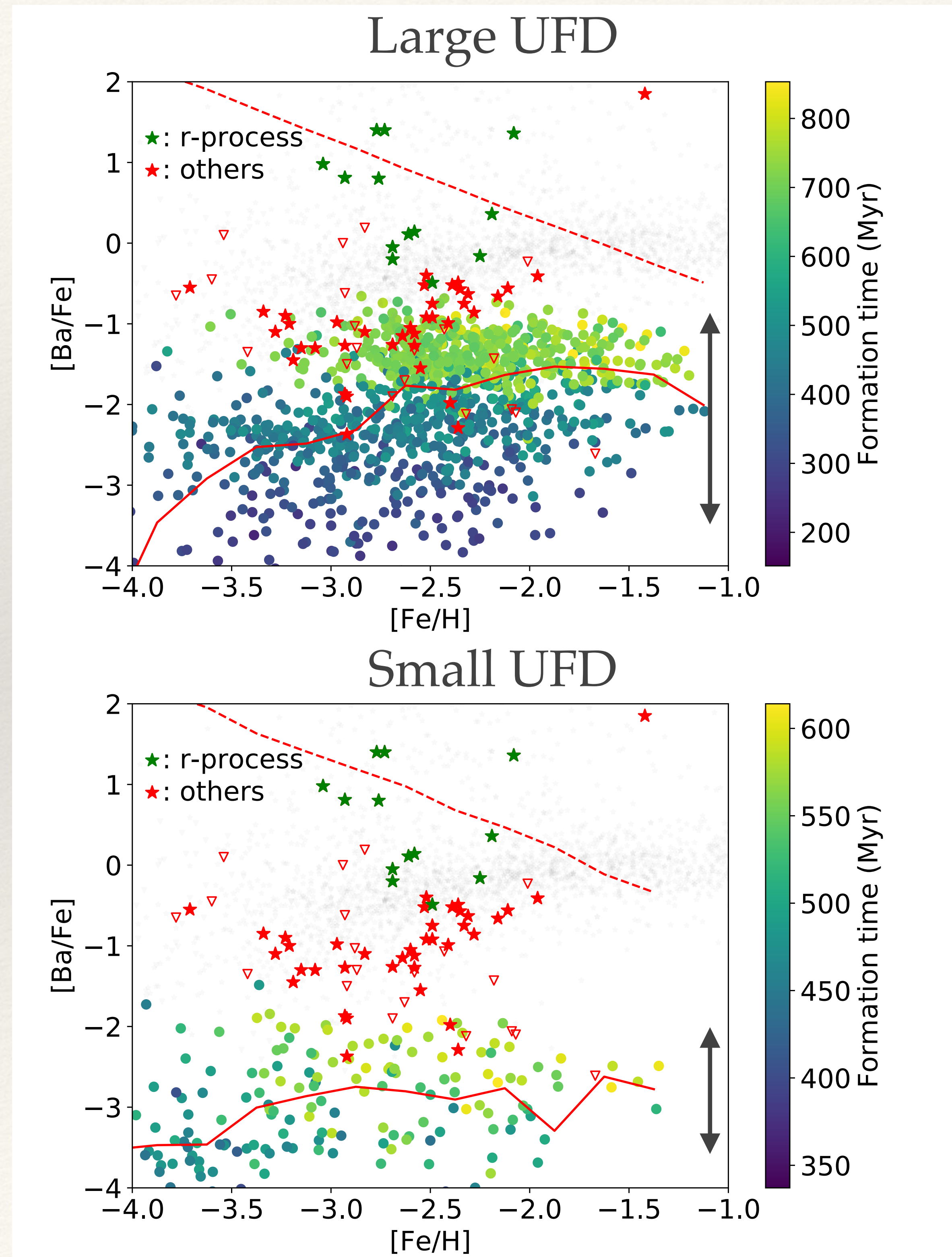


# Results: [Ba/Fe] scatter

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

Normalized to solar

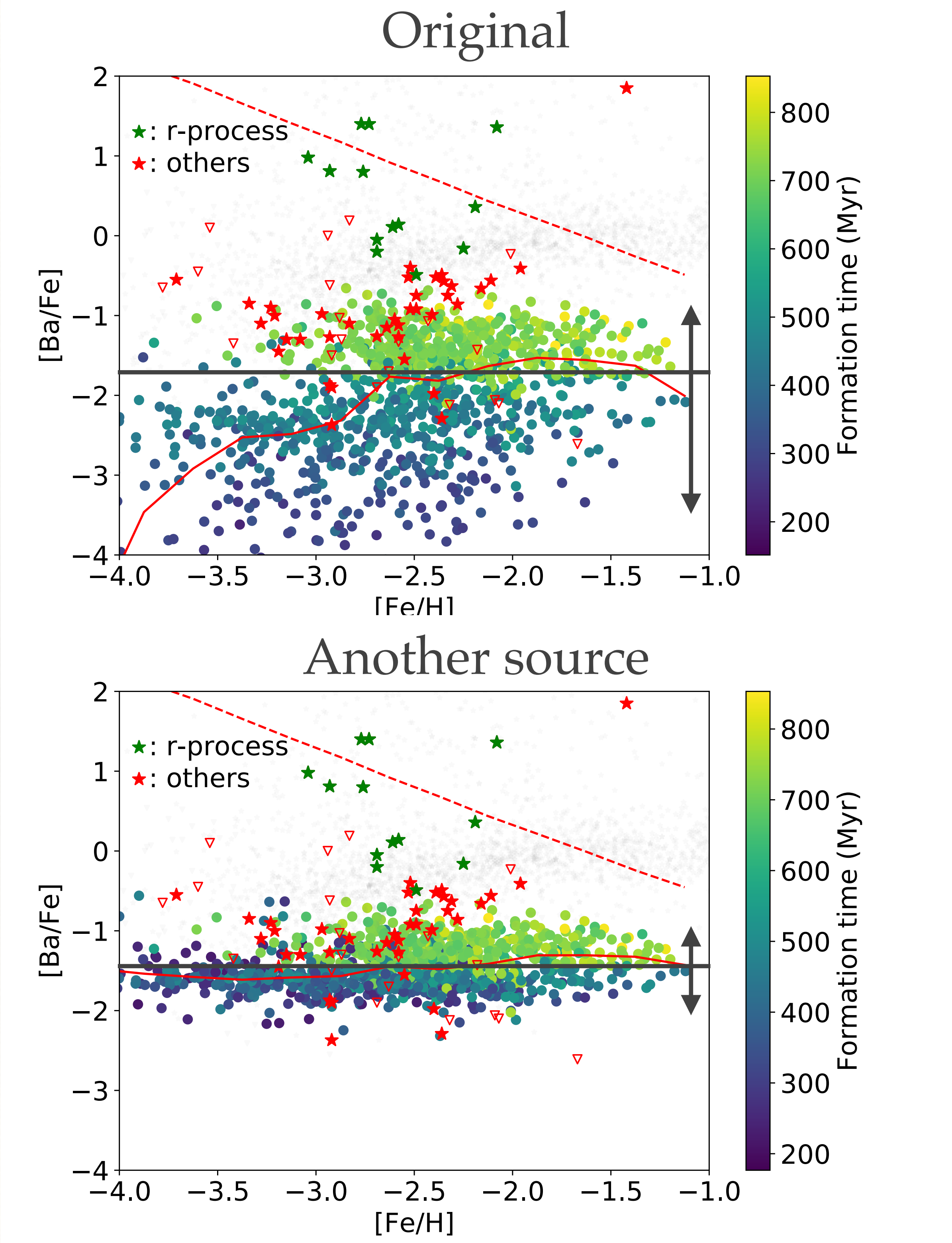
- If star formation duration is long (> ~500Myr), [Ba/Fe] scatter would be too large.
- **The standard model fails to reproduce the Ba abundance.**
- Possible solutions are…
  - Modify IMF (skipped).
  - Enhance Ba production in short timescale and bring [Ba/Fe] up at the left.



