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s, i & r Element Nucleosynthesis

Lessons from Dwarf Galaxies

Ása Skúladóttir
University of Florence

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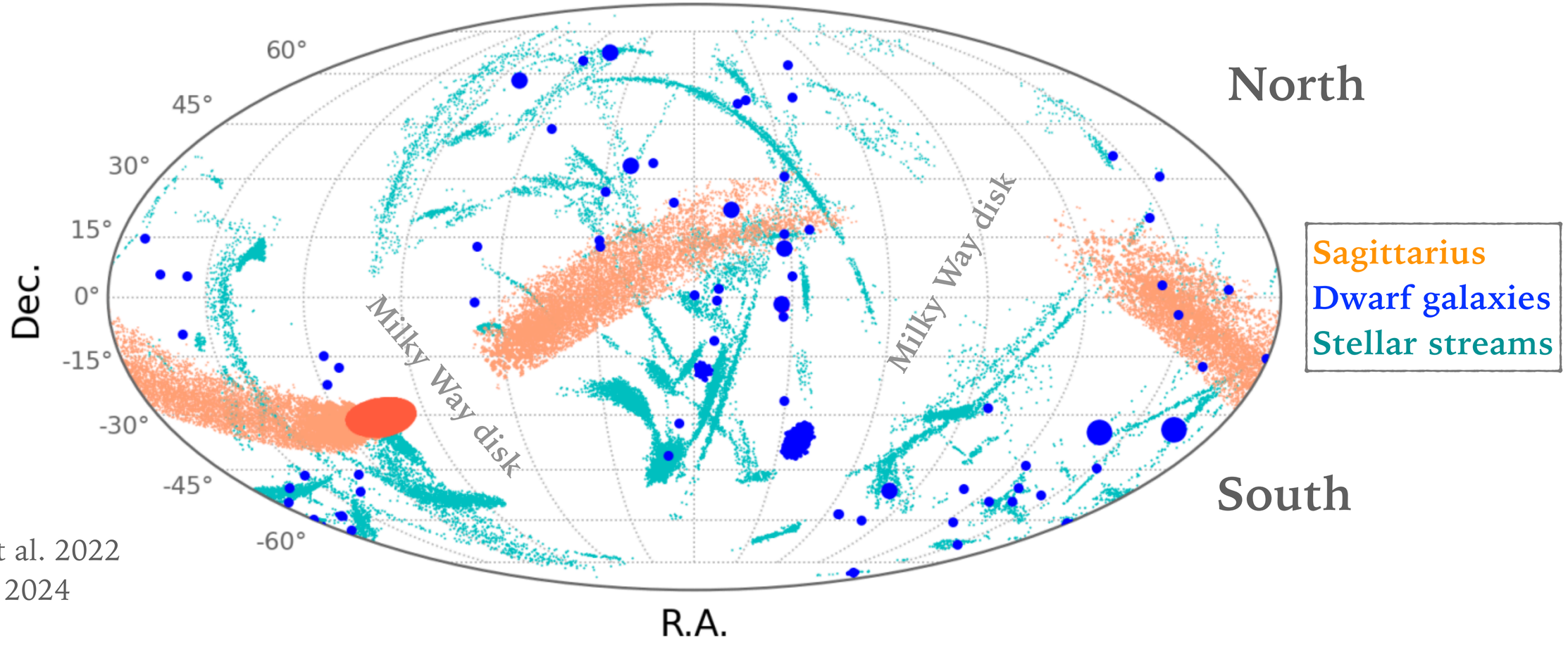
FIRENZE

sirEN conference - Giulianova, Italy - 13th of June 2025

DWARF GALAXIES AROUND THE MILKY WAY

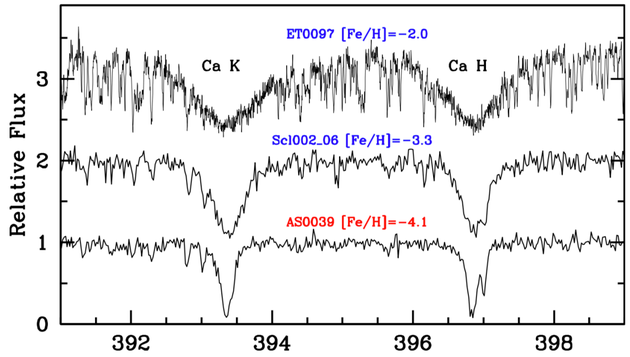
➤ The **Milky Way** has many satellite **dwarf galaxies**, and **stellar streams**.



Data from:
Battaglia et al. 2022
Ibata et al. 2024

DWARF GALAXIES AROUND THE MILKY WAY

VLT

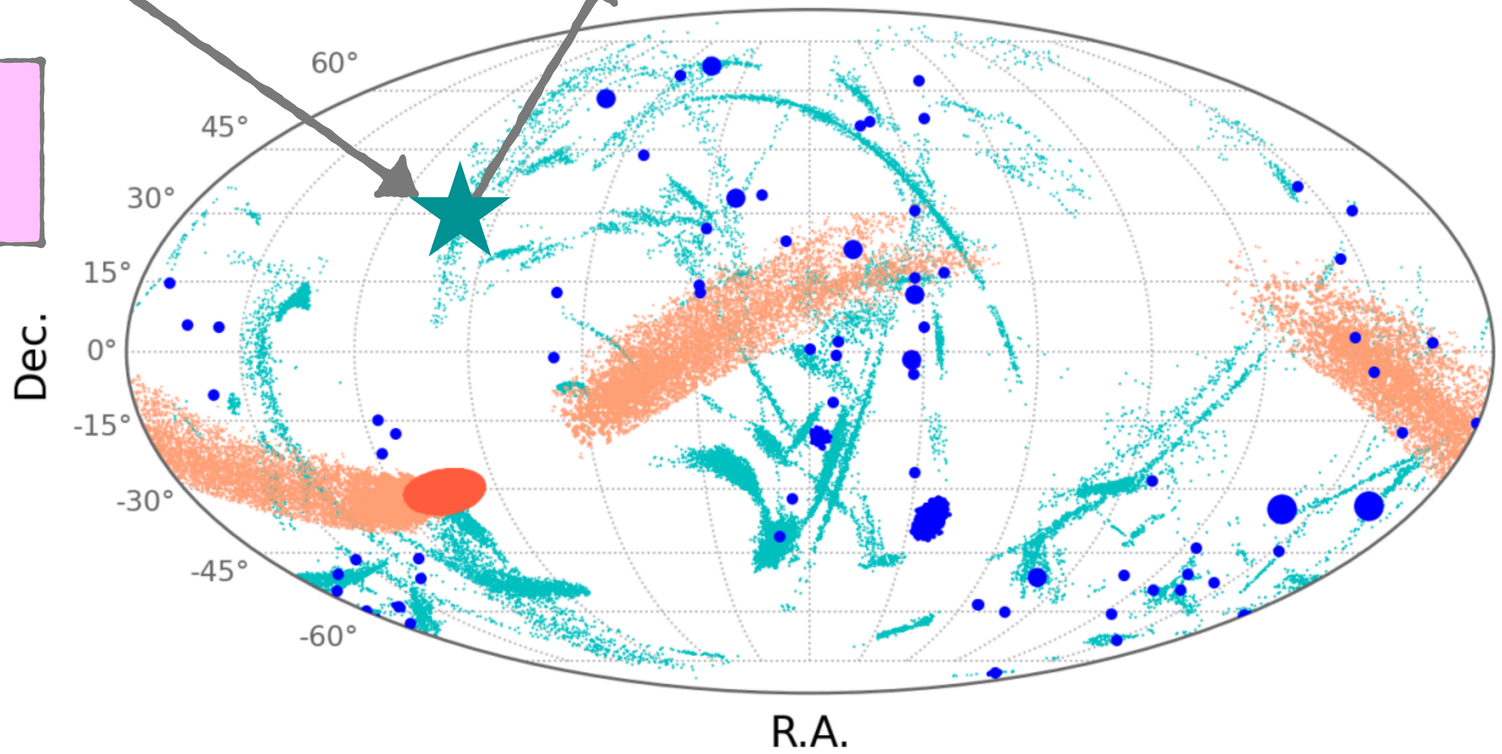


Gaia

Positions
Proper motions
Photometry

Spectra

Chemical abundances
Line-of-sight velocities
Stellar ages



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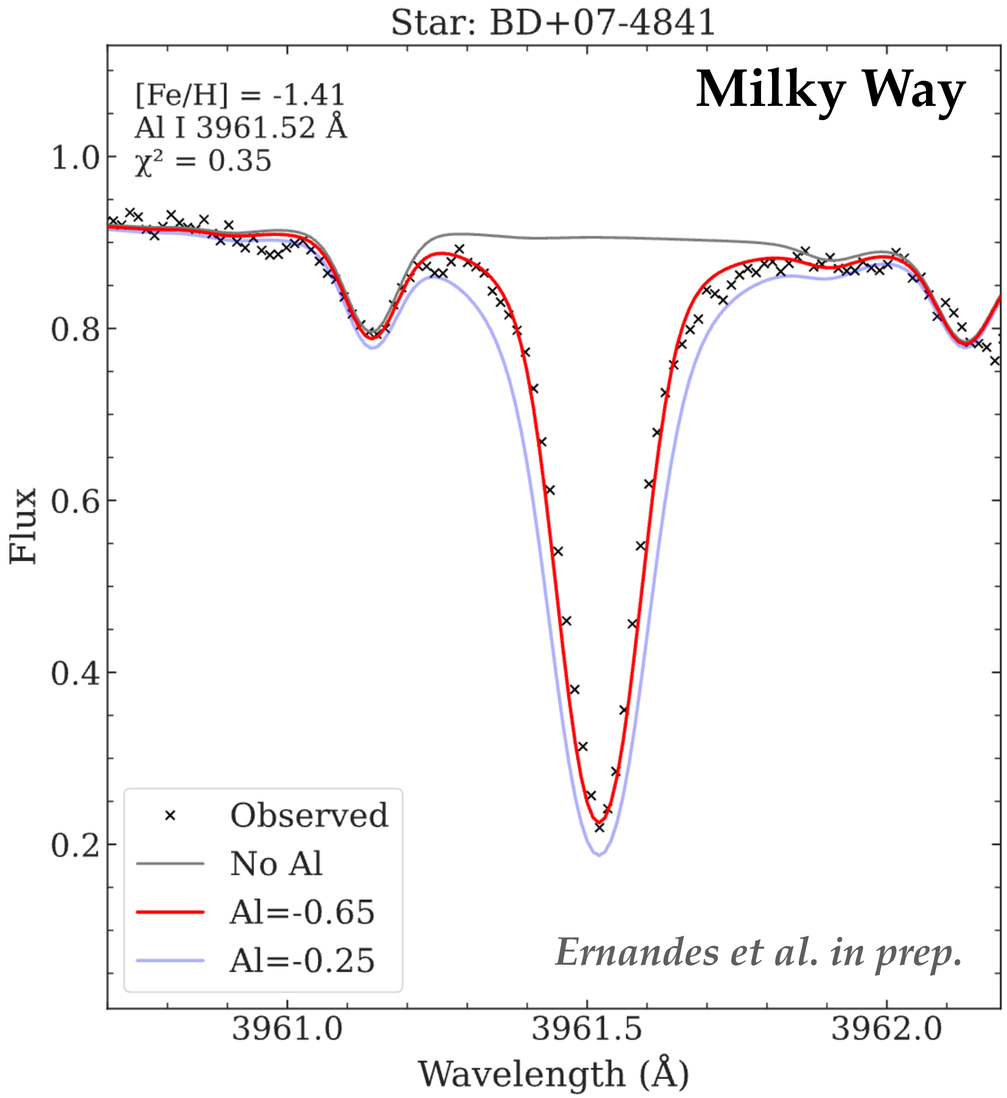
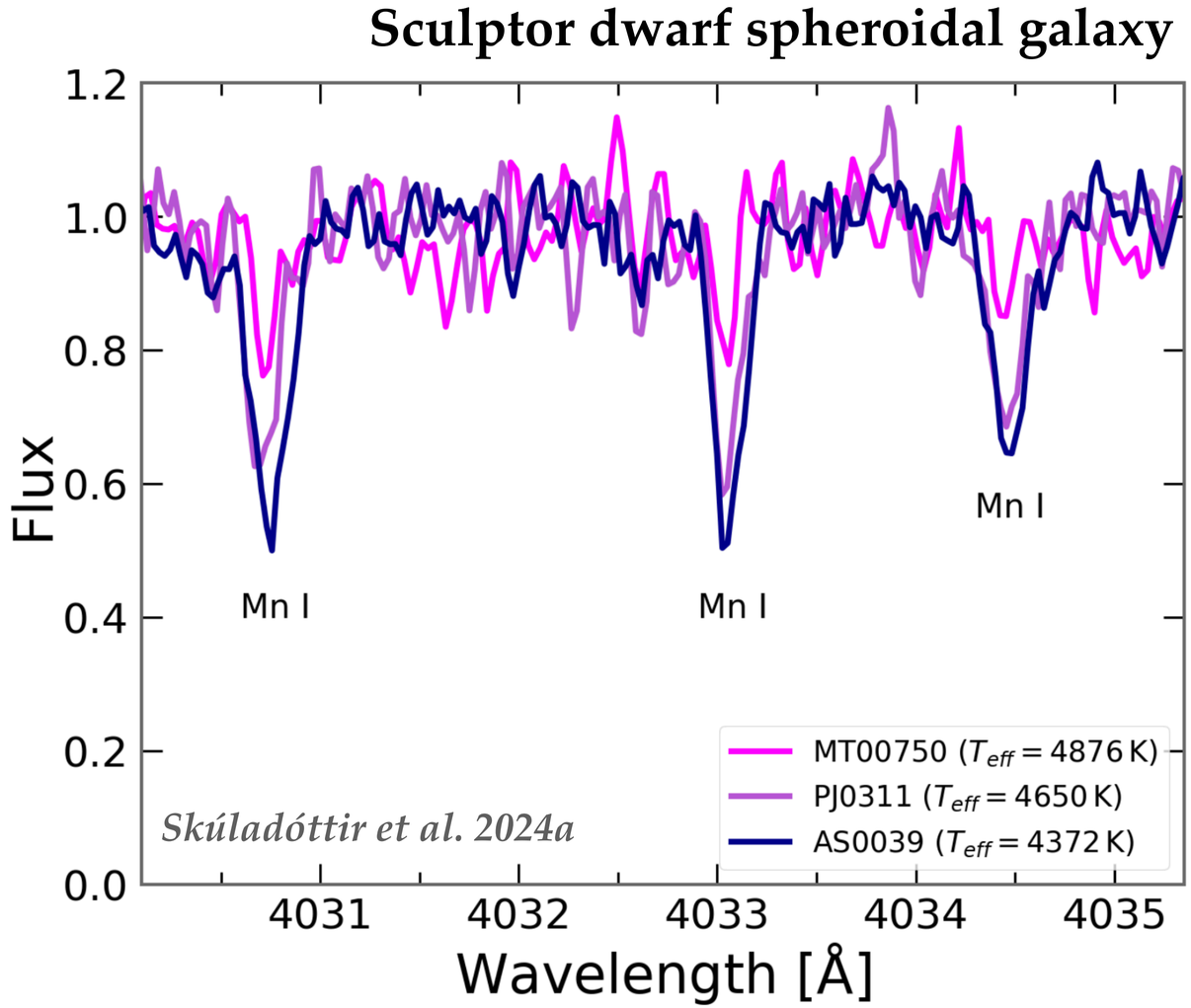
CHALLENGES OF GETTING HIGH-QUALITY SPECTRA





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Tracing individual events

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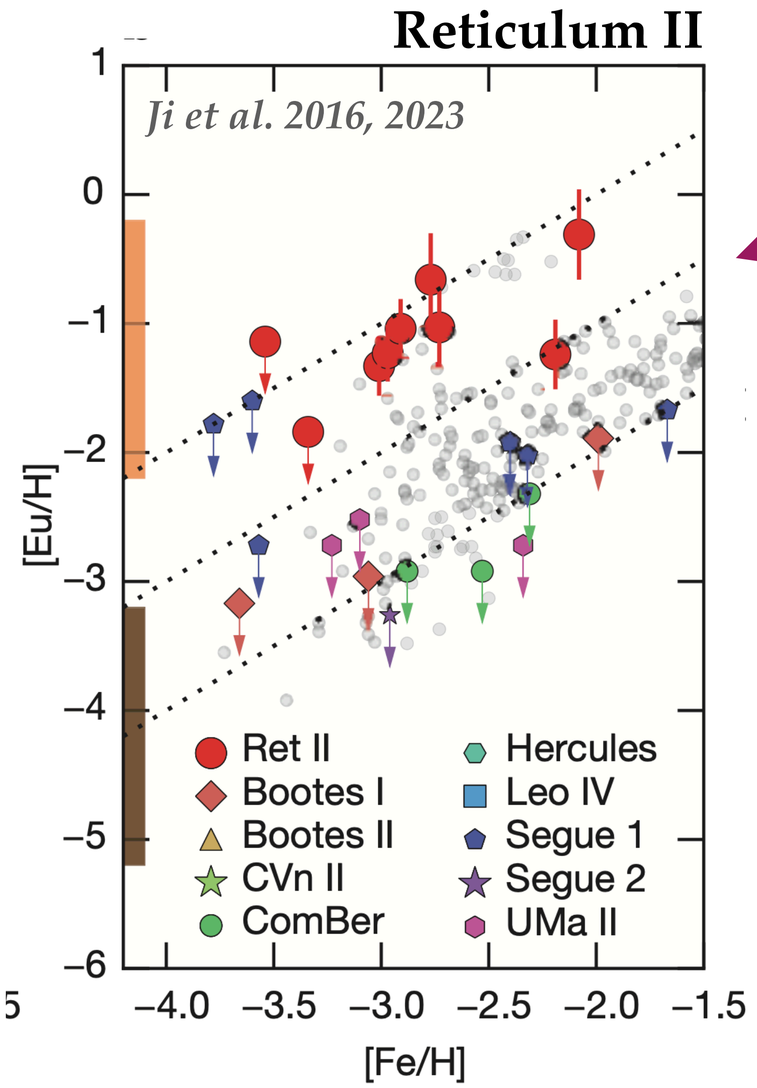
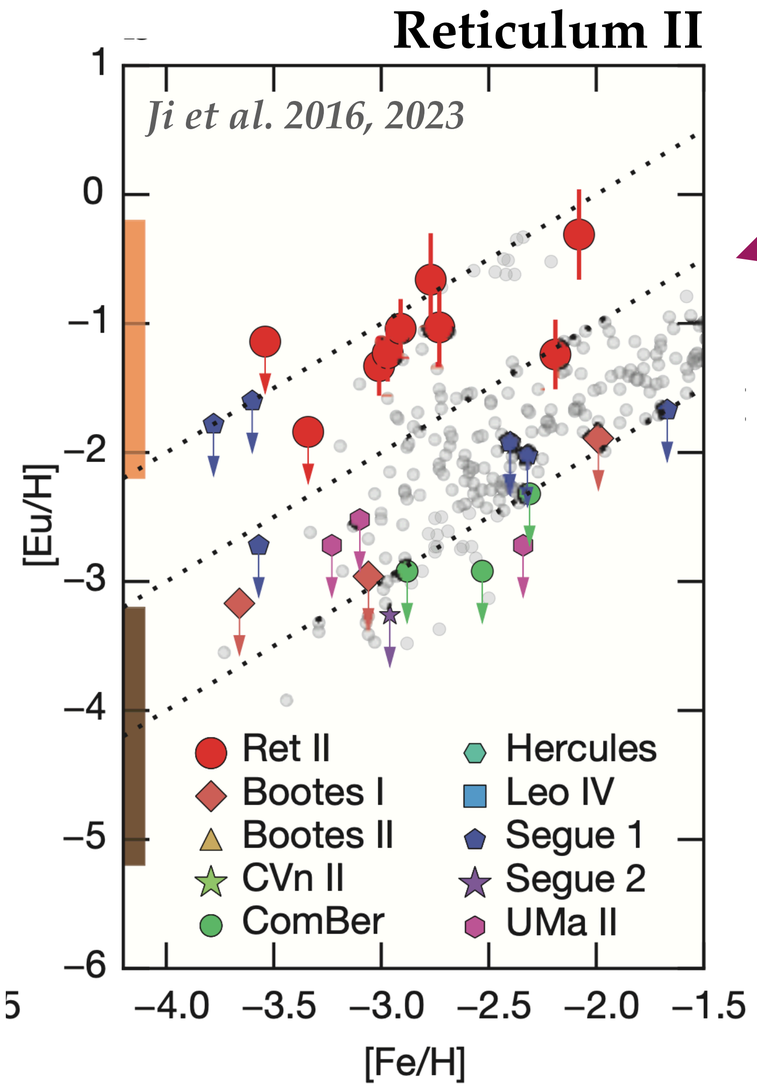
R-PROCESS RICH STARS



Ultra faint dwarf galaxy (UFD) enriched in r-process!