# Results: additional Ba source

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

Normalized to solar




- Adding $3\times10^{-10}$ Msun of Ba from massive stars per 1 Msun of stars formed
- [Ba/Fe] roughly matches while keeping [Ba/Fe] scatter small.

## Discussion1: What is the origin of Ba in UFDs?

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

Normalized to solar

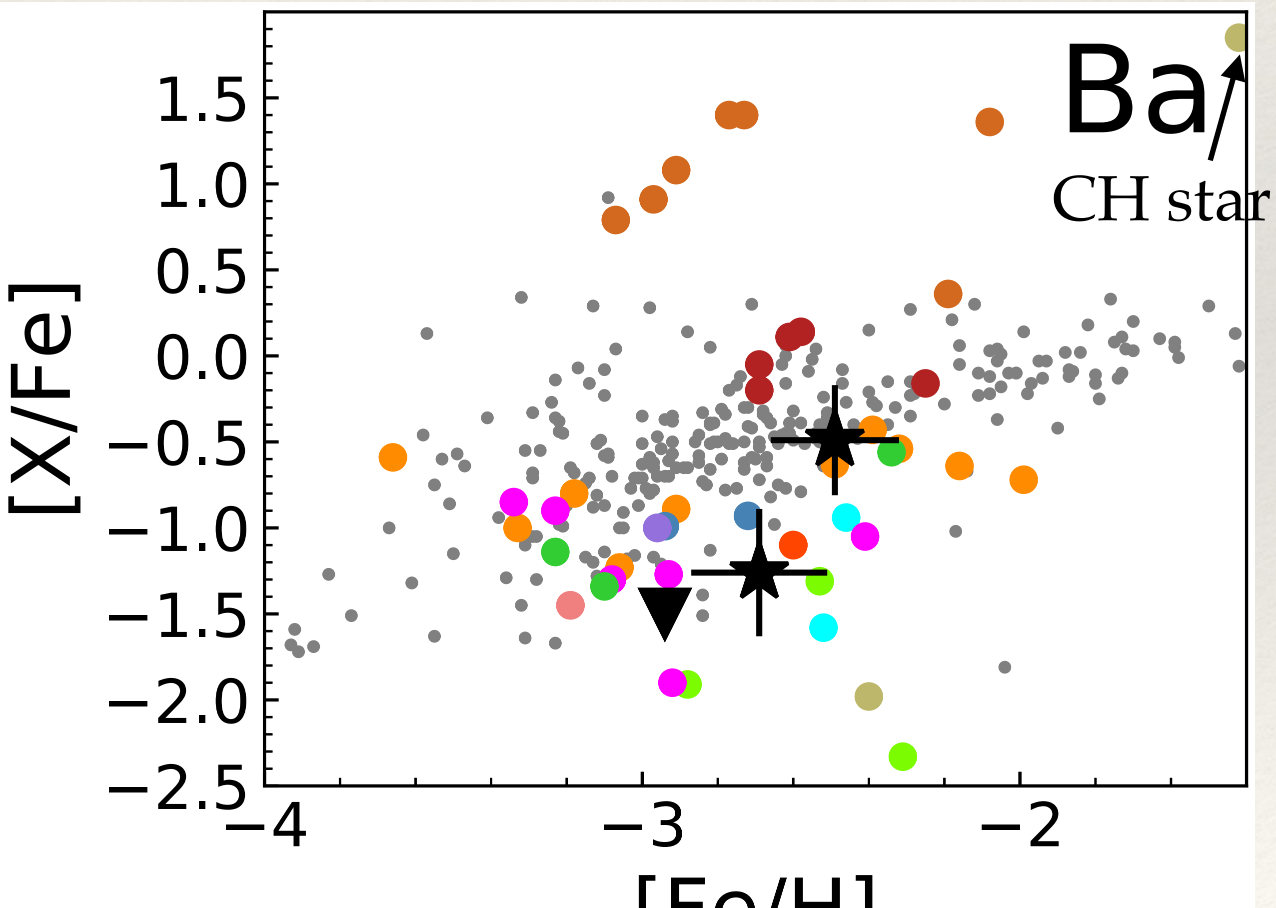
- super-AGB stars?
    - Even with recent yield (Doherty+17) Ba abundance is not reproduced.
- Rotating massive stars?
    - The model uncertainty is still quite large and may reproduce Ba abundance. Further observations (such as the rotation of OB stars) can constrain better.
- Halo stars are mostly r-process dominant. However, super-AGB and rotating massive stars are s-process.
- **r-process or s-process?**: we need observation!

# Discussion2: Diversity among UFDs

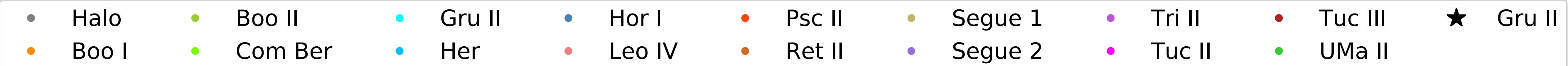
$$[X/Y] = \log_{10}\left[\frac{N_X}{N_Y}\right] + C$$

Normalized to solar

- **What is the origin of the diversity of [Ba/Fe] among UFDs?**
- Possible factors: 1. yield, 2. IMF, 3. SFH, assuming well-sampling.
- Since [Fe/H] is similar, **1.** and **2.** should be similar.
- SFH is important if delayed source (like AGB) is important, but AGB has shown to be subdominant, and there's no other candidates
- **Rare event??**




Original figure: Hansen+20

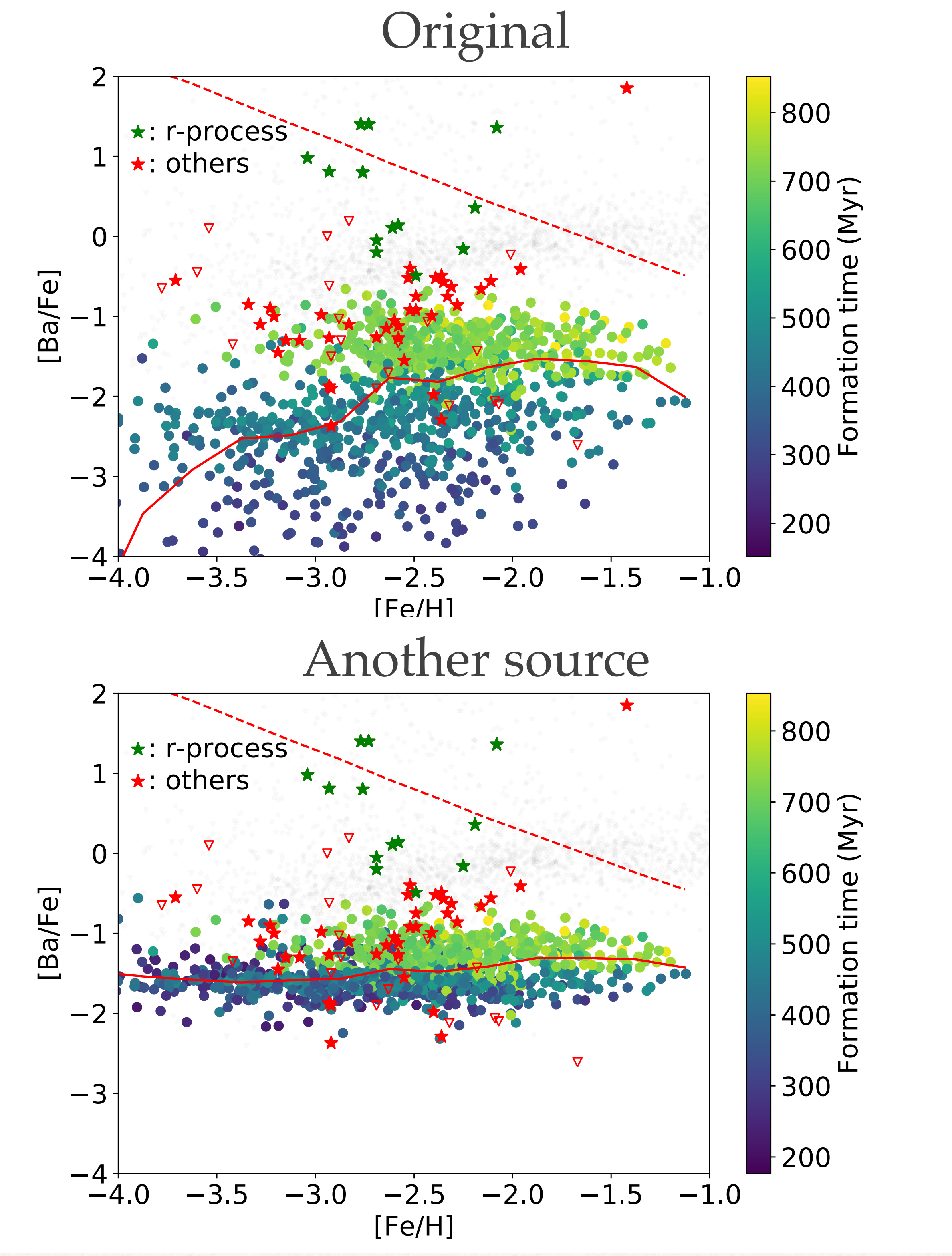


# Conclusion: We need something.

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

Normalized to solar

- Ba cannot be explained only by AGB stars.
- Possible solutions are…
  - Tweaking IMF.
  - Some other Ba source.
  - It should produce $3\times10^{-10}$ Msun of Ba from 1 Msun of stars formed.