R-PROCESS RICH STARS



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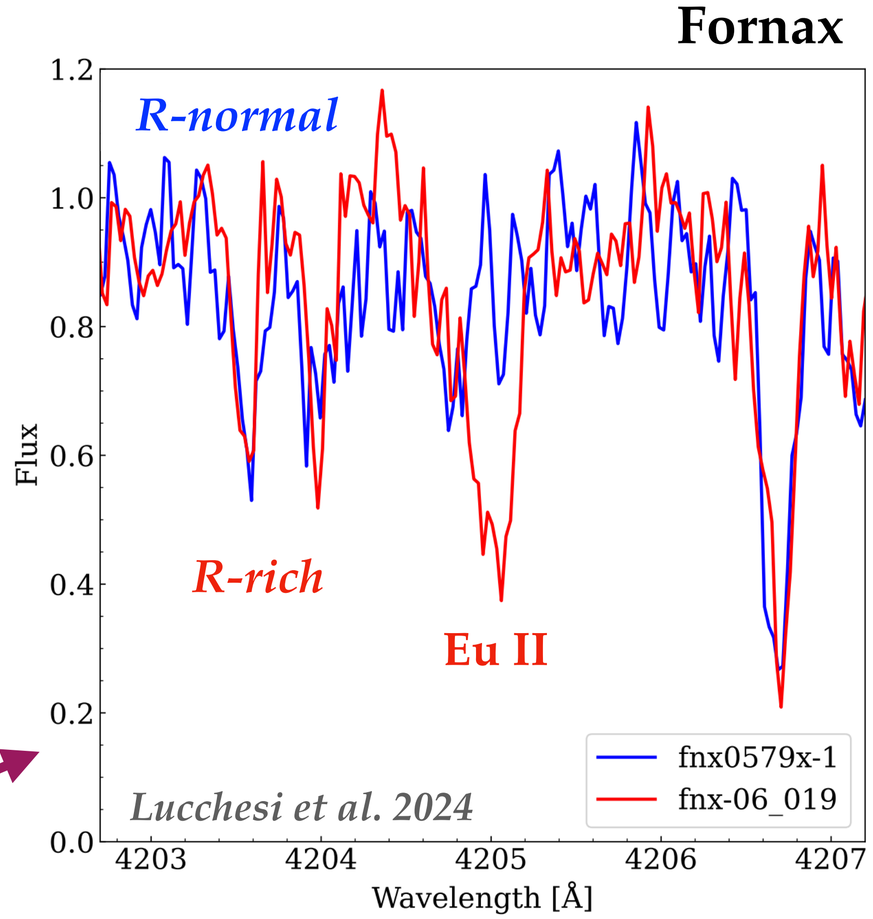
The most metal-poor r-rich star in a dwarf spheroidal galaxy (dSph),
[Fe/H]=-3
[Eu/Fe]=+0.8



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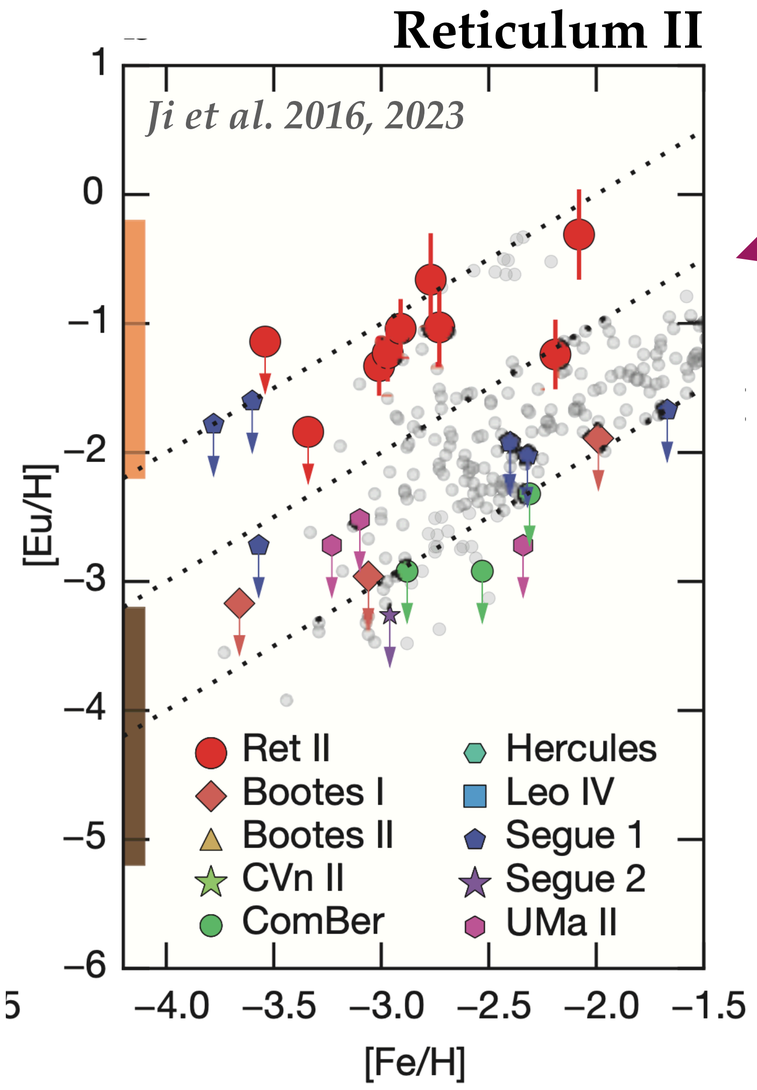

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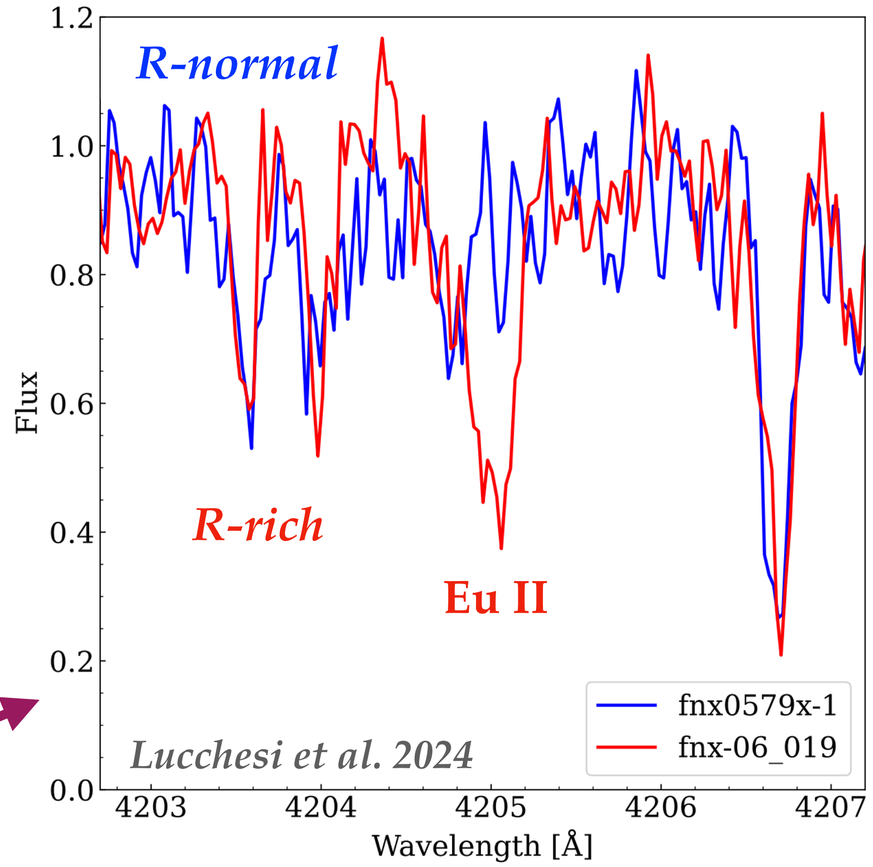
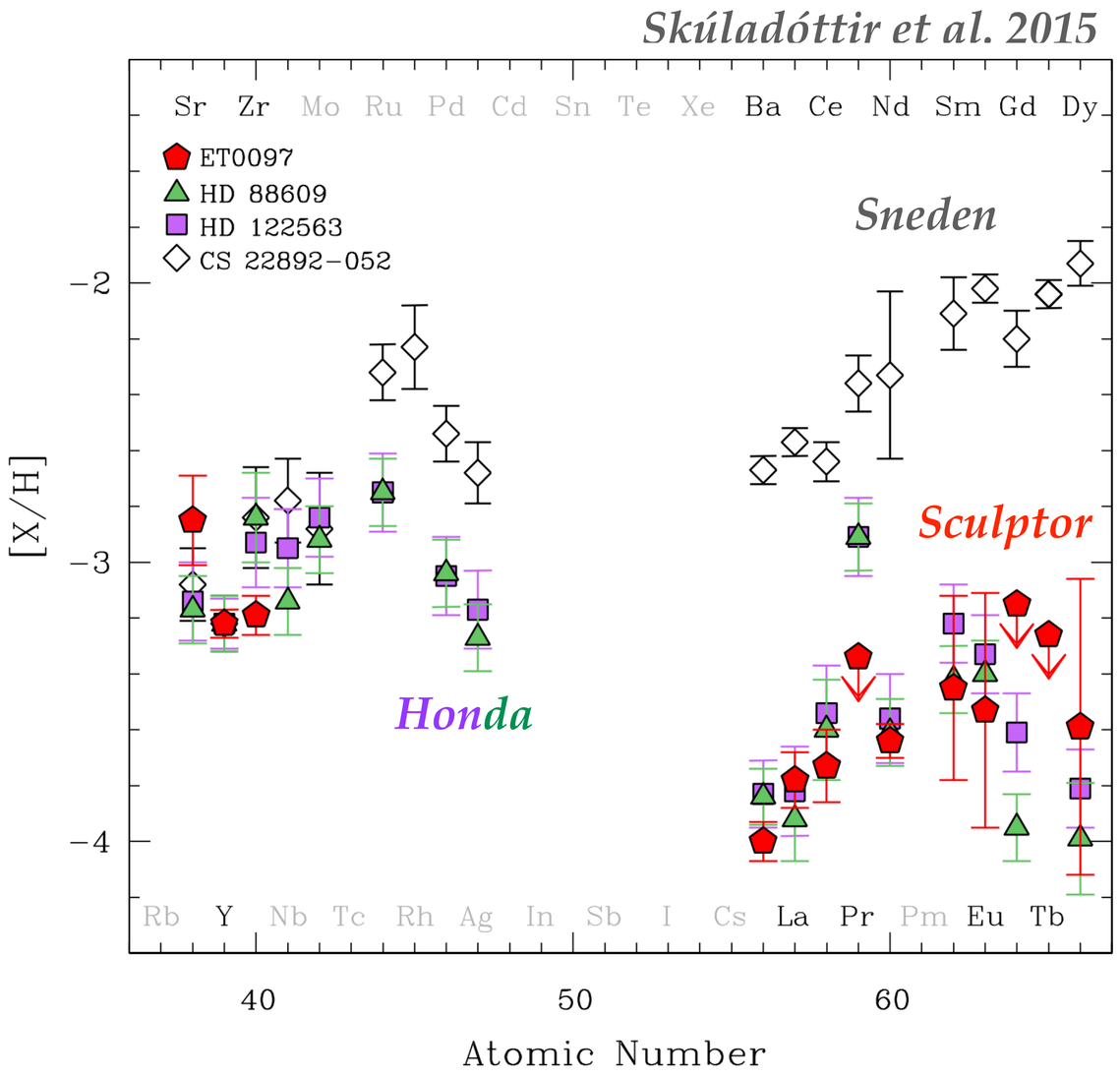


R-process events are rare and prolific.
They can happen in any galaxy
Present in the early Universe (few ~100 Myrs)

HONDA STARS IN DWARF GALAXIES!



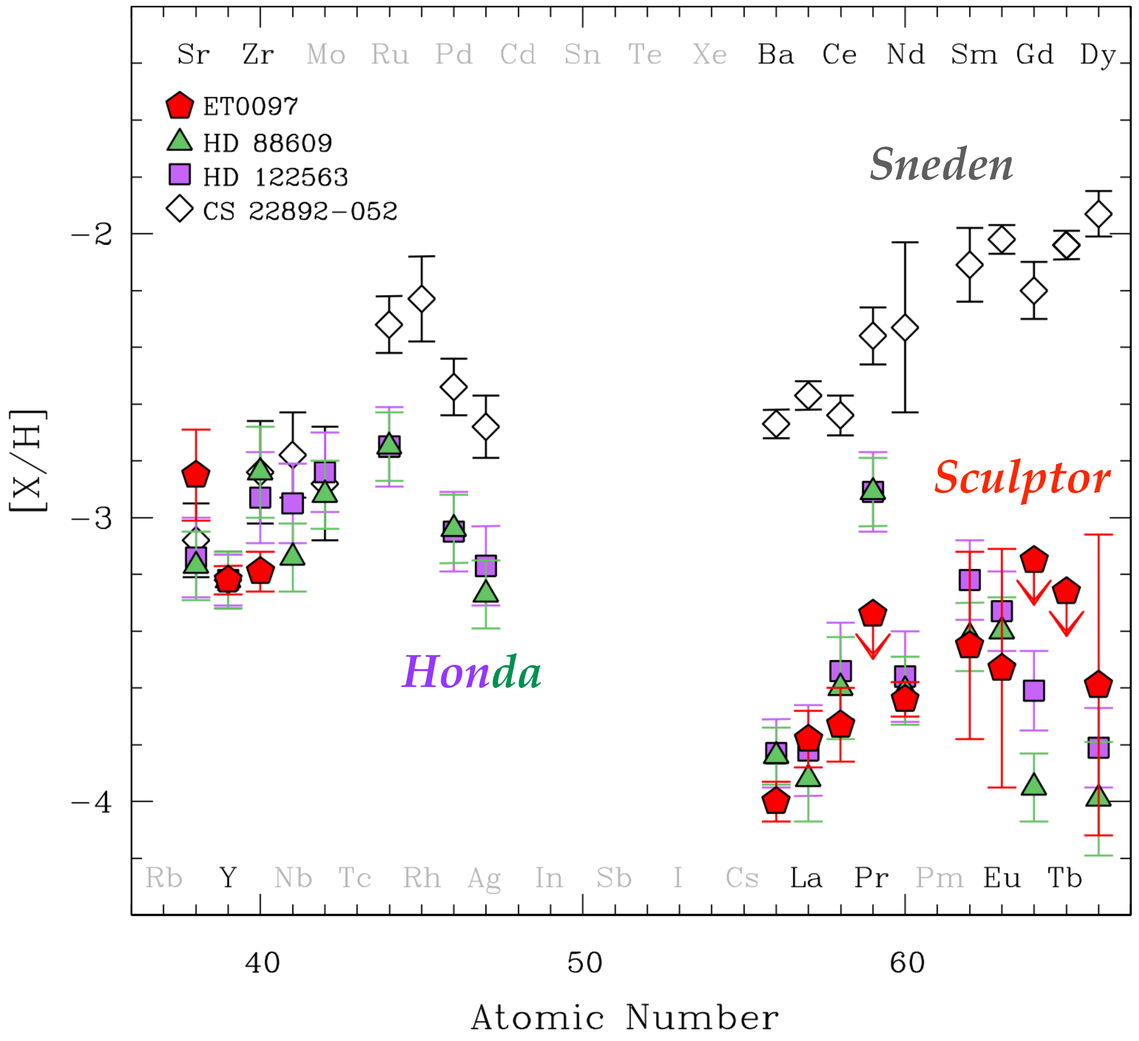
Honda stars (rich in the first peak) can be found in dwarf galaxies…

…but they are typically Carbon-rich!

(See also: Susmitha et al. 2017, Spite et al. 2018)

HONDA STARS IN DWARF GALAXIES!