# dwarf & UFD list

Simon+19

| Dwarf | $M_V$ | $R_{1/2}$ (pc) | Distance (kpc) | $v_{hel}$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | [Fe/H] | $\sigma_{[Fe/H]}$ |
|---|---|---|---|---|---|---|---|
| Tucana IV | $-3.50^{+0.28}_{-0.28}$ | $127^{+26}_{-22}$ | $48.0^{+4.0}_{-4.0}$ | | | | |
| Sculptor | $-10.82^{+0.14}_{-0.14}$ | $279^{+16}_{-16}$ | $86.0^{+5.0}_{-5.0}$ | $111.4^{+0.1}_{-0.1}$ | $9.2^{+1.1}_{-1.1}$ | $-1.73^{+0.03}_{-0.02}$ | $0.44^{+0.02}_{-0.02}$ |
| Cetus II | $0.00^{+0.68}_{-0.68}$ | $17^{+9}_{-5}$ | $30.0^{+3.0}_{-3.0}$ | | | | |
| Cetus III | $-2.45^{+0.57}_{-0.56}$ | $90^{+32}_{-14}$ | $251.0^{+24.0}_{-11.0}$ | | | | |
| Triangulum II | $-1.60^{+0.76}_{-0.76}$ | $16^{+4}_{-4}$ | $28.4^{+1.6}_{-1.6}$ | $-381.7^{+1.1}_{-1.1}$ | $< 3.4^{c}$ | $-2.24^{+0.05}_{-0.05}$ | $0.53^{+0.12}_{-0.38}$ |
| Segue 2 | $-1.98^{+0.88}_{-0.88}$ | $40^{+4}_{-4}$ | $37.0^{+3.0}_{-3.0}$ | $-40.2^{+0.9}_{-0.9}$ | $< 2.2^{c}$ | $-2.14^{+0.16}_{-0.15}$ | $0.39^{+0.12}_{-0.13}$ |
| DESJ0225+0304 | $-1.10^{+0.50}_{-0.30}$ | $19^{+9}_{-5}$ | $23.8^{+0.7}_{-0.5}$ | | | | |
| Hydrus I | $-4.71^{+0.08}_{-0.08}$ | $53^{+4}_{-4}$ | $27.6^{+0.5}_{-0.5}$ | $80.4^{+0.6}_{-0.6}$ | $2.7^{+0.5}_{-0.4}$ | $-2.52^{+0.09}_{-0.09}$ | $0.41^{+0.08}_{-0.08}$ |
| Fornax | $-13.34^{+0.14}_{-0.14}$ | $792^{+18}_{-18}$ | $139.0^{+3.0}_{-3.0}$ | $55.2^{+0.1}_{-0.1}$ | $11.7^{+0.9}_{-0.9}$ | $-1.07^{+0.02}_{-0.01}$ | $0.27^{+0.01}_{-0.01}$ |
| Horologium I | $-3.76^{+0.56}_{-0.56}$ | $40^{+10}_{-9}$ | $87.0^{+13.0}_{-11.0}$ | $112.8^{+2.5}_{-2.6}$ | $4.9^{+2.8}_{-0.9}$ | $-2.76^{+0.10}_{-0.10}$ | $0.17^{+0.20}_{-0.03}$ |
| Horologium II | $-1.56^{+1.02}_{-1.02}$ | $44^{+15}_{-14}$ | $78.0^{+8.0}_{-7.0}$ | | | | |
| Reticulum II | $-3.99^{+0.38}_{-0.38}$ | $51^{+3}_{-3}$ | $31.6^{+1.5}_{-1.4}$ | $62.8^{+0.5}_{-0.5}$ | $3.3^{+0.7}_{-0.7}$ | $-2.65^{+0.07}_{-0.07}$ | $0.28^{+0.09}_{-0.09}$ |
| Eridanus II | $-7.10^{+0.30}_{-0.30}$ | $246^{+17}_{-17}$ | $366.0^{+17.0}_{-17.0}$ | $75.6^{+1.3}_{-1.3}$ | $6.9^{+1.2}_{-0.9}$ | $-2.38^{+0.13}_{-0.13}$ | $0.47^{+0.12}_{-0.09}$ |
| Reticulum III | $-3.30^{+0.29}_{-0.29}$ | $64^{+26}_{-23}$ | $92.0^{+13.0}_{-13.0}$ | | | | |
| Pictor I | $-3.67^{+0.60}_{-0.60}$ | $32^{+15}_{-15}$ | $126.0^{+19.0}_{-16.0}$ | | | | |
| Columba I | $-4.20^{+0.20}_{-0.20}$ | $117^{+12}_{-12}$ | $183.0^{+10.0}_{-10.0}$ | | | | |
| Carina | $-9.45^{+0.05}_{-0.05}$ | $311^{+15}_{-15}$ | $106.0^{+5.0}_{-5.0}$ | $222.9^{+0.1}_{-0.1}$ | $6.6^{+1.2}_{-1.2}$ | $-1.80^{+0.02}_{-0.02}$ | $0.24^{d}$ |
| Pictor II | $-3.20^{+0.40}_{-0.50}$ | $47^{+20}_{-13}$ | $45.0^{+5.0}_{-5.0}$ | | | | |
| Carina II | $-4.50^{+0.10}_{-0.10}$ | $92^{+8}_{-8}$ | $36.2^{+0.6}_{-0.6}$ | $477.2^{+1.2}_{-1.2}$ | $3.4^{+1.2}_{-0.8}$ | $-2.44^{+0.09}_{-0.09}$ | $0.22^{+0.10}_{-0.07}$ |
| Carina III | $-2.40^{+0.20}_{-0.20}$ | $30^{+8}_{-8}$ | $27.8^{+0.6}_{-0.6}$ | $284.6^{+3.4}_{-3.1}$ | $5.6^{+4.3}_{-2.1}$ | | |
| Ursa Major II | $-4.43^{+0.26}_{-0.26}$ | $139^{+9}_{-9}$ | $34.7^{+2.0}_{-1.9}$ | $-116.5^{+1.9}_{-1.9}$ | $5.6^{+1.4}_{-1.4}$ | $-2.23^{+0.21}_{-0.24}$ | $0.67^{+0.20}_{-0.15}$ |
| Leo T | $-8.00^{e}$ | $118^{+11}_{-11}$ | $409.0^{+29.0}_{-27.0}$ | $38.1^{+2.0}_{-2.0}$ | $7.5^{+1.6}_{-1.6}$ | $-1.91^{+0.12}_{-0.14}$ | $0.43^{+0.13}_{-0.09}$ |
| Segue 1 | $-1.30^{+0.73}_{-0.73}$ | $24^{+4}_{-4}$ | $23.0^{+2.0}_{-2.0}$ | $208.5^{+0.9}_{-0.9}$ | $3.7^{+1.4}_{-1.1}$ | $-2.71^{+0.45}_{-0.39}$ | $0.95^{+0.42}_{-0.26}$ |

| Dwarf | $M_V$ | $R_{1/2}$ (pc) | Distance (kpc) | $v_{hel}$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | [Fe/H] | $\sigma_{[Fe/H]}$ |
|---|---|---|---|---|---|---|---|
| Leo I | $-11.78^{+0.28}_{-0.28}$ | $270^{+17}_{-16}$ | $254.0^{+16.0}_{-15.0}$ | $282.9^{+0.5}_{-0.5}$ | $9.2^{+0.4}_{-0.4}$ | $-1.48^{+0.02}_{-0.01}$ | $0.26^{+0.01}_{-0.01}$ |
| Sextans | $-8.94^{+0.06}_{-0.06}$ | $456^{+15}_{-15}$ | $95.0^{+3.0}_{-3.0}$ | $224.3^{+0.1}_{-0.1}$ | $7.9^{+1.3}_{-1.3}$ | $-1.97^{+0.04}_{-0.04}$ | $0.38^{+0.03}_{-0.03}$ |
| Ursa Major I | $-5.13^{+0.38}_{-0.38}$ | $295^{+28}_{-28}$ | $97.3^{+6.0}_{-5.7}$ | $-55.3^{+1.4}_{-1.4}$ | $7.0^{+1.0}_{-1.0}$ | $-2.16^{+0.11}_{-0.13}$ | $0.62^{+0.10}_{-0.08}$ |
| Willman 1 | $-2.90^{+0.74}_{-0.74}$ | $33^{+8}_{-8}$ | $45.0^{+10.0}_{-10.0}$ | $-14.1^{+1.0}_{-1.0}$ | $4.0^{+0.8}_{-0.8}$ | $-2.19^{+0.08}_{-0.08}$ | |
| Leo II | $-9.74^{+0.04}_{-0.04}$ | $171^{+10}_{-10}$ | $233.0^{+14.0}_{-14.0}$ | $78.3^{+0.6}_{-0.6}$ | $7.4^{+0.4}_{-0.4}$ | $-1.68^{+0.02}_{-0.03}$ | $0.34^{+0.02}_{-0.02}$ |
| Leo V | $-4.29^{+0.36}_{-0.36}$ | $49^{+16}_{-16}$ | $169.0^{+4.0}_{-4.0}$ | $170.9^{+2.1}_{-1.9}$ | $2.3^{+3.2}_{-1.6}$ | $-2.48^{+0.21}_{-0.21}$ | $0.47^{+0.23}_{-0.13}$ |
| Leo IV | $-4.99^{+0.26}_{-0.26}$ | $114^{+13}_{-13}$ | $154.0^{+5.0}_{-5.0}$ | $132.3^{+1.4}_{-1.4}$ | $3.3^{+1.7}_{-1.7}$ | $-2.29^{+0.19}_{-0.22}$ | $0.56^{+0.19}_{-0.14}$ |
| Crater II | $-8.20^{+0.10}_{-0.10}$ | $1066^{+86}_{-86}$ | $117.5^{+1.1}_{-1.1}$ | $87.5^{+0.4}_{-0.4}$ | $2.7^{+0.3}_{-0.3}$ | $-1.98^{+0.10}_{-0.10}$ | $0.22^{+0.04}_{-0.03}$ |
| Virgo I | $-0.80^{+0.90}_{-0.90}$ | $38^{+12}_{-11}$ | $87.0^{+13.0}_{-8.0}$ | | | | |
| Hydra II | $-4.86^{+0.37}_{-0.37}$ | $67^{+13}_{-13}$ | $151.0^{+8.0}_{-7.0}$ | $303.1^{+1.4}_{-1.4}$ | $< 3.6^{c}$ | $-2.02^{+0.08}_{-0.08}$ | $0.40^{+0.48}_{-0.26}$ |
| Coma Berenices | $-4.28^{+0.25}_{-0.25}$ | $69^{+5}_{-4}$ | $42.0^{+1.6}_{-1.5}$ | $98.1^{+0.9}_{-0.9}$ | $4.6^{+0.8}_{-0.8}$ | $-2.43^{+0.11}_{-0.11}$ | $0.46^{+0.09}_{-0.08}$ |
| Canes Venatici II | $-5.17^{+0.32}_{-0.32}$ | $71^{+11}_{-11}$ | $160.0^{+4.0}_{-4.0}$ | $-128.9^{+1.2}_{-1.2}$ | $4.6^{+1.0}_{-1.0}$ | $-2.35^{+0.16}_{-0.19}$ | $0.57^{+0.15}_{-0.12}$ |
| Canes Venatici I | $-8.73^{+0.06}_{-0.06}$ | $437^{+18}_{-18}$ | $211.0^{+6.0}_{-6.0}$ | $30.9^{+0.6}_{-0.6}$ | $7.6^{+0.4}_{-0.4}$ | $-1.91^{+0.04}_{-0.04}$ | $0.39^{+0.03}_{-0.02}$ |
| Boötes II | $-2.94^{+0.74}_{-0.75}$ | $39^{+5}_{-5}$ | $42.0^{+1.0}_{-1.0}$ | $-117.0^{+5.2}_{-5.2}$ | $10.5^{+7.4}_{-7.4}$ | $-2.79^{+0.06}_{-0.10}$ | $< 0.35^{c}$ |
| Boötes I | $-6.02^{+0.25}_{-0.25}$ | $191^{+8}_{-8}$ | $66.0^{+2.0}_{-2.0}$ | $101.8^{+0.7}_{-0.7}$ | $4.6^{+0.8}_{-0.6}$ | $-2.35^{+0.09}_{-0.08}$ | $0.44^{+0.07}_{-0.06}$ |
| Ursa Minor | $-9.03^{+0.05}_{-0.05}$ | $405^{+21}_{-21}$ | $76.0^{+4.0}_{-4.0}$ | $-247.2^{+0.8}_{-0.8}$ | $9.5^{+1.2}_{-1.2}$ | $-2.12^{+0.03}_{-0.02}$ | $0.33^{+0.02}_{-0.03}$ |
| Draco II | $-0.80^{+0.40}_{-1.00}$ | $19^{+4}_{-3}$ | $21.5^{+0.4}_{-0.4}$ | $-342.5^{+1.1}_{-1.2}$ | $< 5.9^{c}$ | $-2.70^{+0.10}_{-0.10}$ | $< 0.24^{c}$ |
| Hercules | $-5.83^{+0.17}_{-0.17}$ | $216^{+20}_{-20}$ | $132.0^{+6.0}_{-6.0}$ | $45.0^{+1.1}_{-1.1}$ | $5.1^{+0.9}_{-0.9}$ | $-2.47^{+0.13}_{-0.12}$ | $0.47^{+0.11}_{-0.08}$ |
| Draco | $-8.88^{+0.05}_{-0.05}$ | $231^{+17}_{-17}$ | $82.0^{+6.0}_{-6.0}$ | $-290.7^{+0.7}_{-0.8}$ | $9.1^{+1.2}_{-1.2}$ | $-2.00^{+0.02}_{-0.02}$ | $0.34^{+0.02}_{-0.02}$ |
| Sagittarius | $-13.50^{+0.15}_{-0.15}$ | $2662^{+193}_{-193}$ | $26.7^{+1.3}_{-1.3}$ | $139.4^{+0.6}_{-0.6}$ | $9.6^{+0.4}_{-0.4}$ | $-0.53^{+0.03}_{-0.02}$ | $0.17^{+0.02}_{-0.02}$ |
| Sagittarius II | $-5.20^{+0.10}_{-0.10}$ | $33^{+2}_{-2}$ | $70.1^{+2.3}_{-2.3}$ | | | | |
| Indus II | $-4.30^{+0.19}_{-0.19}$ | $181^{+70}_{-64}$ | $214.0^{+16.0}_{-16.0}$ | | | | |
| Grus II | $-3.90^{+0.22}_{-0.22}$ | $93^{+16}_{-12}$ | $53.0^{+5.0}_{-5.0}$ | | | | |