Skúladóttir et al. 2015



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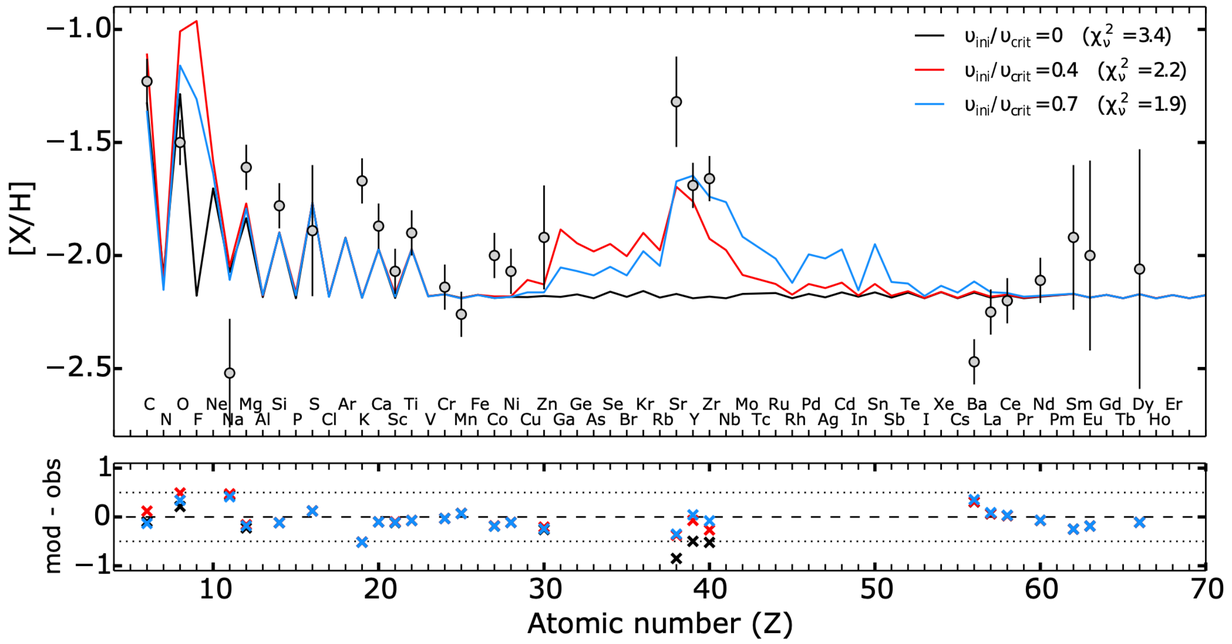
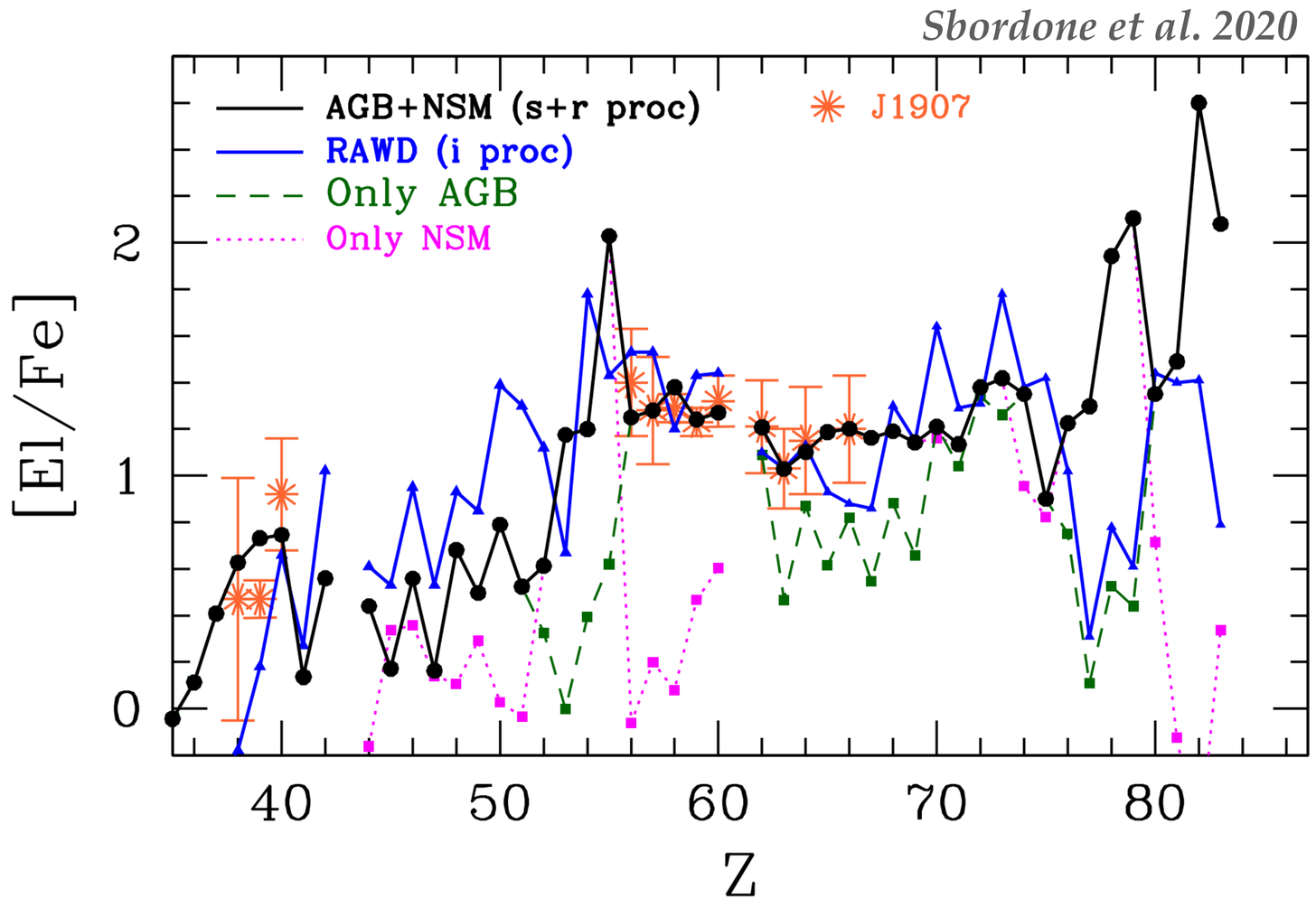
Massive star models of A. Choplin (Skúladóttir et al. 2020)



CEMP-R/S STAR IN SAGITTARIUS



Signature of the i-process?

Are the CEMP-s and r/s stars the same as in the Milky Way?

Population studies of CEMP-s and r/s star severely lacking!

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The r-process

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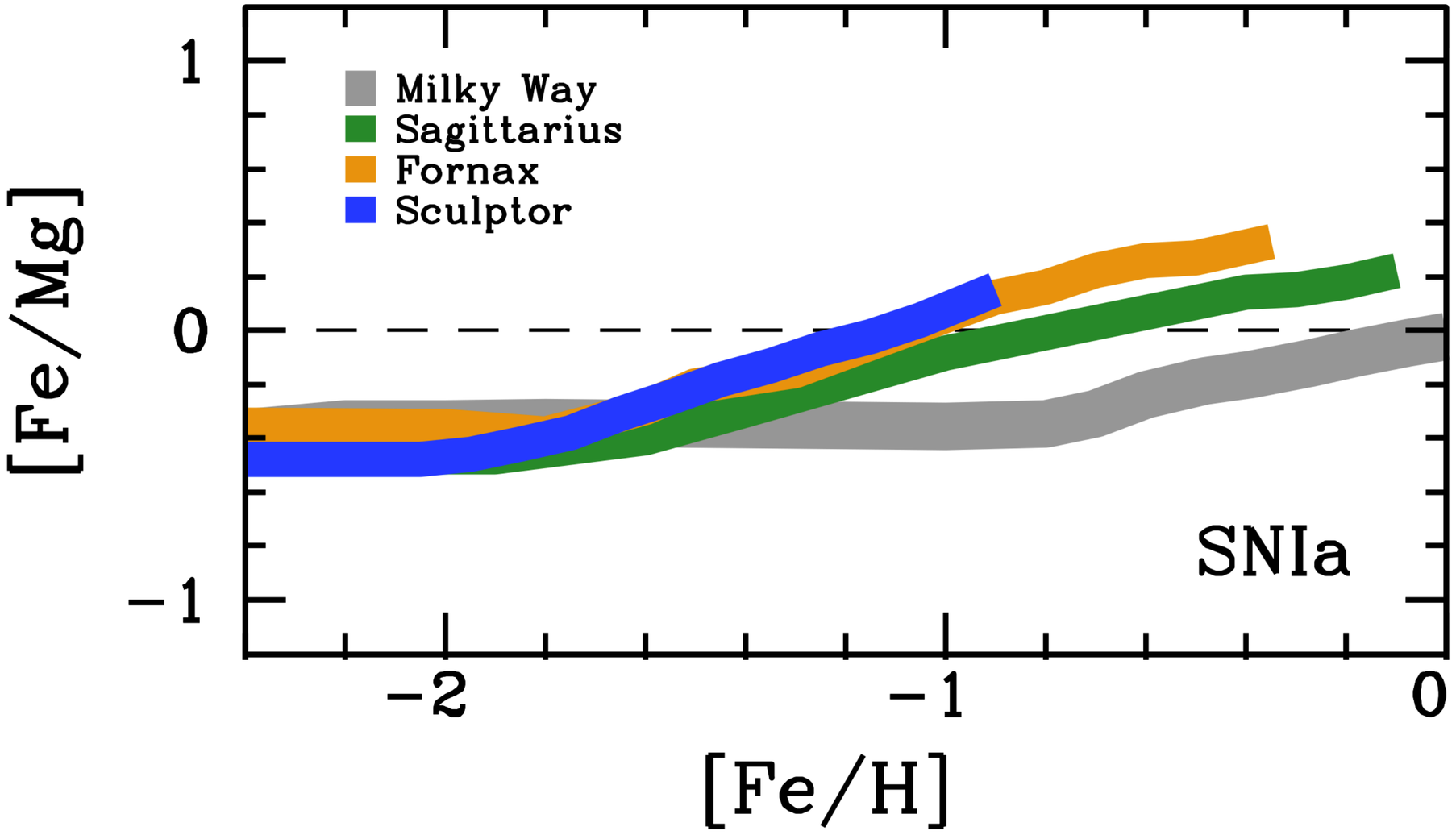
Skúladóttir & Salvadori 2020

DELAYED PROCESSES – SUPERNOVA TYPE IA



Skúladóttir & Salvadori 2020

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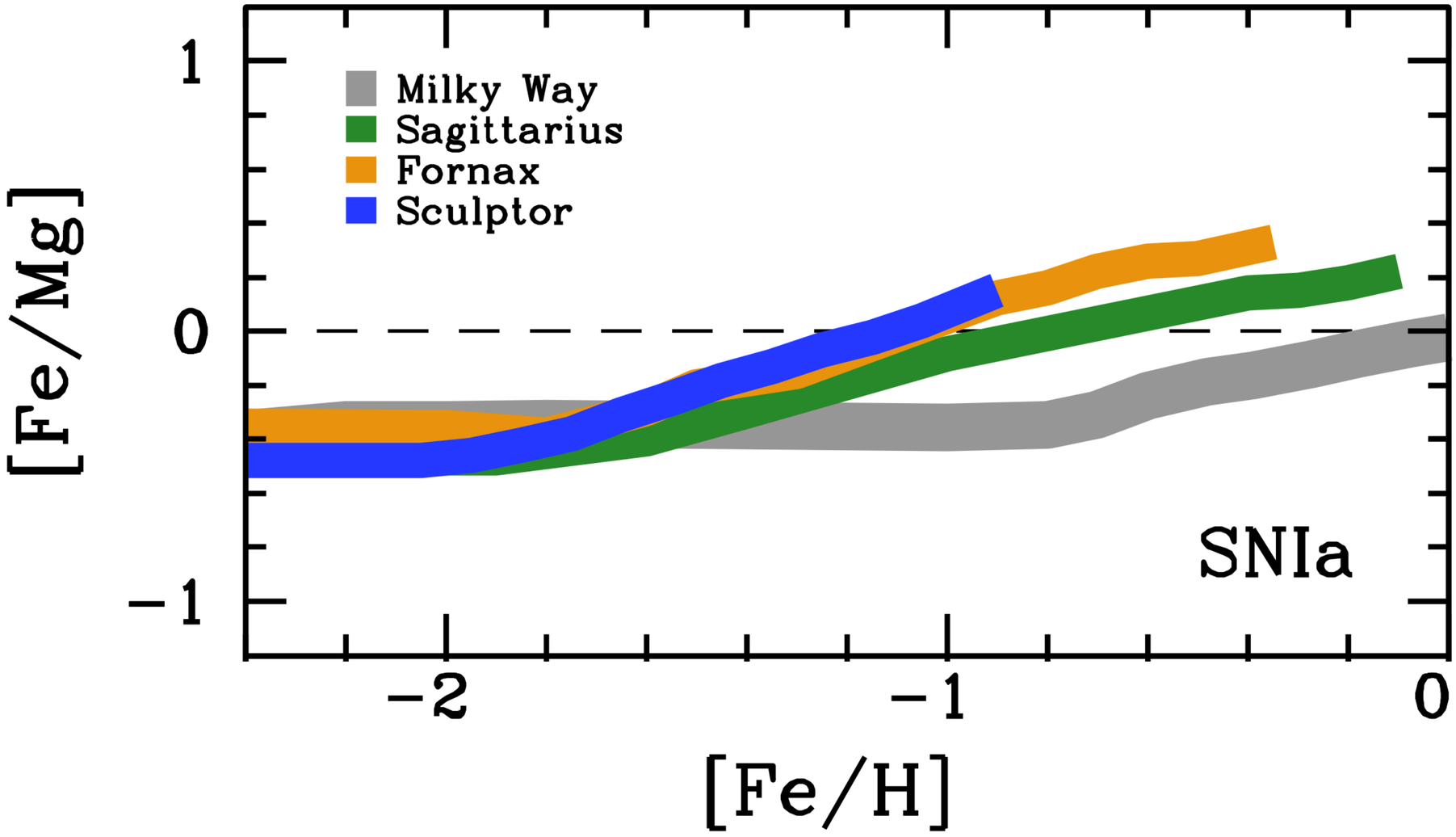

Time

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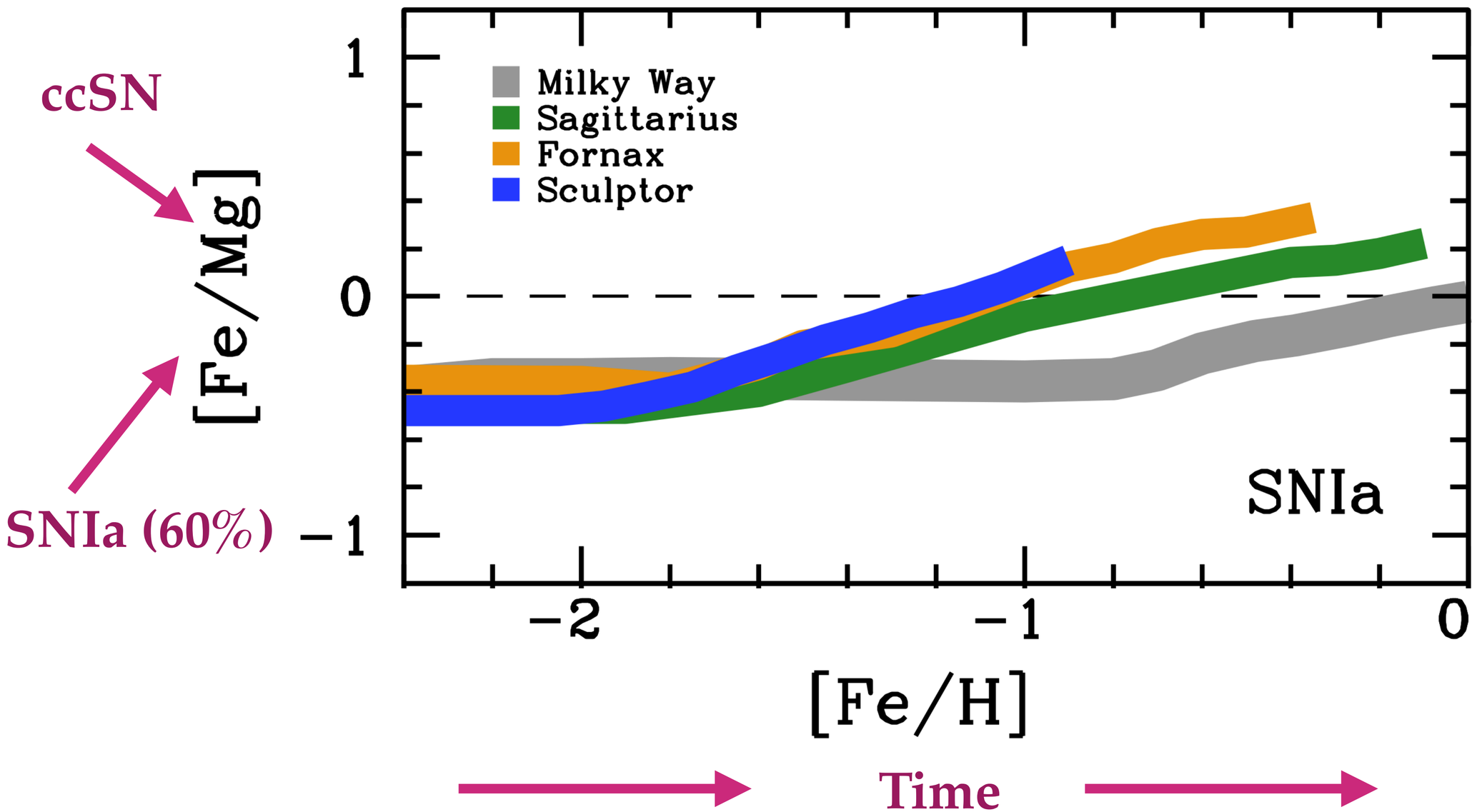

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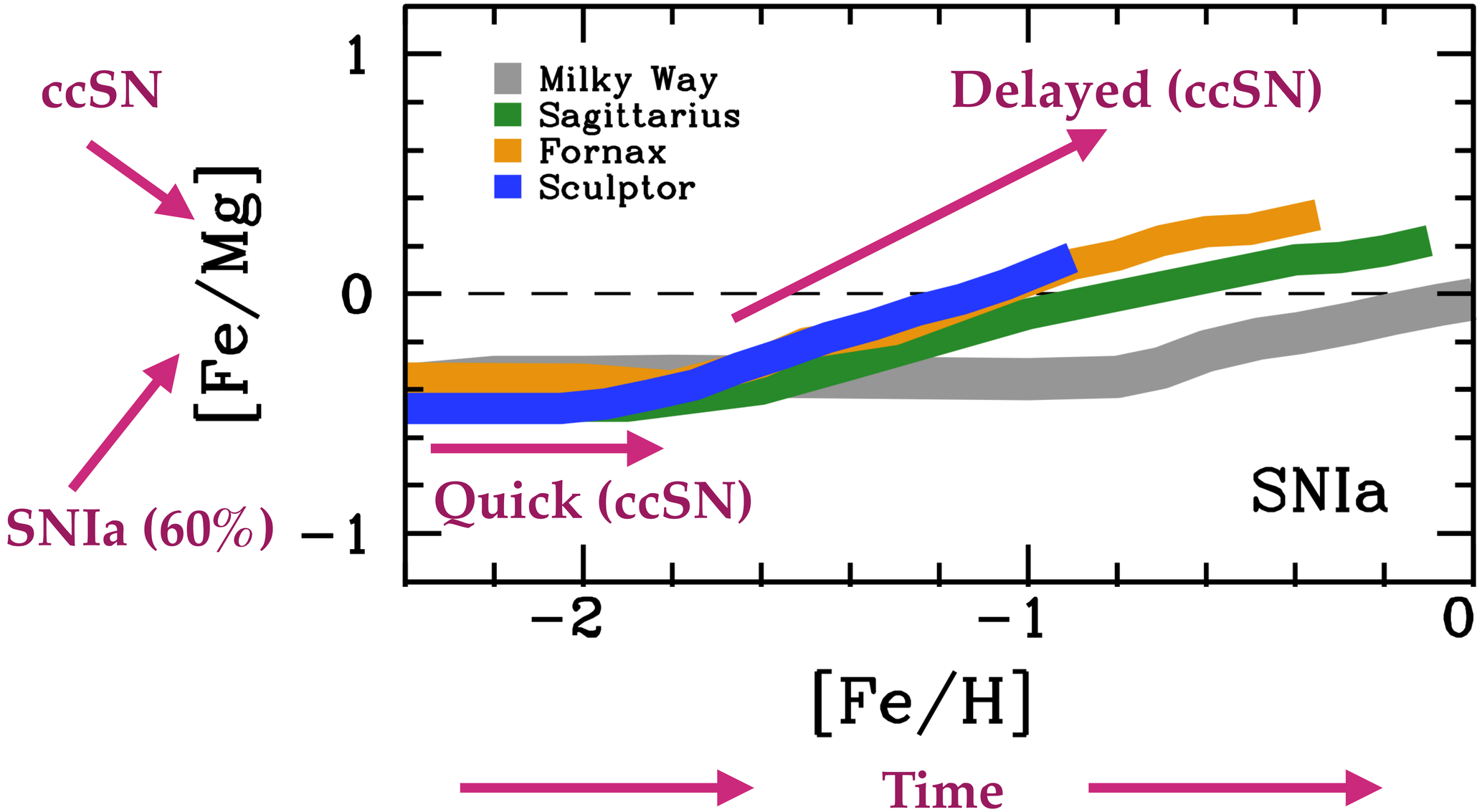