| Dwarf | $M_V$ | $R_{1/2}$ (pc) | Distance (kpc) | $v_{hel}$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | [Fe/H] | $\sigma_{[Fe/H]}$ |
|---|---|---|---|---|---|---|---|
| Pegasus III | $-4.10^{+0.50}_{-0.50}$ | $78^{+31}_{-25}$ | $205.0^{+20.0}_{-20.0}$ | $-222.9^{+2.6}_{-2.6}$ | $5.4^{+3.0}_{-2.5}$ | $-2.40^{+0.15}_{-0.15}$ | |
| Aquarius II | $-4.36^{+0.14}_{-0.14}$ | $160^{+26}_{-26}$ | $107.9^{+3.3}_{-3.3}$ | $-71.1^{+2.5}_{-2.5}$ | $5.4^{+3.4}_{-0.9}$ | $-2.30^{+0.50}_{-0.50}$ | |
| Tucana II | $-3.90^{+0.20}_{-0.20}$ | $121^{+35}_{-35}$ | $58.0^{+8.0}_{-8.0}$ | $-129.1^{+3.5}_{-3.5}$ | $8.6^{+4.4}_{-2.7}$ | $-2.90^{+0.15}_{-0.16}$ | $0.29^{+0.15}_{-0.12}$ |
| Grus I | $-3.47^{+0.59}_{-0.59}$ | $28^{+23}_{-23}$ | $120.0^{+12.0}_{-11.0}$ | $-140.5^{+2.4}_{-1.6}$ | $2.9^{+2.1}_{-1.0}$ | $-1.42^{+0.55}_{-0.42}$ | $0.41^{+0.49}_{-0.23}$ |
| Pisces II | $-4.23^{+0.38}_{-0.38}$ | $60^{+10}_{-10}$ | $183.0^{+15.0}_{-15.0}$ | $-226.5^{+2.7}_{-2.7}$ | $5.4^{+3.6}_{-2.4}$ | $-2.45^{+0.07}_{-0.07}$ | $0.48^{+0.70}_{-0.29}$ |
| Tucana V | $-1.60^{+0.49}_{-0.49}$ | $16^{+5}_{-5}$ | $55.0^{+9.0}_{-9.0}$ | | | | |
| Phoenix II | $-2.70^{+0.40}_{-0.40}$ | $37^{+8}_{-8}$ | $84.3^{+4.0}_{-4.0}$ | | | | |
| Tucana III | $-1.49^{+0.20}_{-0.20}$ | $37^{+9}_{-9}$ | $25.0^{+2.0}_{-2.0}$ | $-102.3^{+0.4}_{-0.4}$ | $< 1.2^{c}$ | $-2.42^{+0.07}_{-0.08}$ | $< 0.19^{c}$ |