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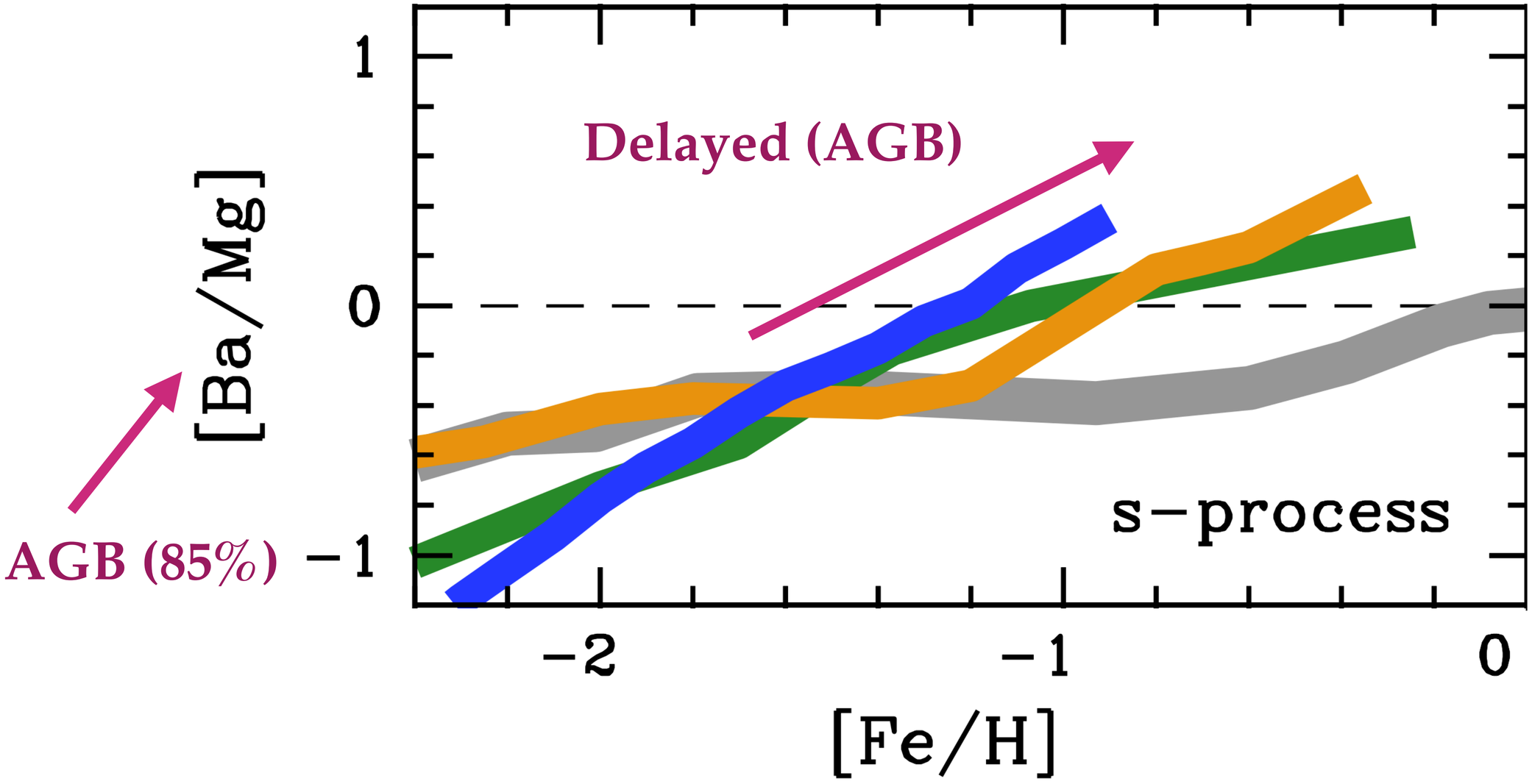
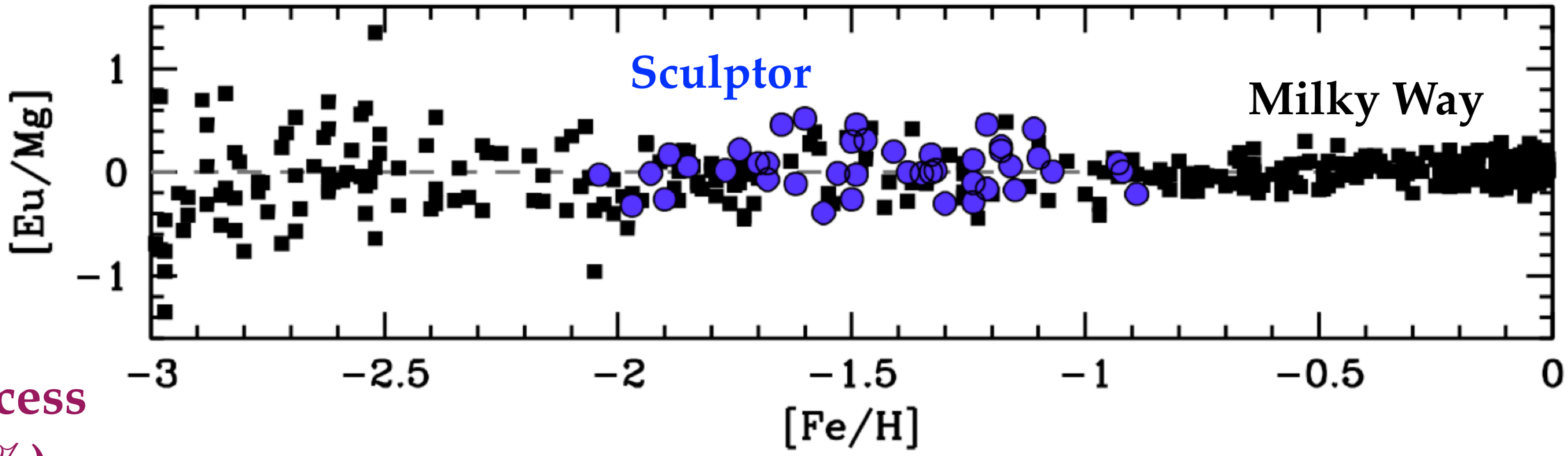
DELAYED PROCESSES – AGB STARS



DELAYED PROCESSES – R-PROCESS

Skúladóttir et al. 2019



r-process (94%)

DELAYED PROCESSES – R-PROCESS

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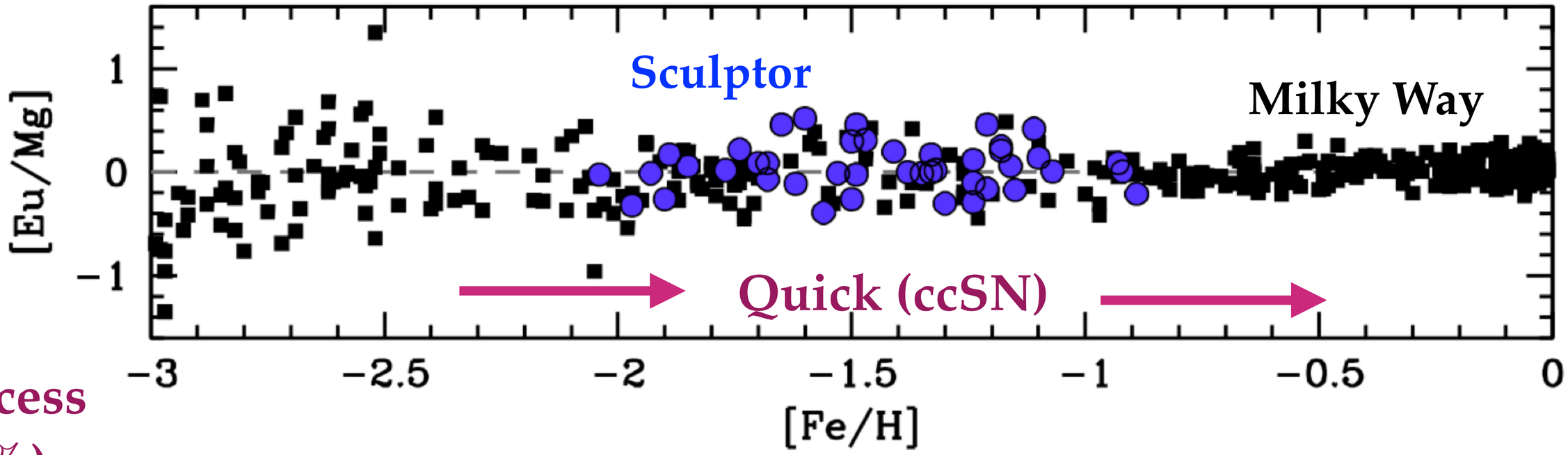

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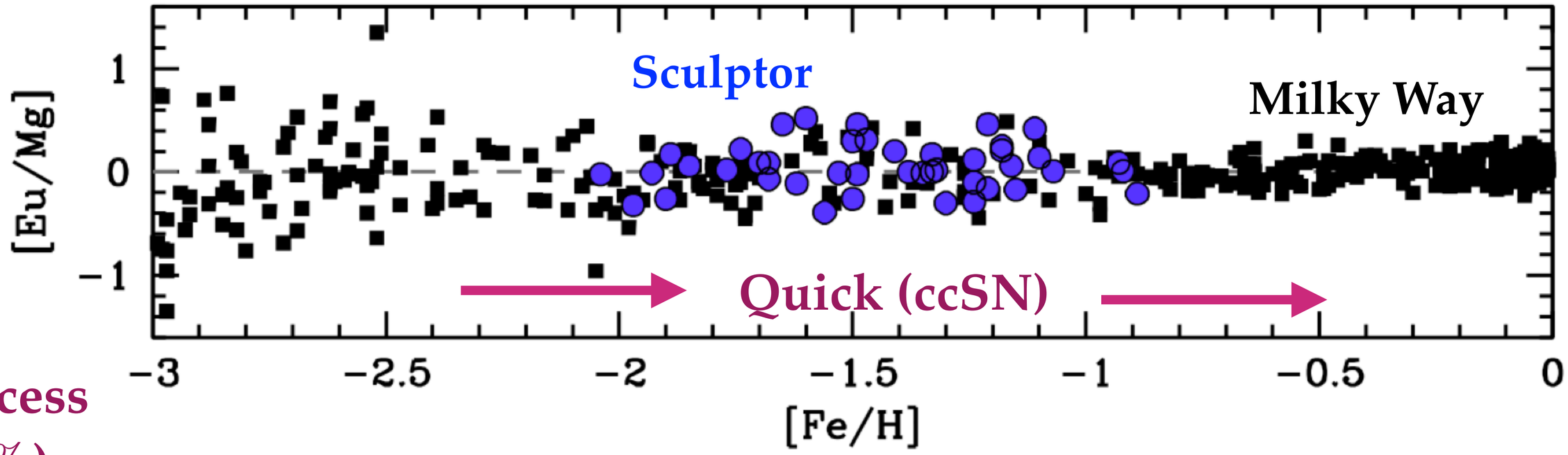
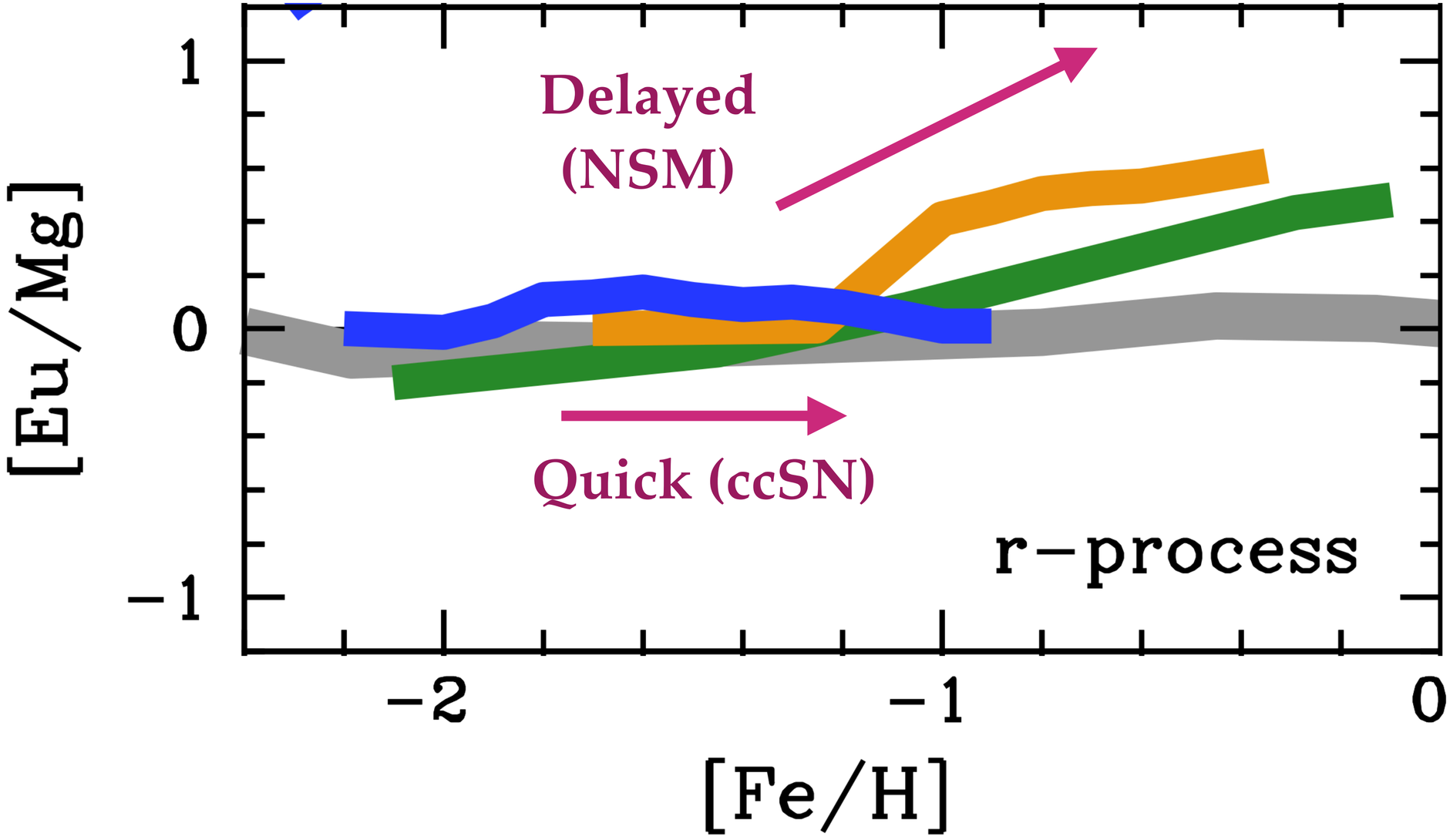


r-process (94%)

The r-process in Sculptor and the Milky Way is not delayed

Skúladóttir & Salvadori 2020

DELAYED PROCESSES – R-PROCESS



Skúladóttir & Salvadori 2020

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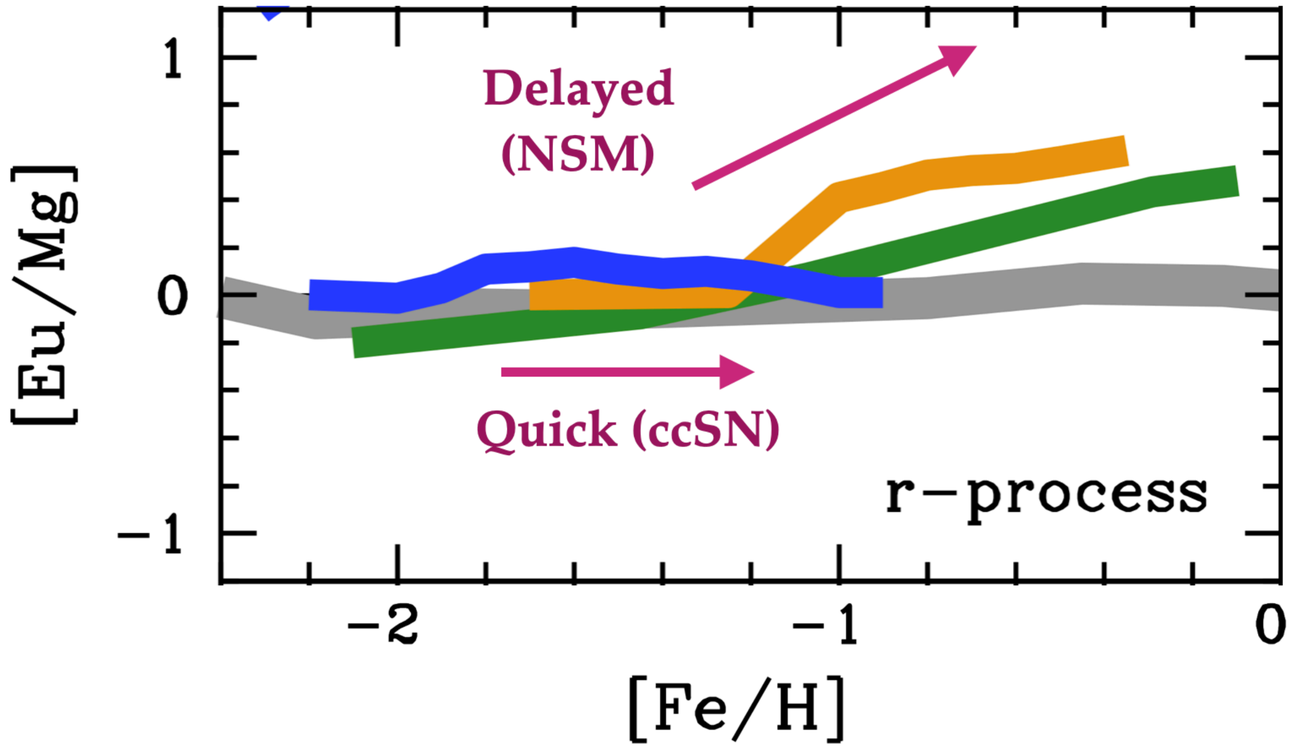
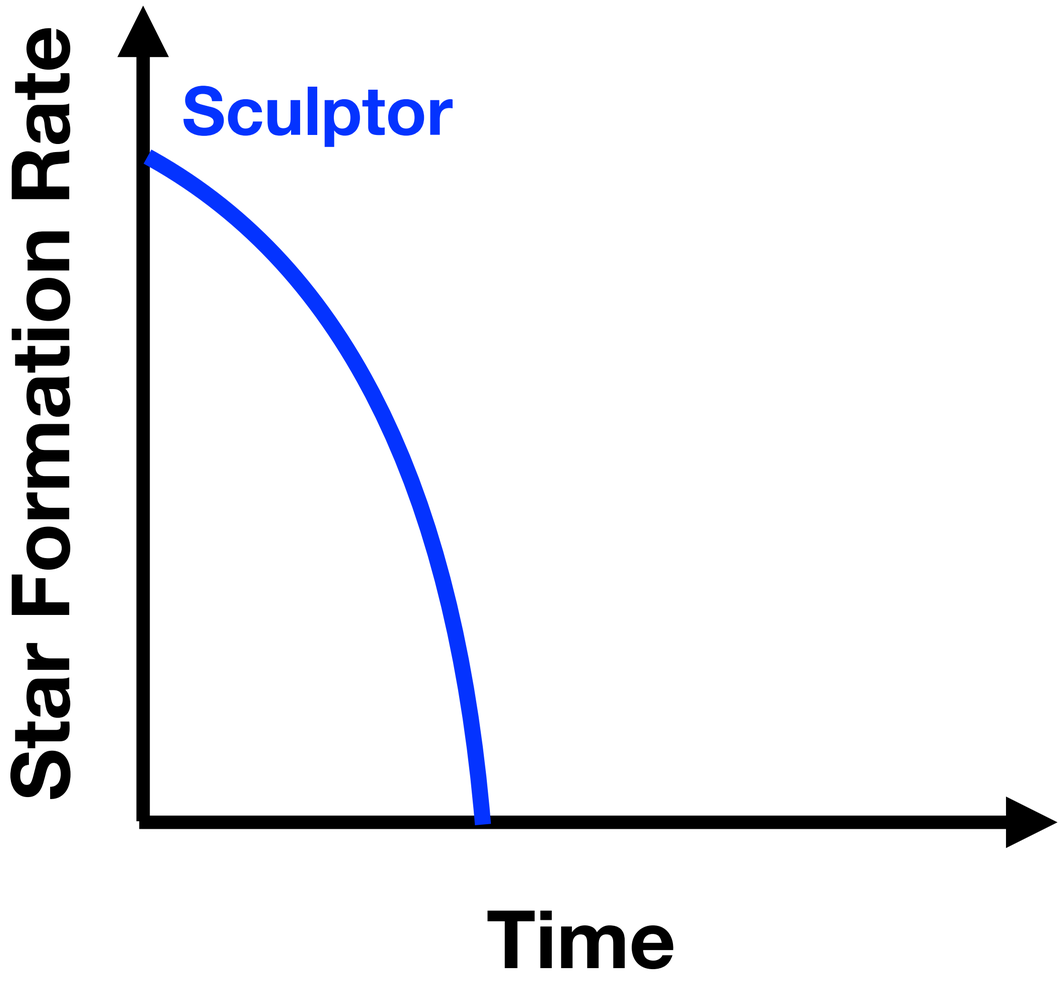


Two processes are needed to explain the data: Quick (ccSN) and Delayed (NSM)

Skúladóttir & Salvadori 2020

WHY IS SCULPTOR DOMINATED BY THE QUICK R-PROCESS?



Star formation in Sculptor is too short!

Skúladóttir & Salvadori 2020

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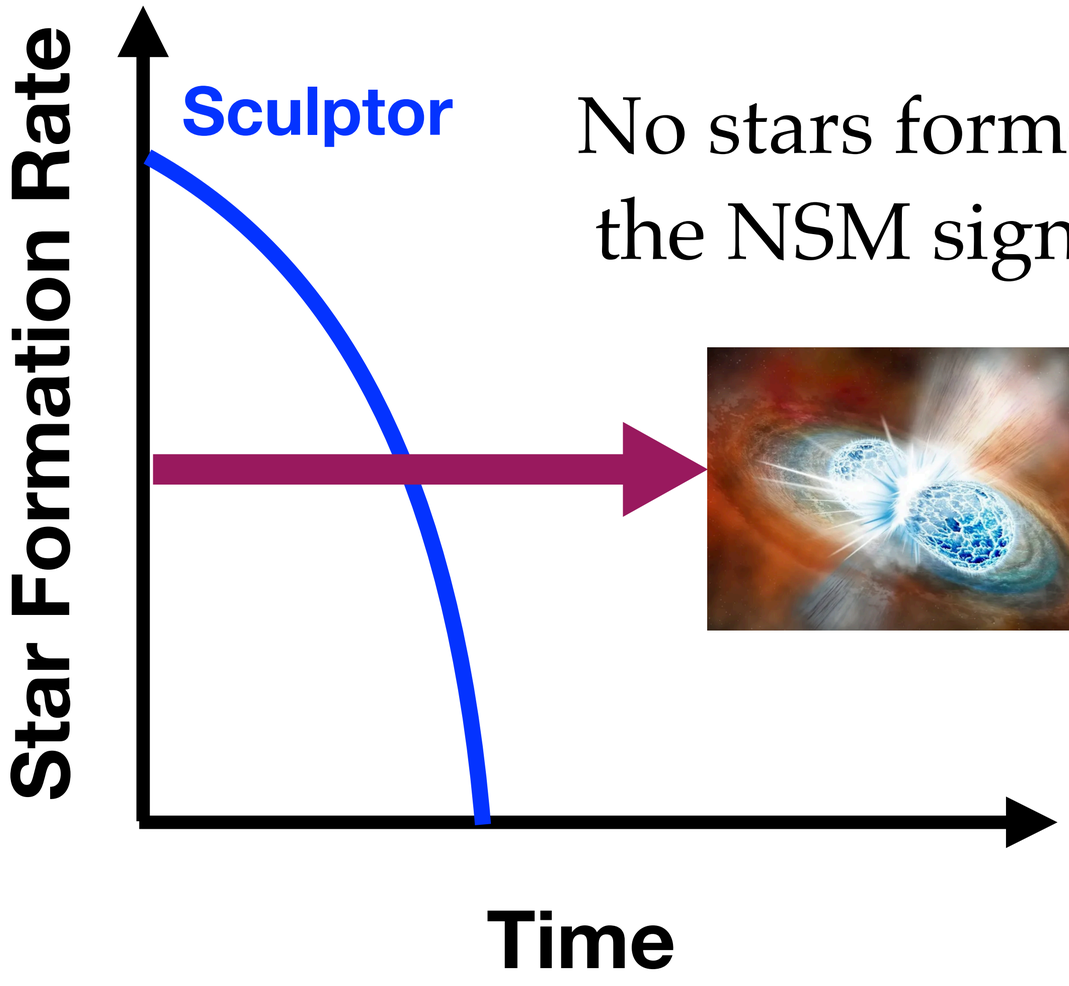
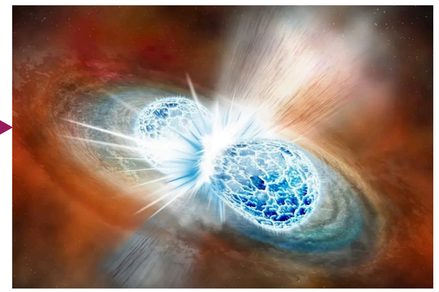


No stars formed with the NSM signatures!



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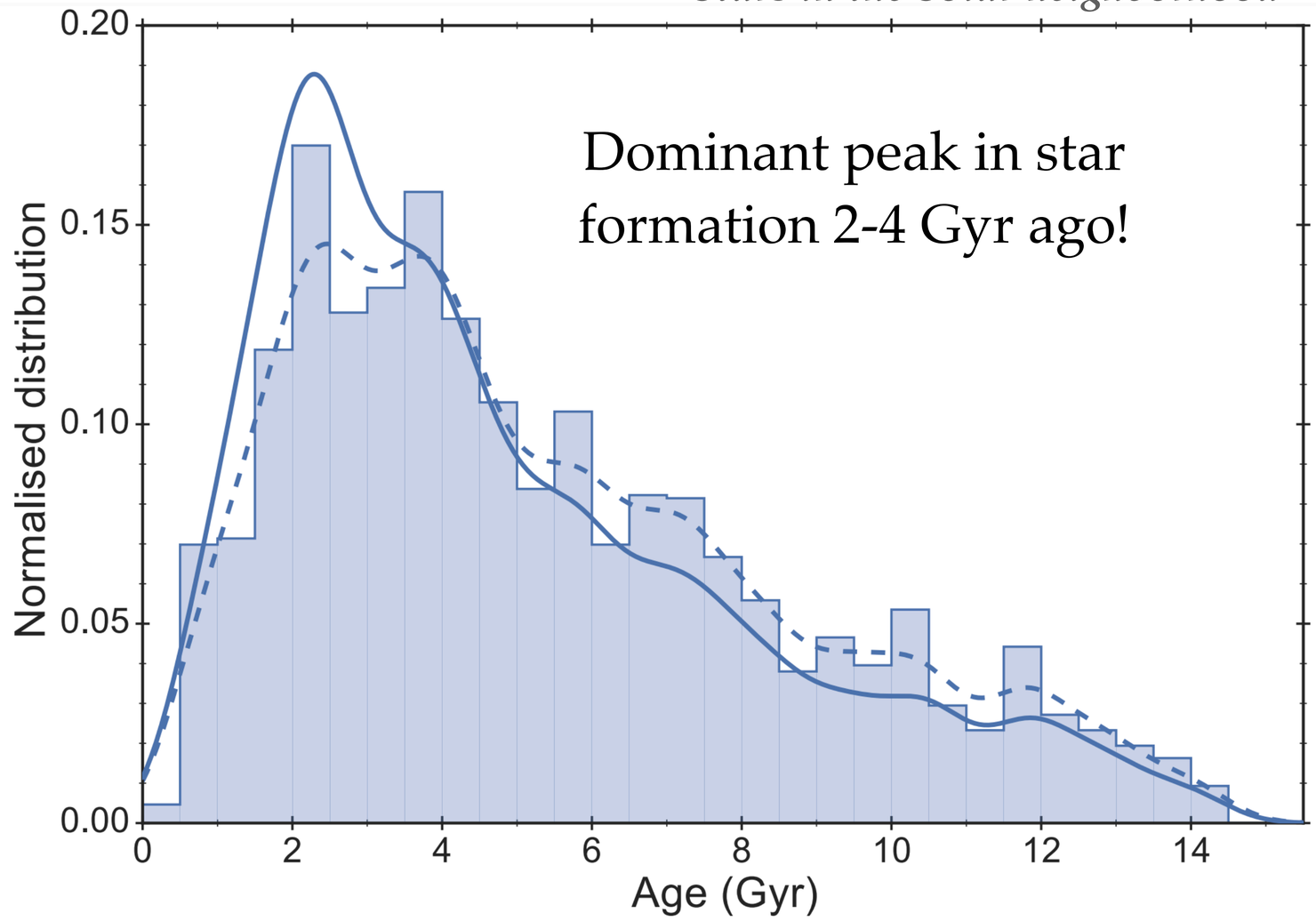
Skúladóttir & Salvadori 2020

WHY IS THE MILKY WAY DOMINATED BY THE QUICK R-PROCESS?

Stars in the Solar neighborhood



Star formation in the Milky Way is too recent!

Silva Aguirre et al. 2018

Skúladóttir & Salvadori 2020

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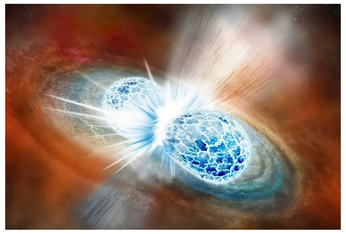

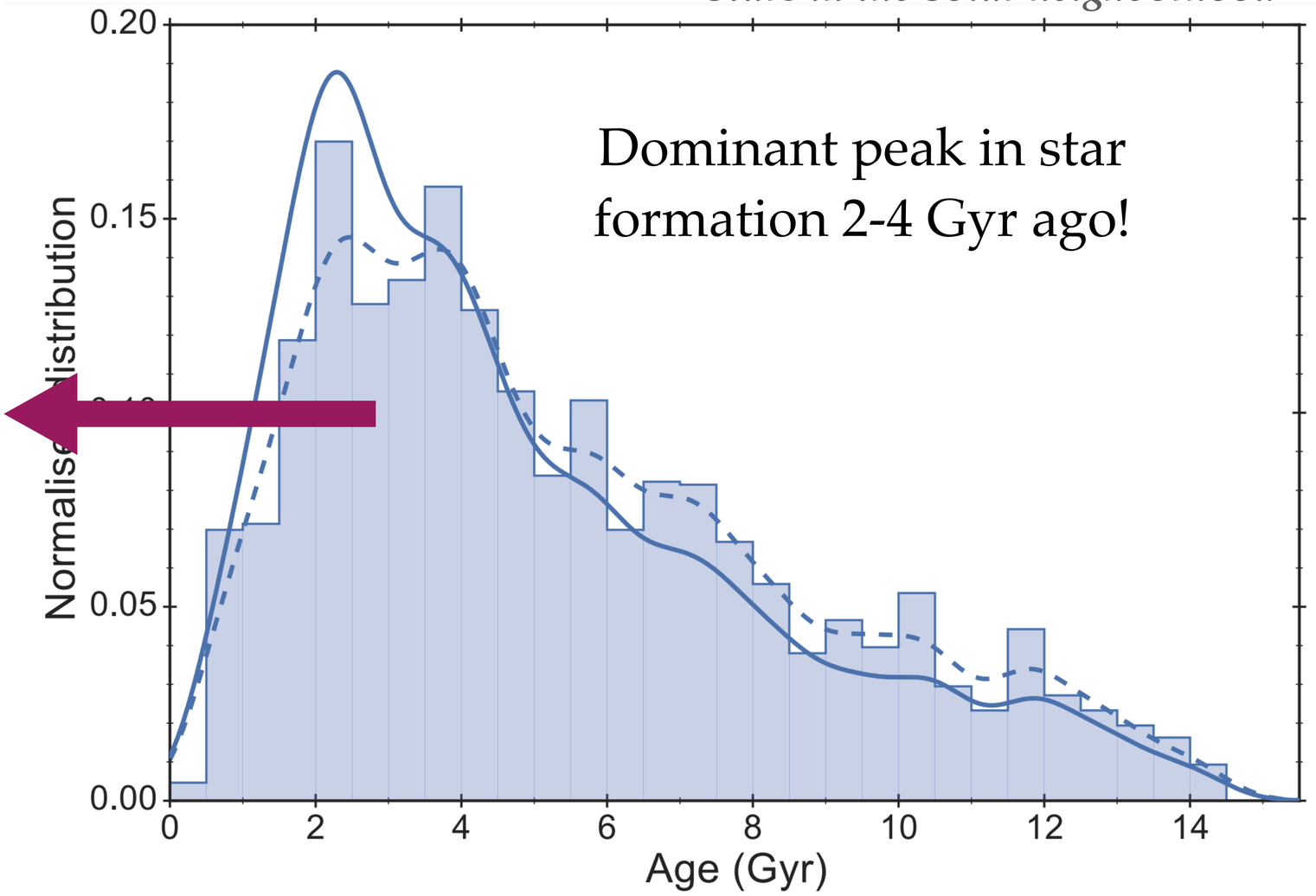

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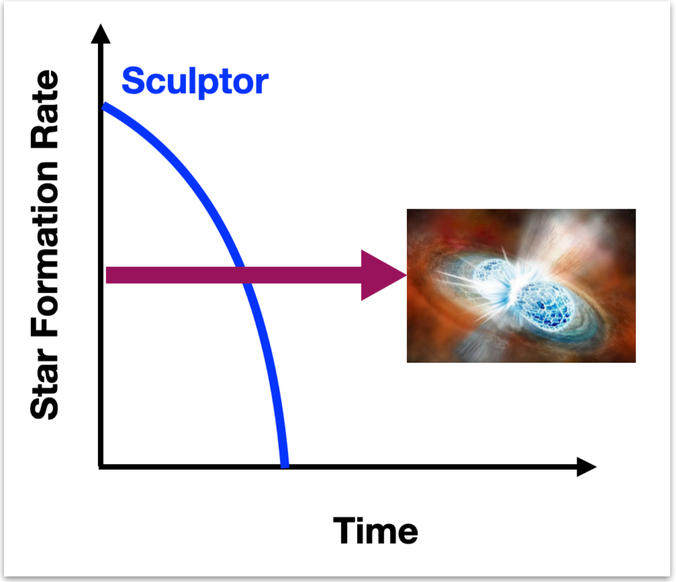
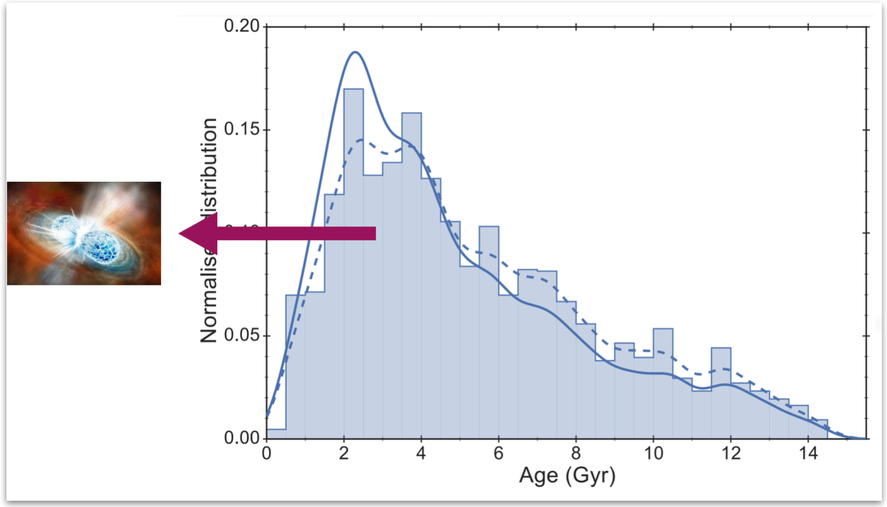
TIMESCALE OF NEUTRON STAR MERGERS



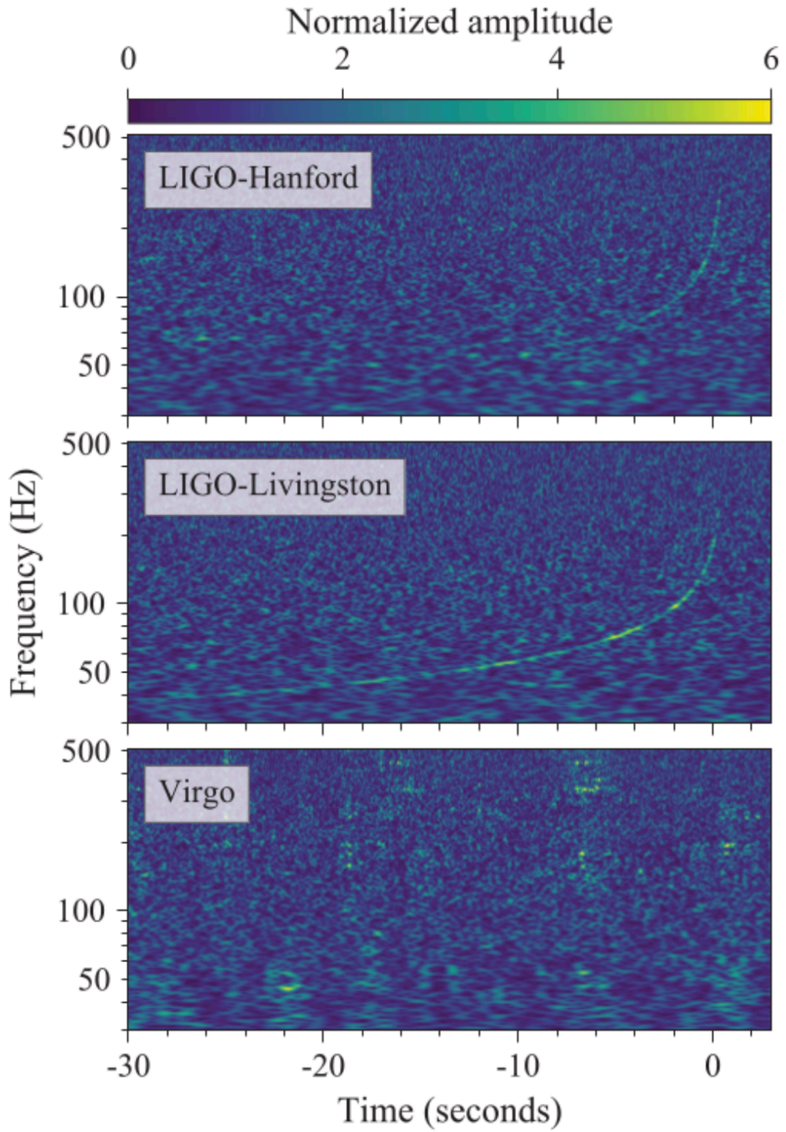


Typical timescales of NSM are ≳2 Gyr

This is the timescale that it takes NSM to rival ccSN in production of r-process elements*

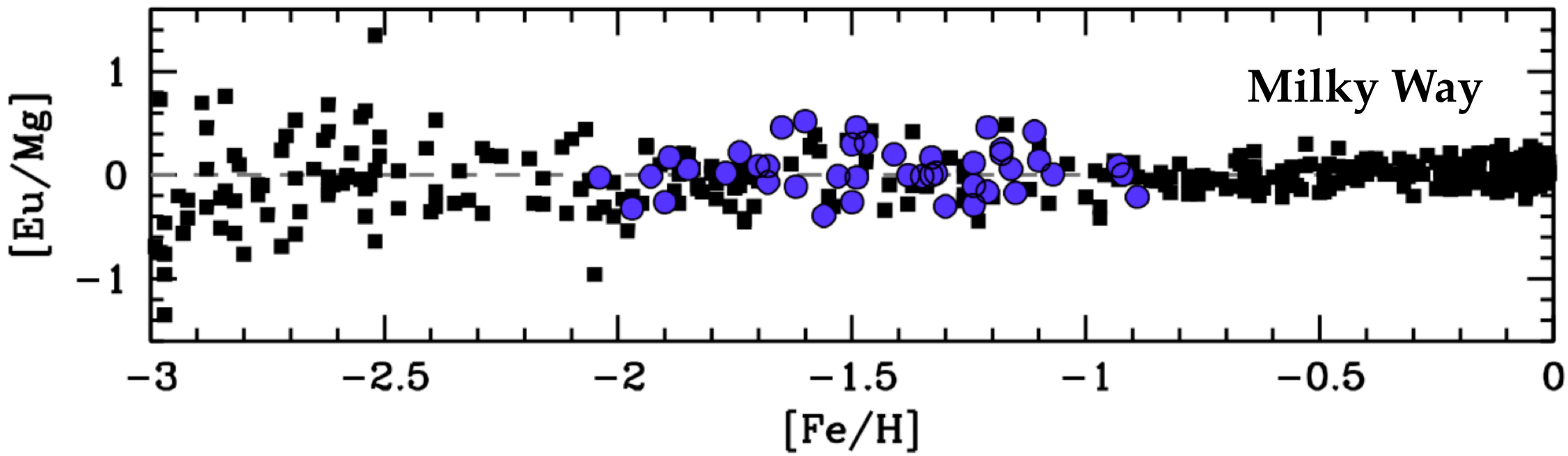
**In Skúladóttir & Salvadori 2020 we estimated ≳4 Gyr, but taking into account more data I recommend a revised more conservative ≳2 Gyr timescale*

TIMESCALE OF NEUTRON STAR MERGERS – OTHER EVIDENCE



- GW170817 from a non-star forming region! Estimated delay time >6.8 Gyr (Blanchard et al. 2017).
- Other Kilonovae also found far from star formation (e.g. talk by Hotokezaka).
- Significant fraction of short gamma ray bursts found in early type galaxies (Berger 2014).
- Different intrinsic distribution of GRBS
  - Short GRBs: peak at z~1.5, 9.5 Gyr ago (Ghirlanda et al. 2022).
  - Long GRBs: peak at z~3.5, 12 Gyr ago. (Salvaterra et al. 2012).