Sun: Mv = 4.8

100 Lsun = -0.2

$10^4$ Lsun = -5.2

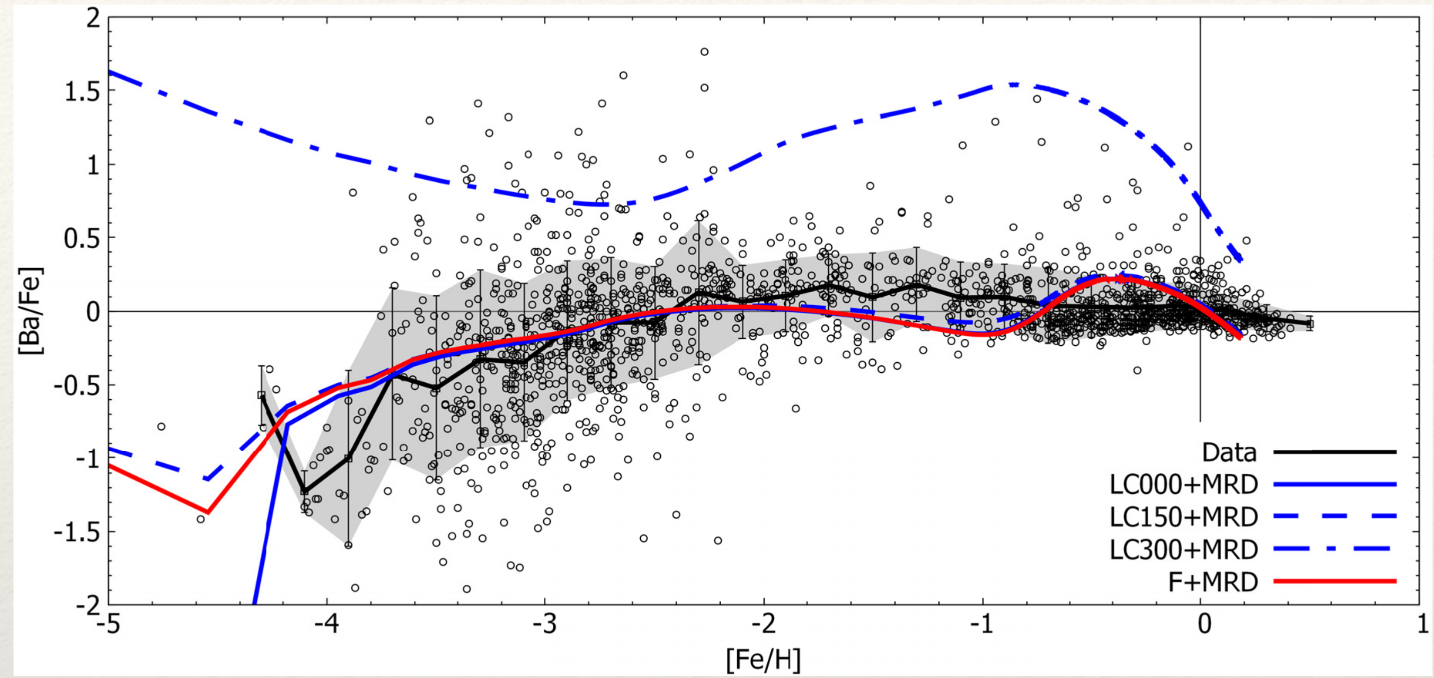
$10^5$ Lsun = -7.7

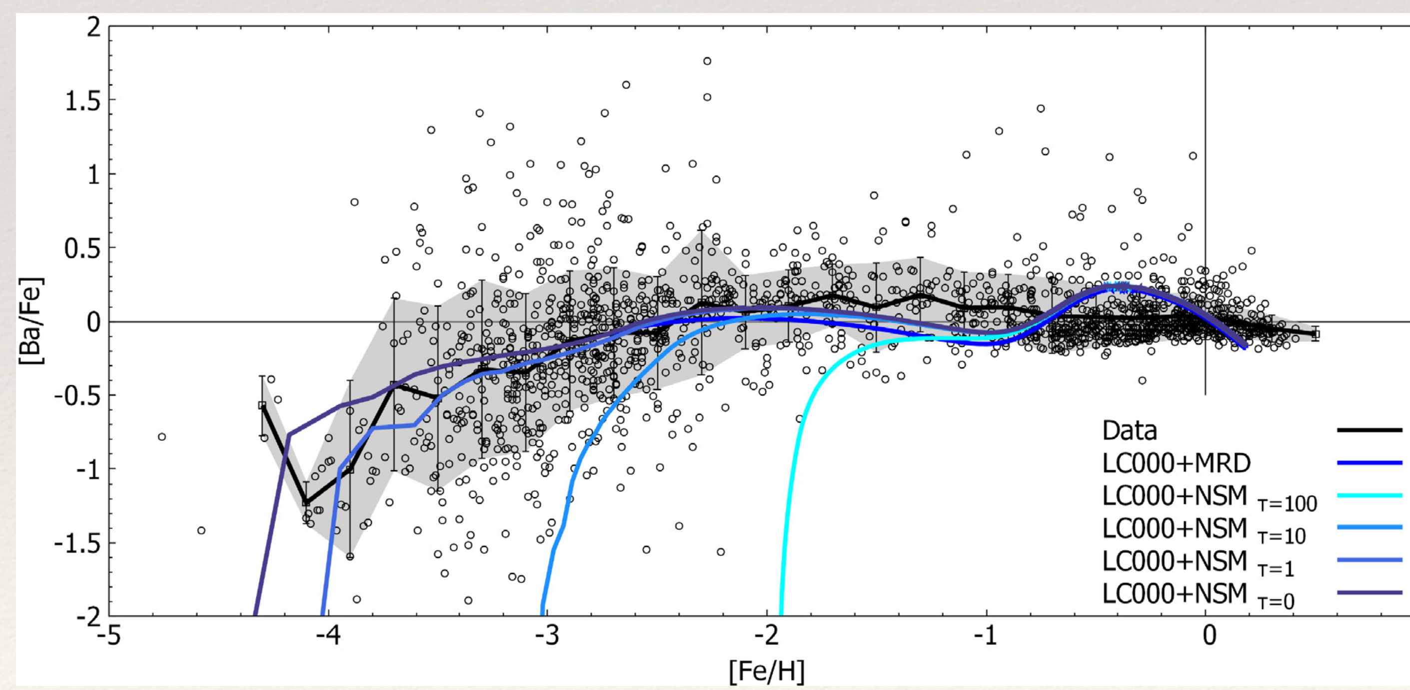
# Ba modeling in Milky-Way

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

Normalized to solar

- Rizutti+18: Rotating Massive stars (RMS)
  - r-process from NSM or Magneto-Rotationally Driven (MRD) SNe
  - The origin of Ba at [Fe/H] < -2 is mostly r-process.