R-PROCESS



The quick source (ccSN) is the dominant r-process source at **all** metallicities in the Milky Way disk

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The s/i-processes

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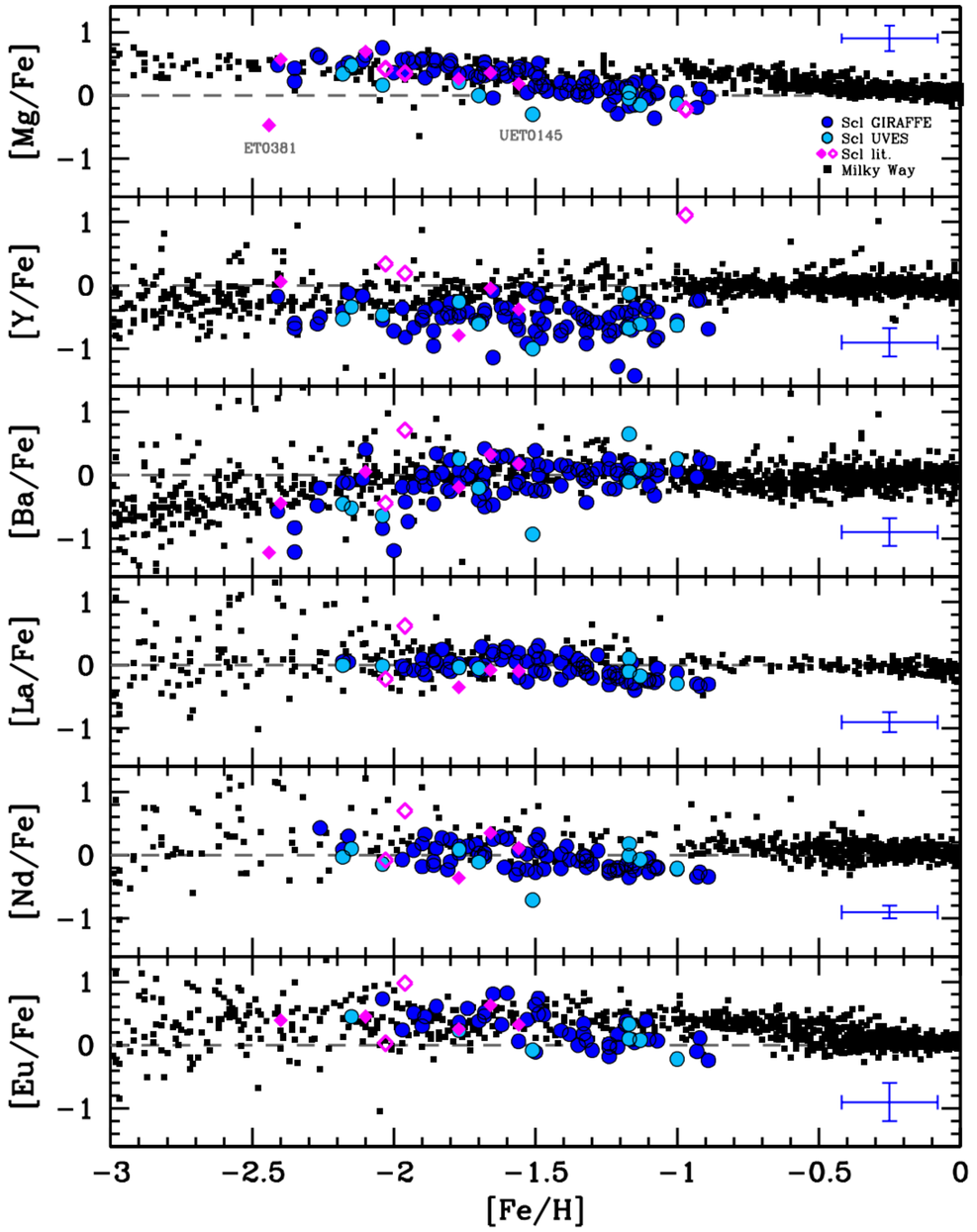
N-CAPTURE ELEMENTS IN DWARF GALAXIES

N-capture elements measured in 100 stars in the Sculptor dwarf spheroidal galaxy

Skúladóttir et al. 2019, 2020



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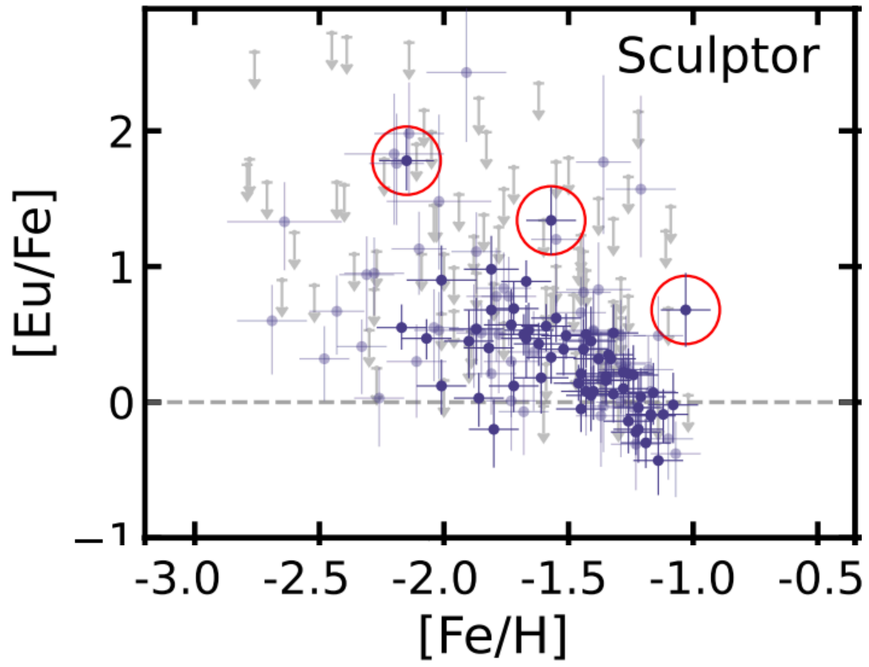
See also Henderson et al. 2025



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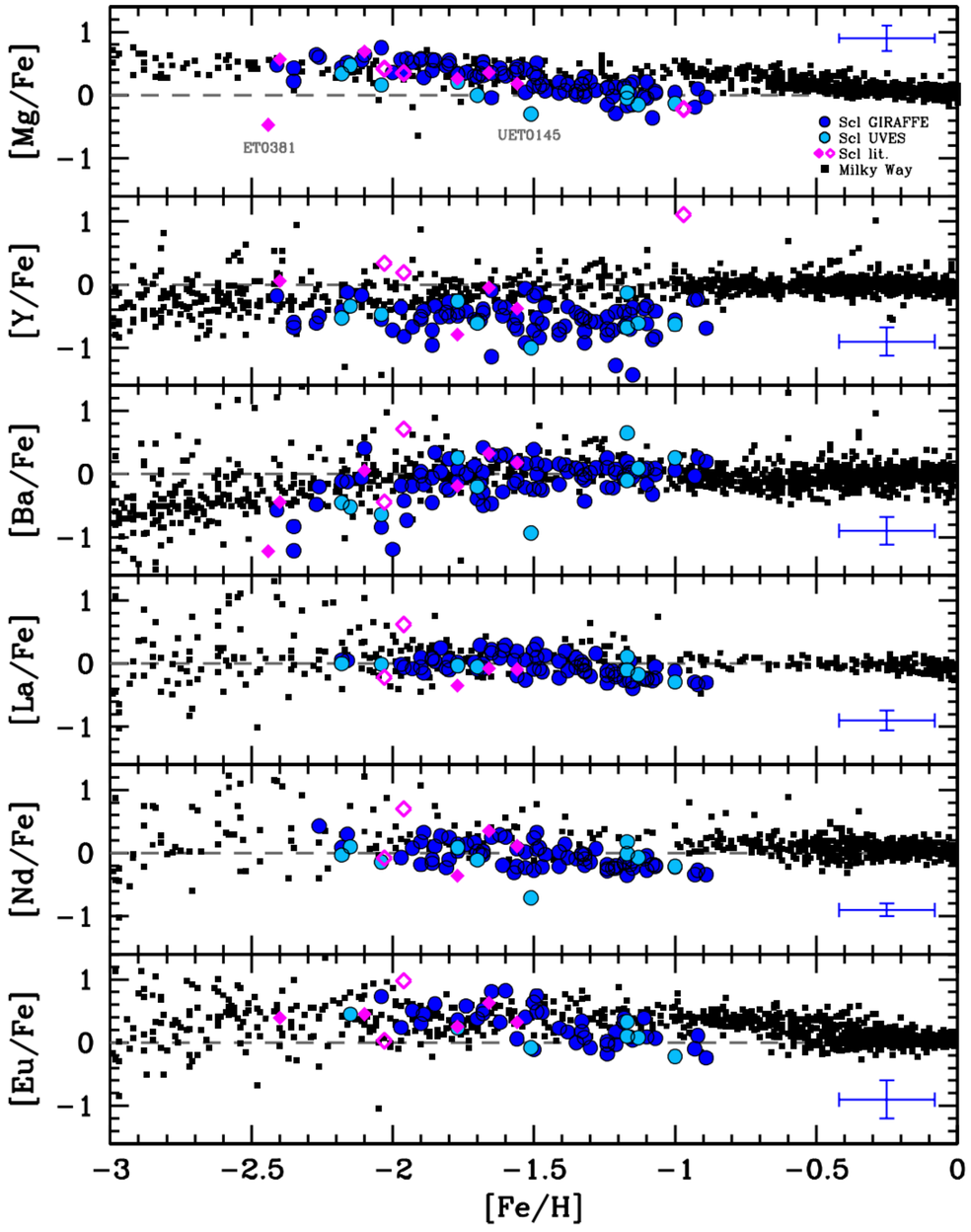
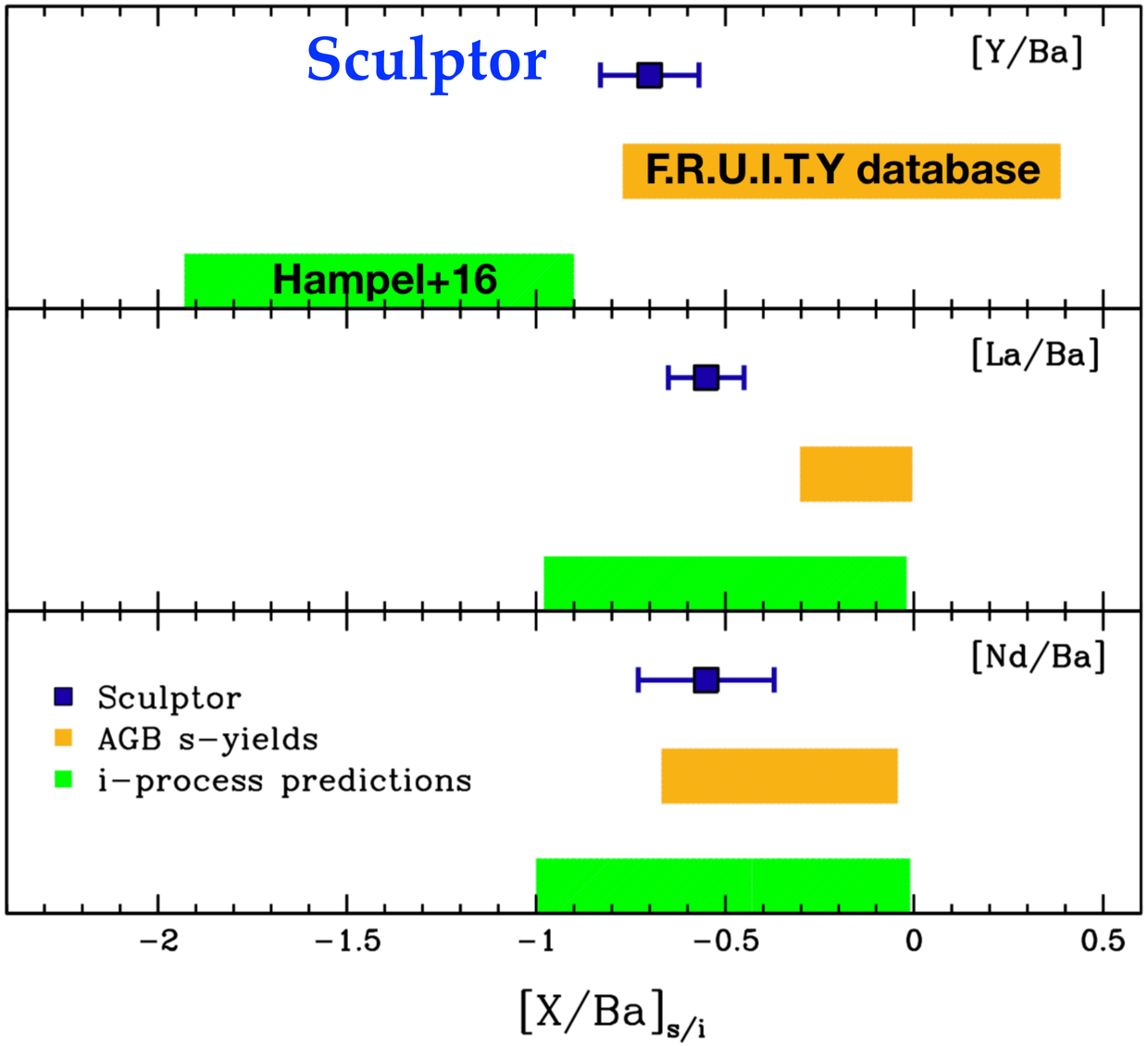


THE S/I PROCESSES IN SCULPTOR

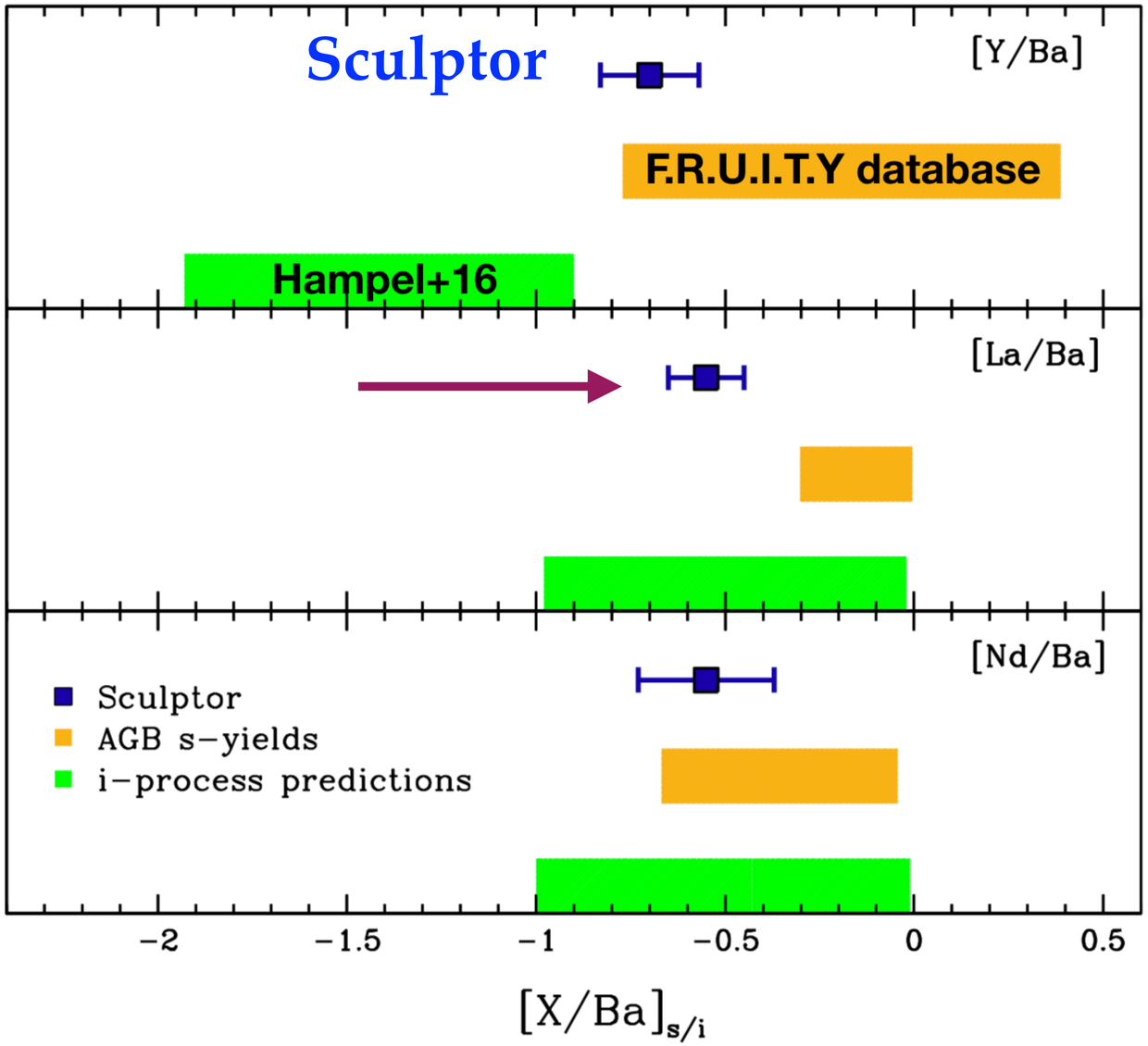
Skúladóttir et al. 2020



Taking all the n-capture elements formed in Sculptor and removing the r-process gave us the $[X/Ba]_{s/i}$ values.

THE S/I PROCESSES IN SCULPTOR

Skúladóttir et al. 2020



Taking all the n-capture elements formed in Sculptor and removing the r-process gave us the $[X/Ba]_{s/i}$ values.

The i-process is **needed** to explain the chemical abundances in Sculptor!

THE I-PROCESS SOURCE IN SCULPTOR

$[Fe/H] \approx -2$

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[Fe/H] ≈ -2

Not massive stars
(delayed production)

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(Sculptor's SFH is short)

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Metal-poor AGB stars with M>1.5 $M_\odot$?

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Accreting white dwarf?

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Chemical clocks

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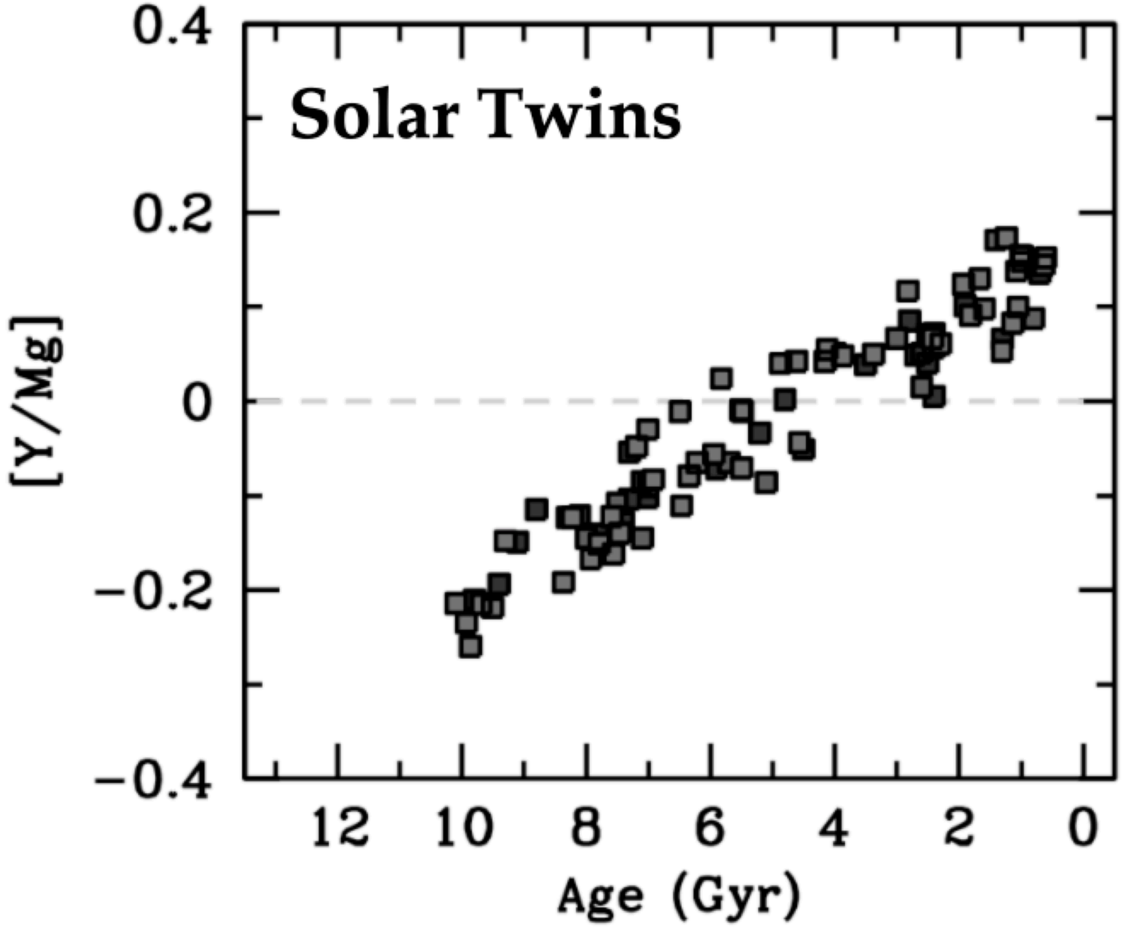
CHEMICAL CLOCKS

Nissen 2015, 2017, Spina et al. 2016,
Tucci-Maia et al. 2016



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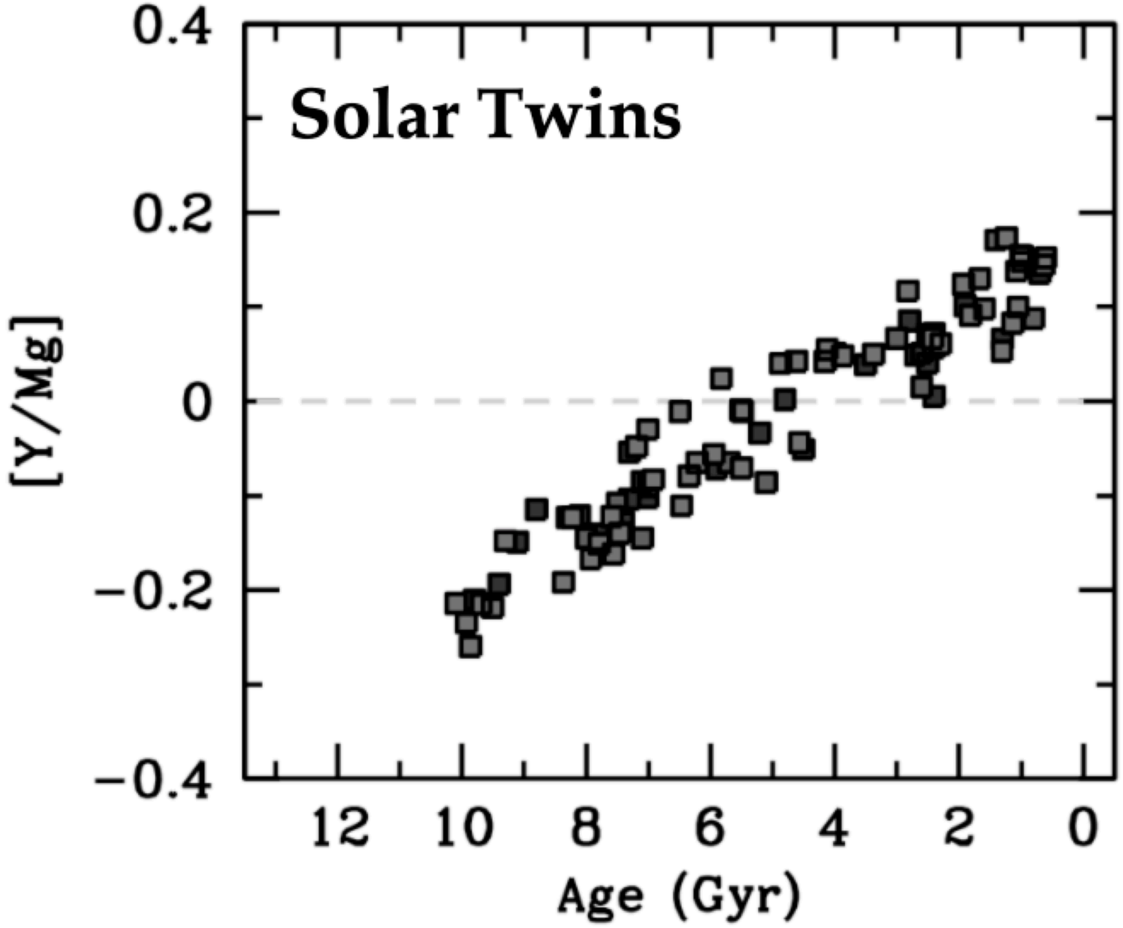

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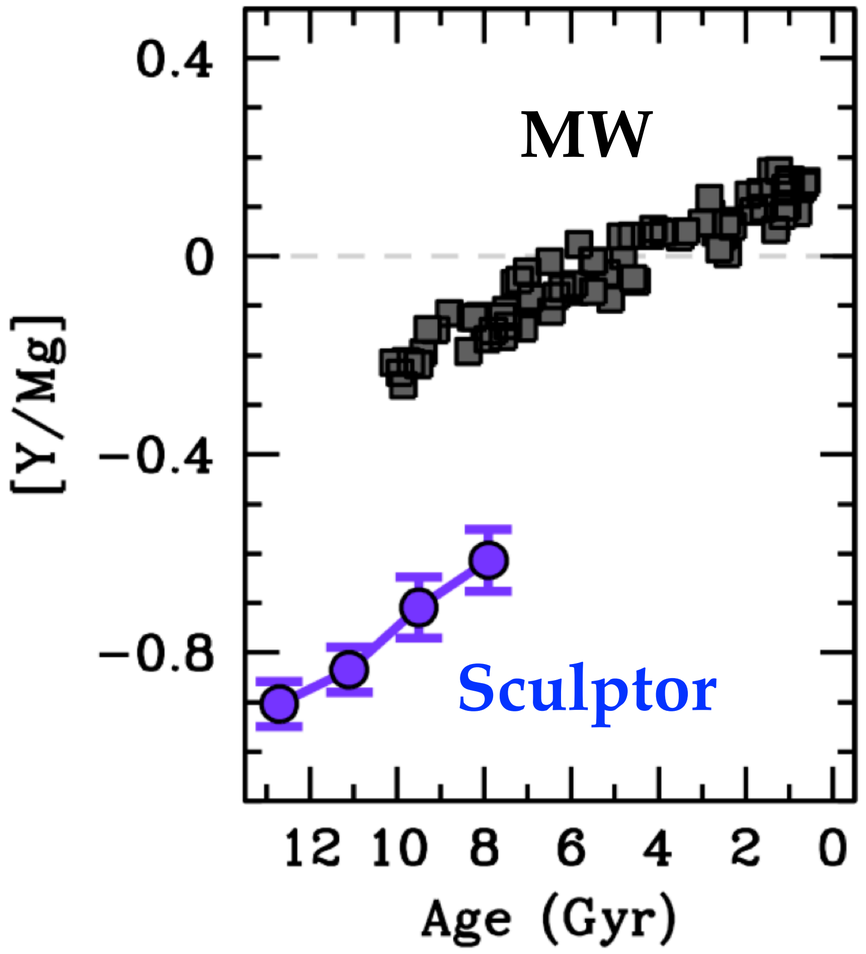
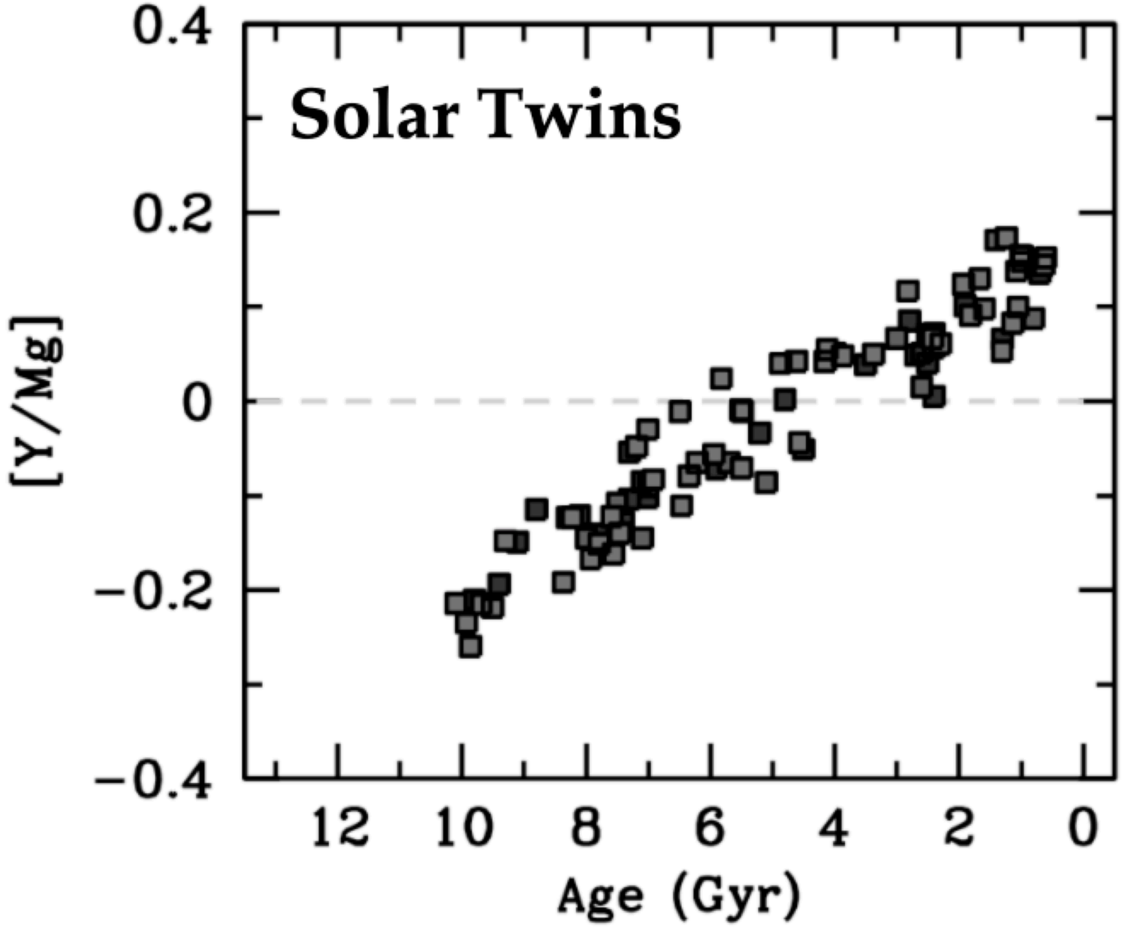
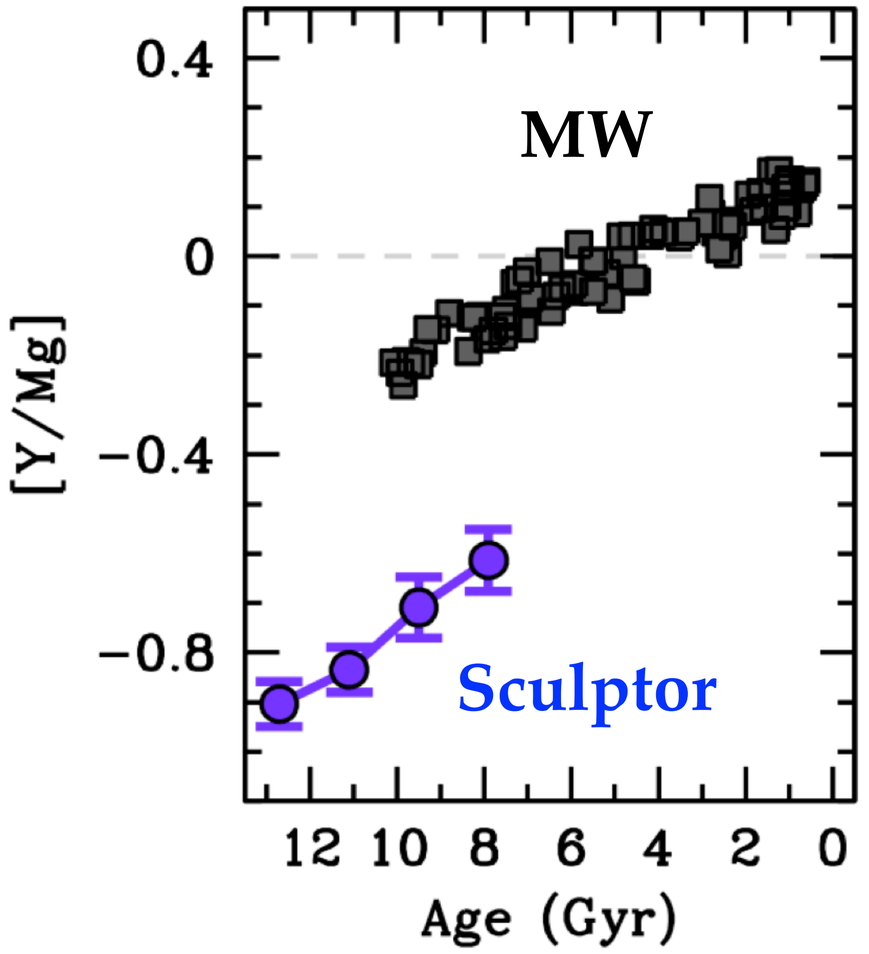


CHEMICAL CLOCKS

Nissen 2015, 2017, Spina et al. 2016, Tucci-Maia et al. 2016



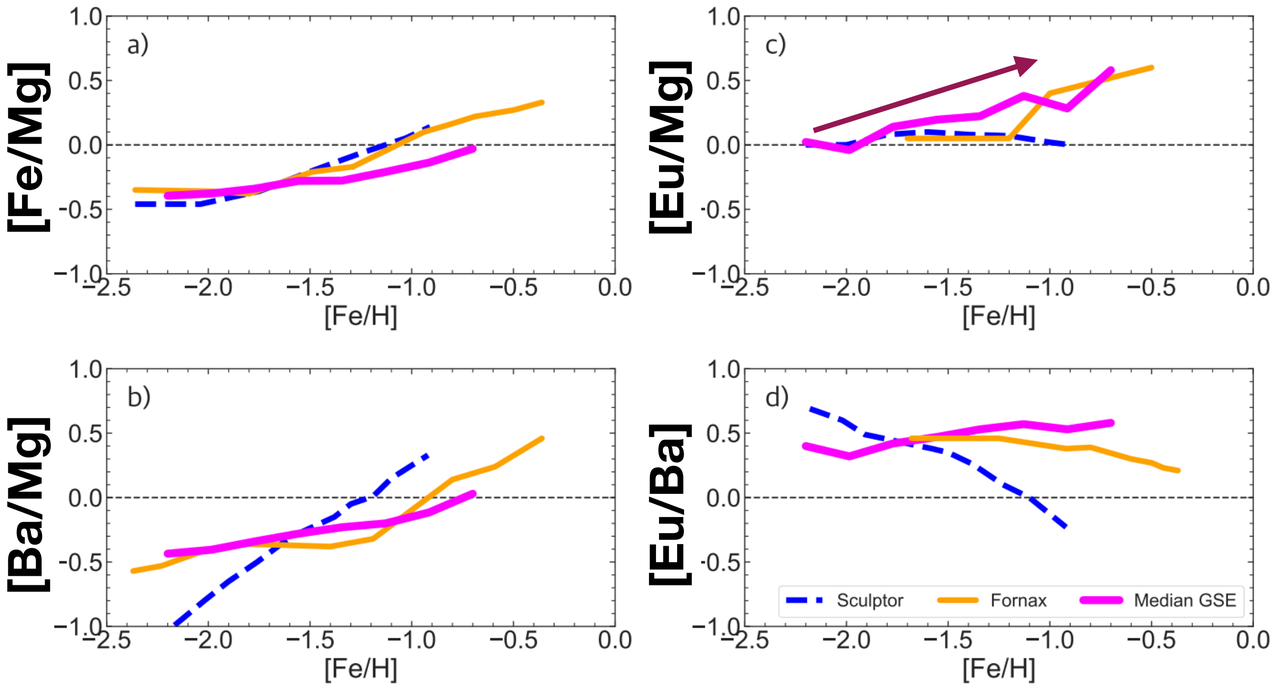
Skúladóttir et al. 2019

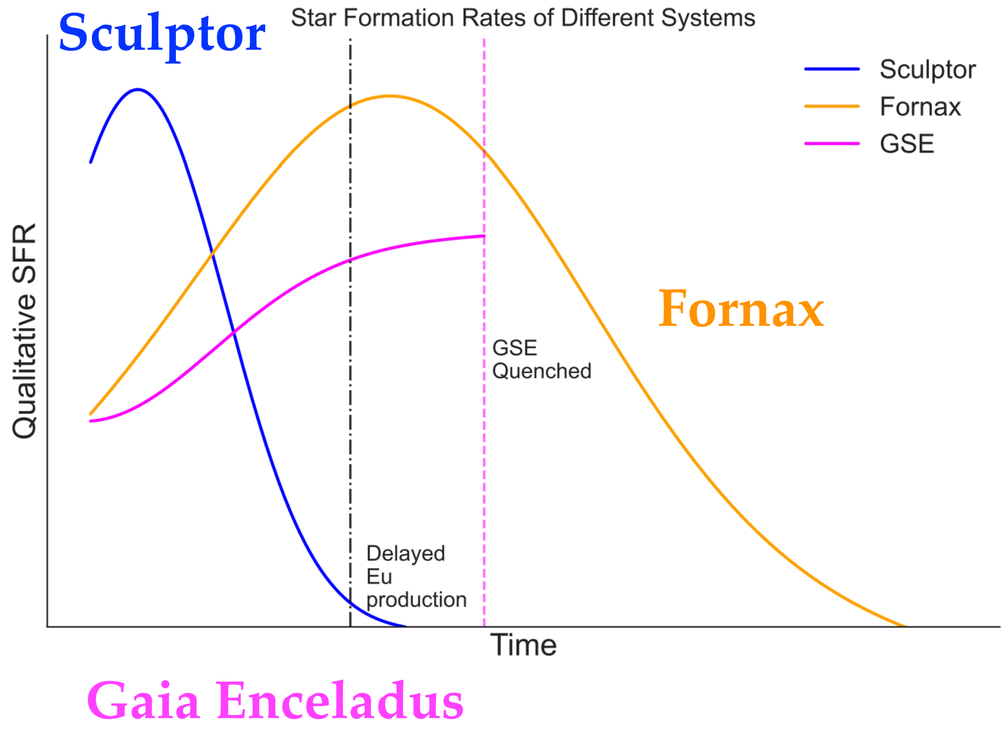


Chemical clocks are not universal

Ernandes et al. 2024, 2025

USING "CHEMICAL CLOCKS"