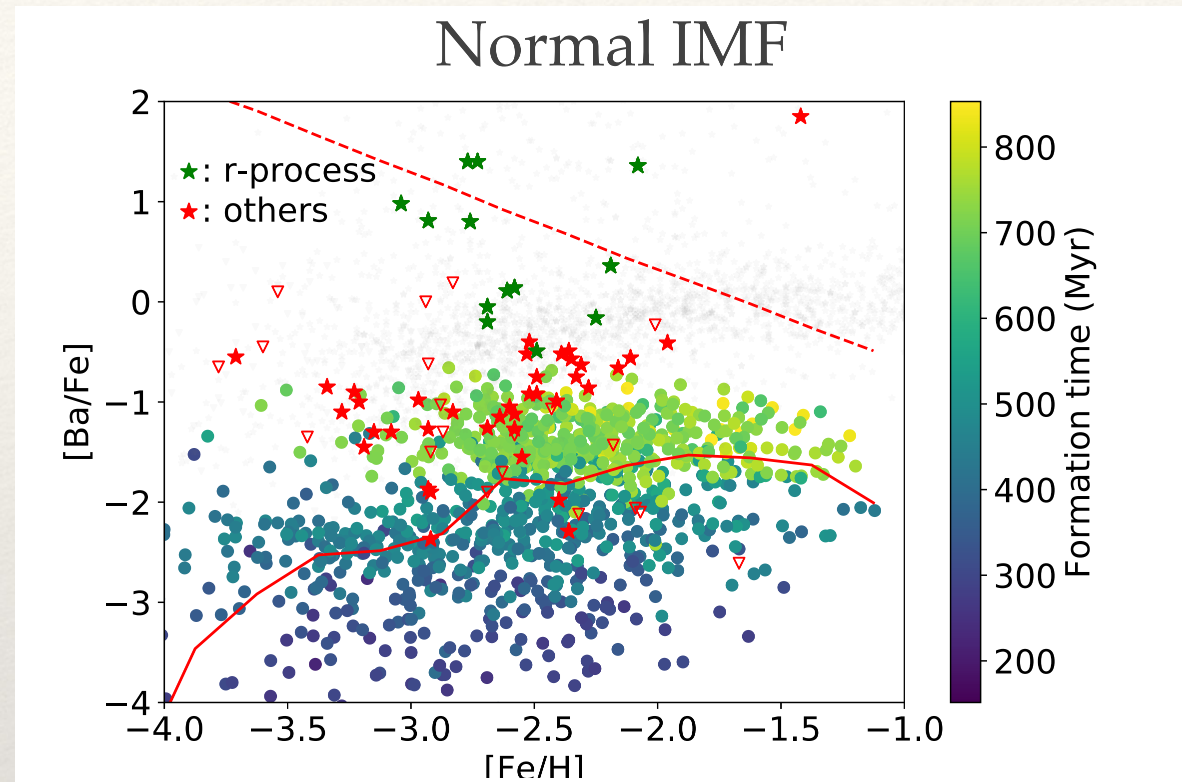

Rizutti+18

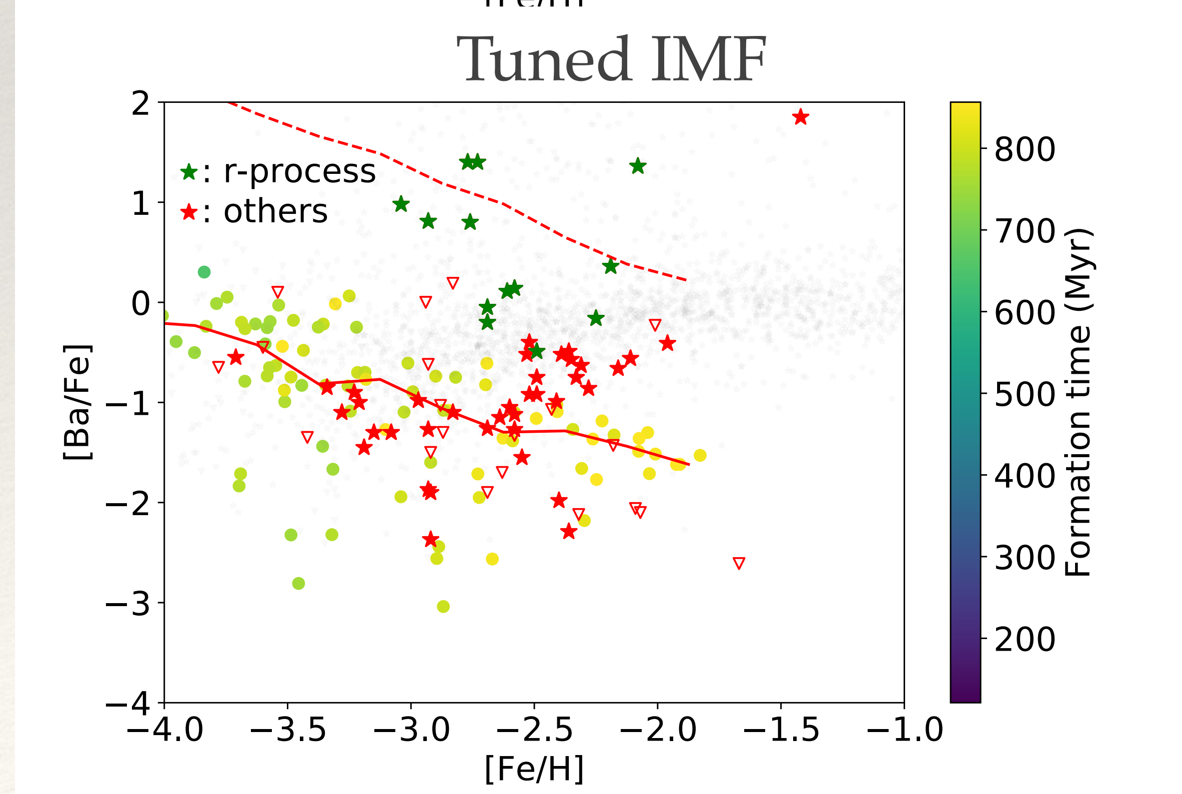
# Results: Modify IMF

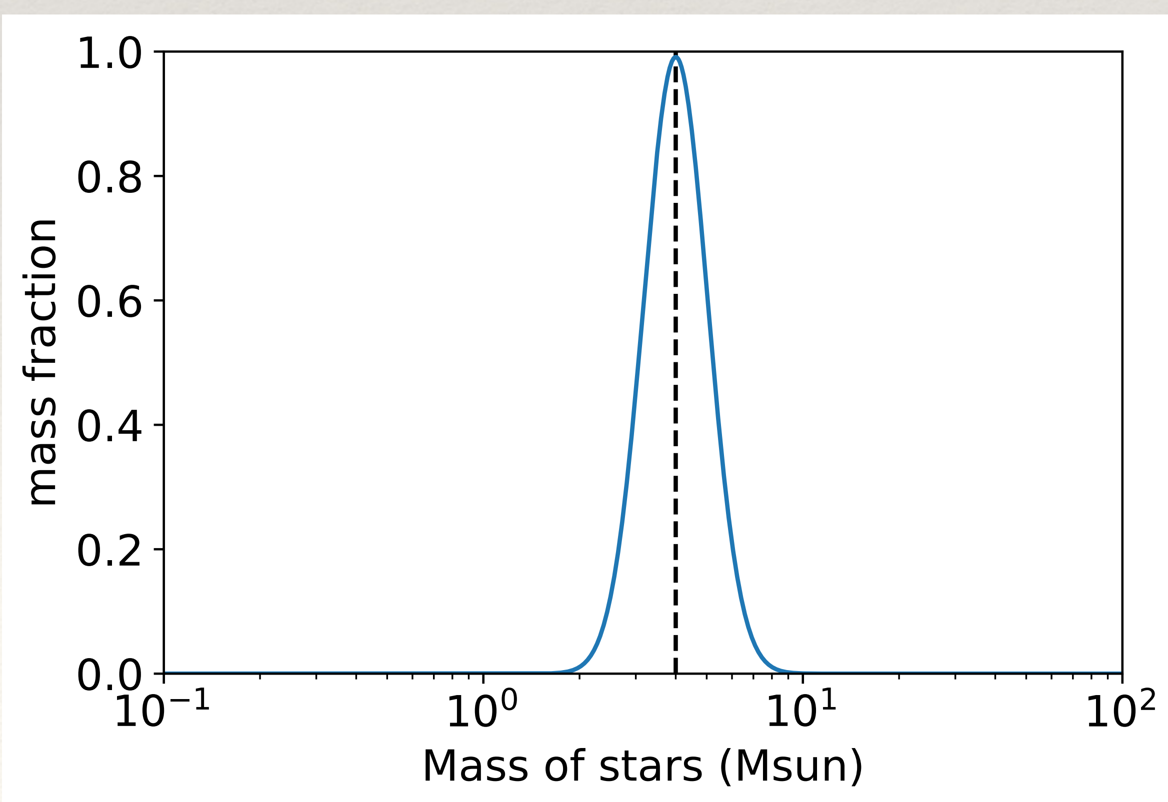
$$[X/Y] = \log_{10}\left[\frac{N_X}{N_Y}\right] + C$$

Normalized to solar

- Choosing IMF with smaller number of massive stars, [Ba/Fe] can be adjusted
- [Ba/Fe] **decreases** as [Fe/H] increases, as type-Ia is not negligible



# Discussion1: Comparison to MW

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

Normalized to solar

- The origin of Ba is "main" r-process and "main" s-process.
  - → (NSM or some other r-process) and (low-mass) AGB stars.
- **The stochasticity of r-process diversify [Ba/Fe]: MW should be somewhere between Eu-detected and other UFDs.**

- If we fix [Fe/H]:
  - MW is at higher density peak.
  - MW is larger than UFDs because of larger mixing mass.
  - → **Stochasticity ("0 or 1"-ness) is more important in UFDs than in MW.**