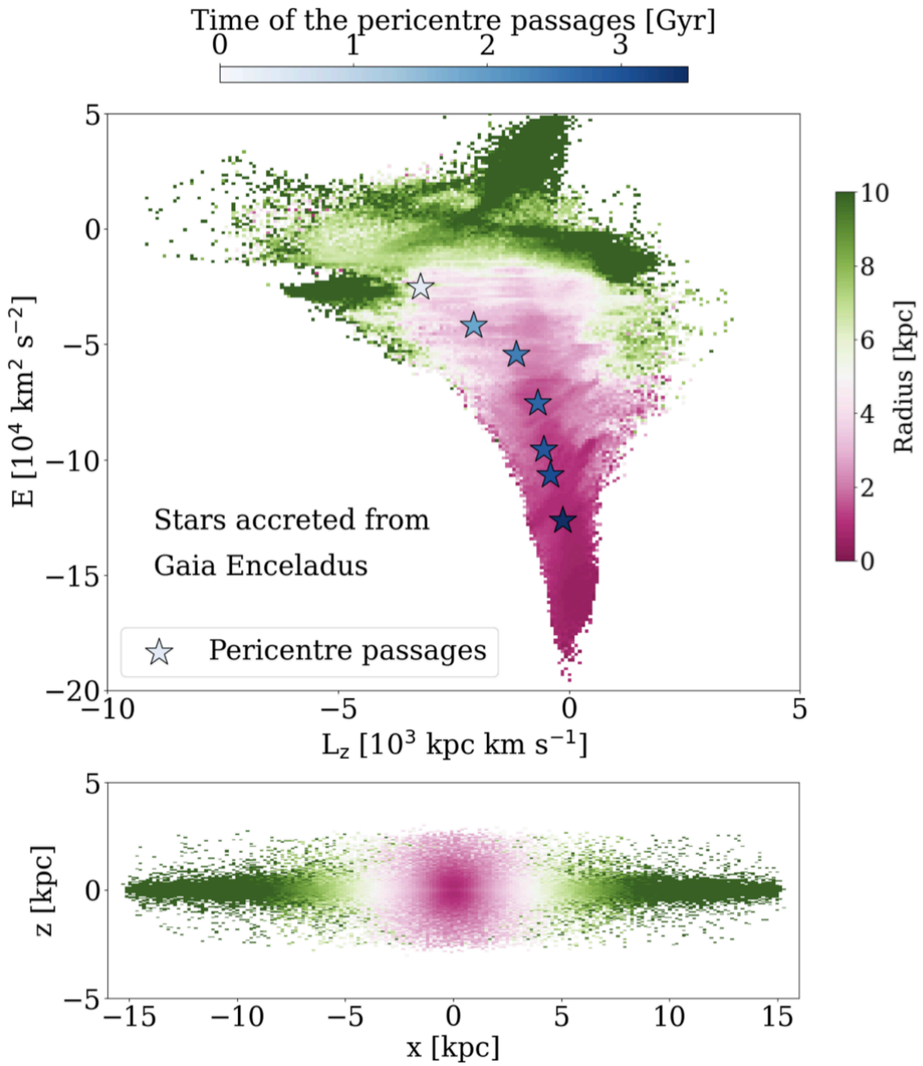
Gaia Enceladus

Gaia Enceladus was the last major merger event of the Milky Way

Comparing the abundance trends reveals its star formation history

USING "CHEMICAL CLOCKS"

Skúladóttir et al. 2025
(Published next Monday!)



USING "CHEMICAL CLOCKS"

Skúladóttir et al. 2025
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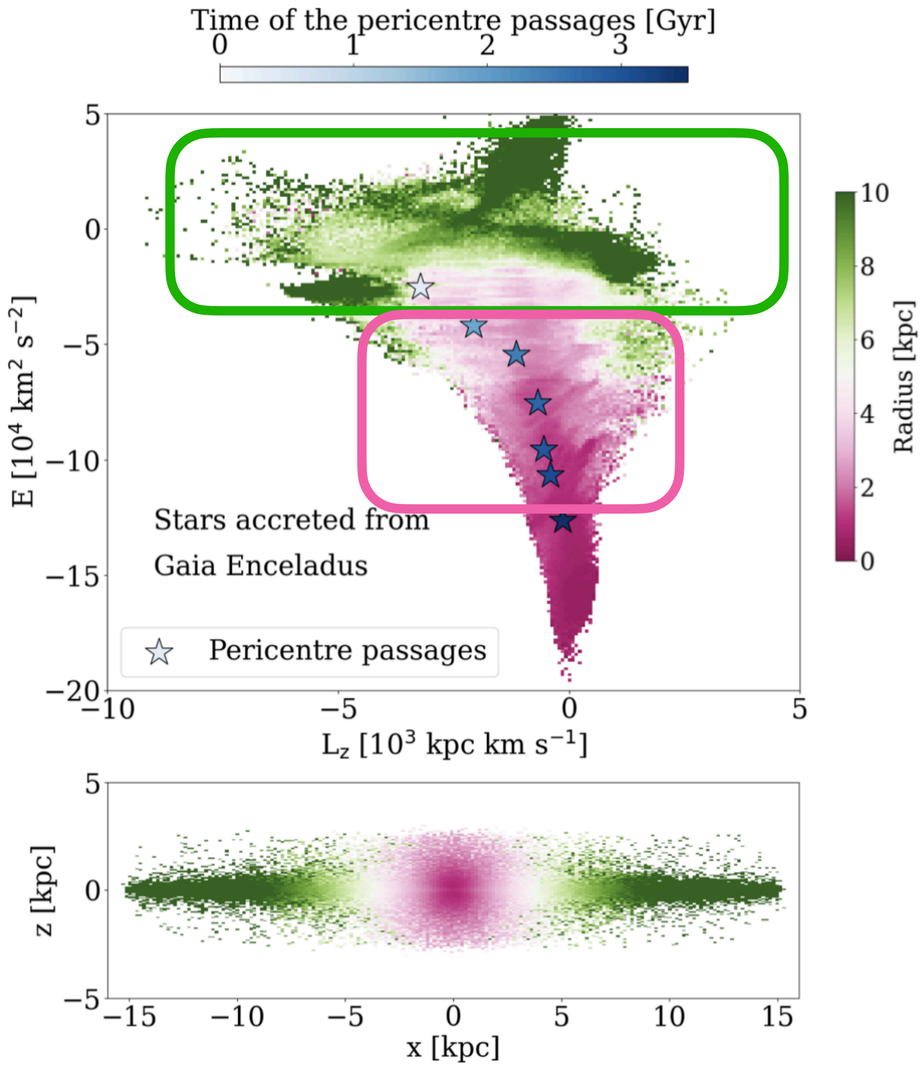

USING "CHEMICAL CLOCKS"

Skúladóttir et al. 2025
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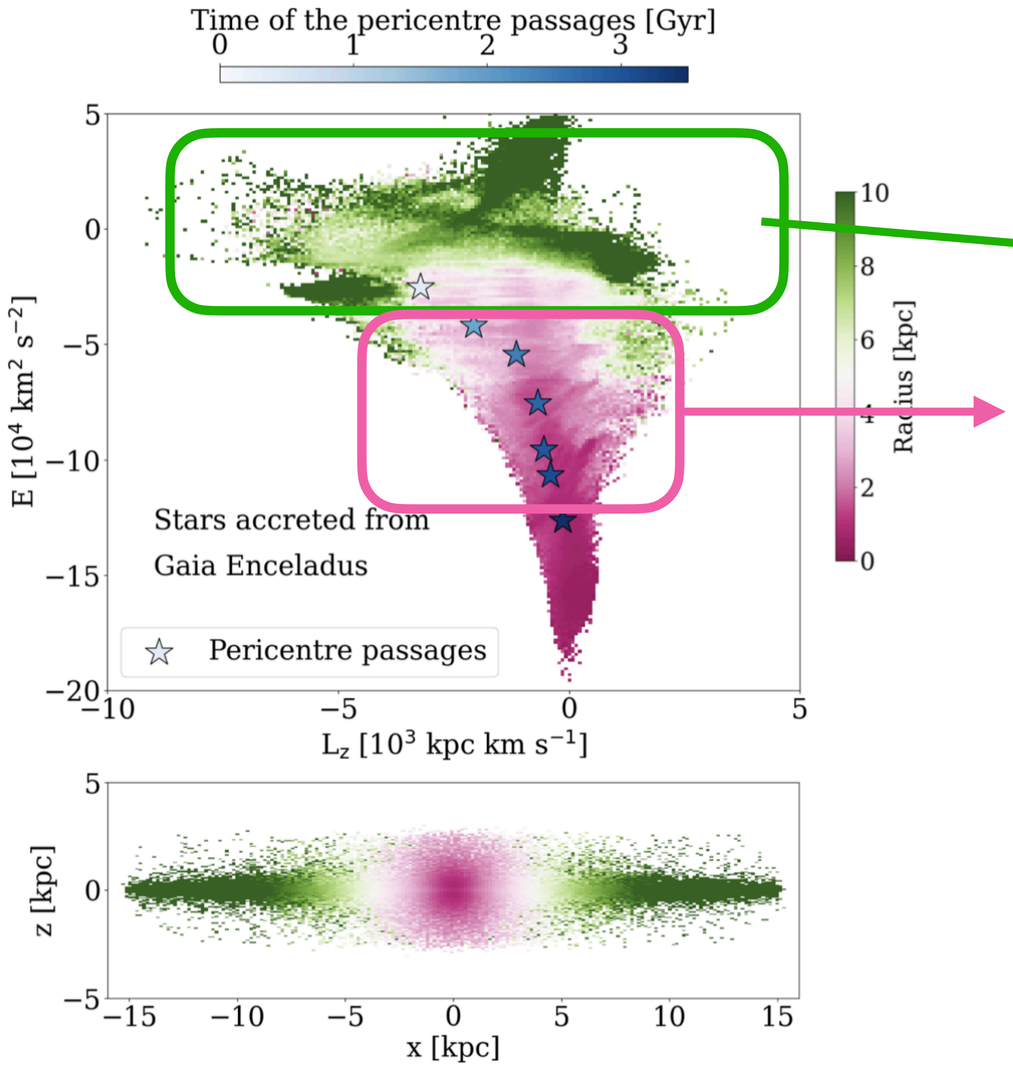
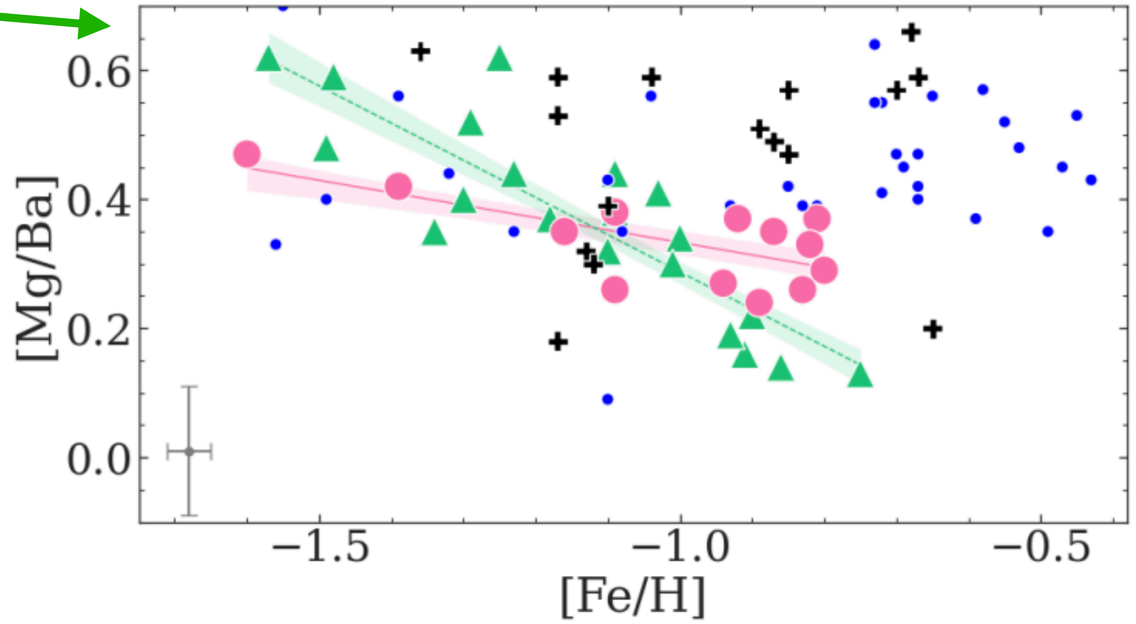


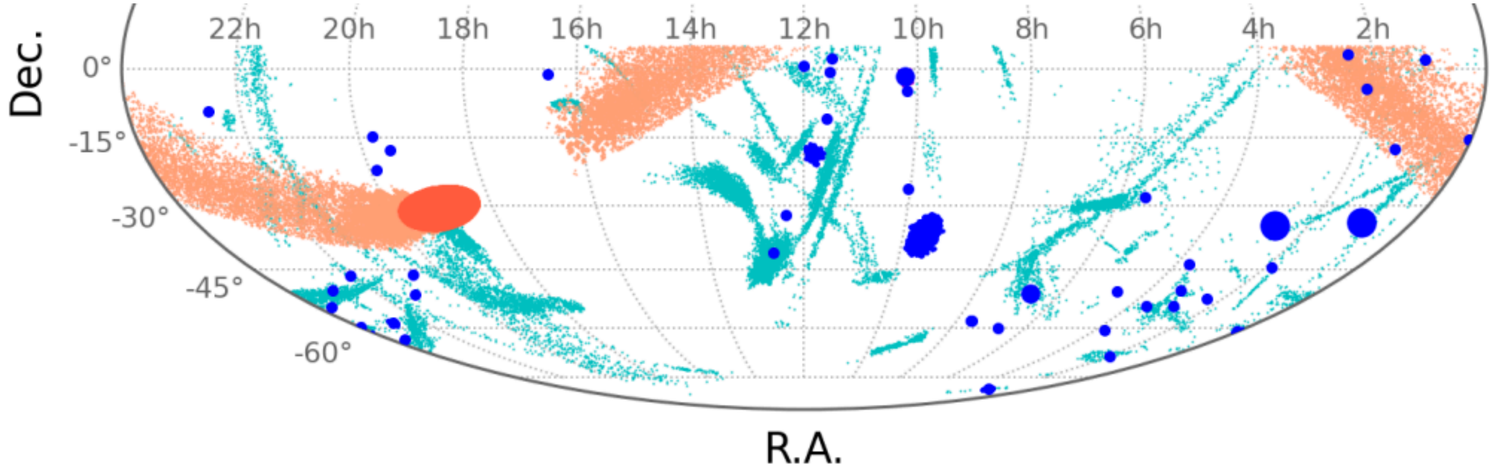
Stars accreted first from the outer regions of Gaia Enceladus



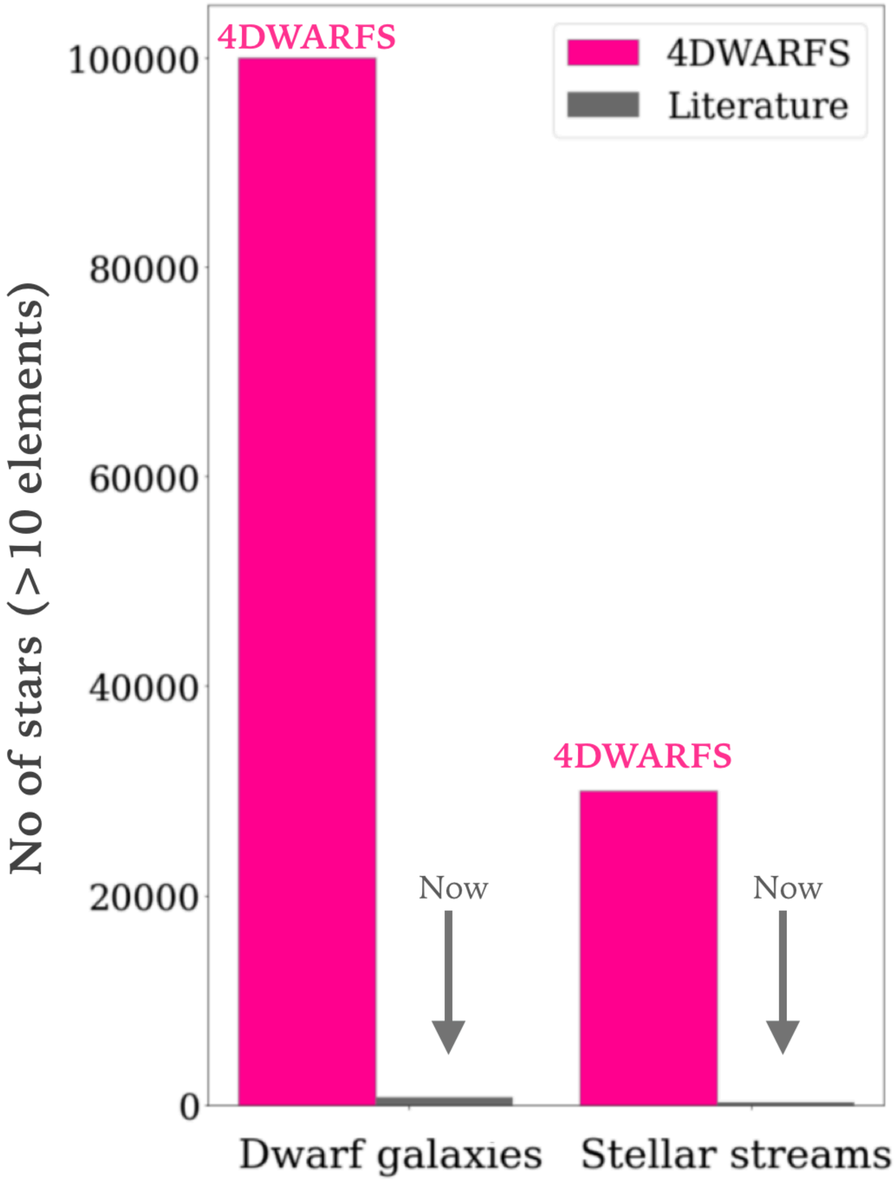
Stars accreted later from the inner regions of Gaia Enceladus

4DWARFS SURVEY

- **4DWARFS - Survey of Dwarf Galaxies and their Stellar streams (PI: Skúladóttir).**
- All dwarf galaxies and streams in the south.
- Large discovery space of unexpected findings.
- First light in 2025



Skúladóttir et al. 2023



LESSONS FROM DWARF GALAXIES

UNIVERSITÀ DEGLI STUDI FIRENZE

- There are (at least) two r-process sources - quick (ccSN) and delayed (NSM).
- Neutron star mergers have typical timescales of ≳2 Gyr.
- The i-process is needed to explain the n-capture elements in the Sculptor dwarf spheroidal galaxy.
  - Metal-poor AGB stars with $M > 1.5\ M_{\odot}$?
- Chemical clocks are not universal - but they are useful!
- Data are lacking - but Data are coming!

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