DWARF GALAXIES
AND THEIR STELLAR STREAMS

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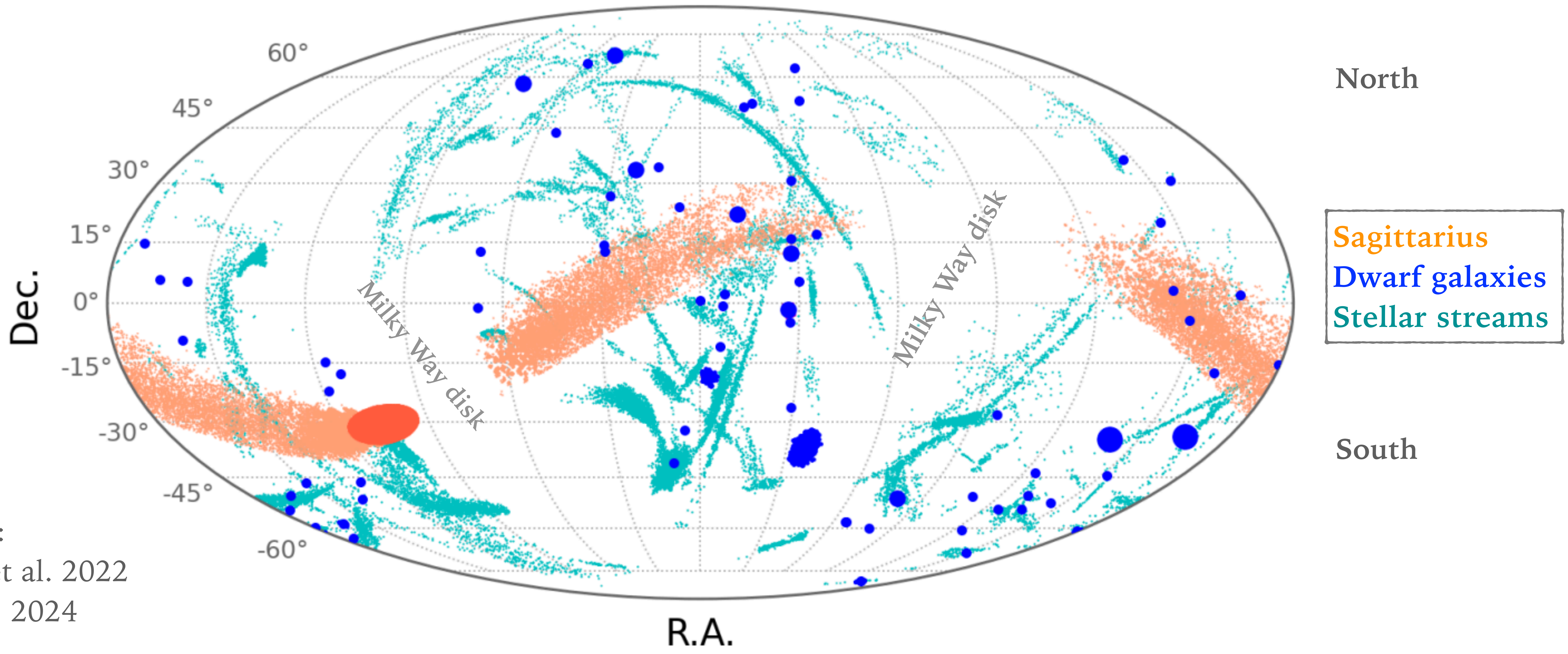
University of Florence

"Between the Lines" ESO Workshop - 3nd of December 2024

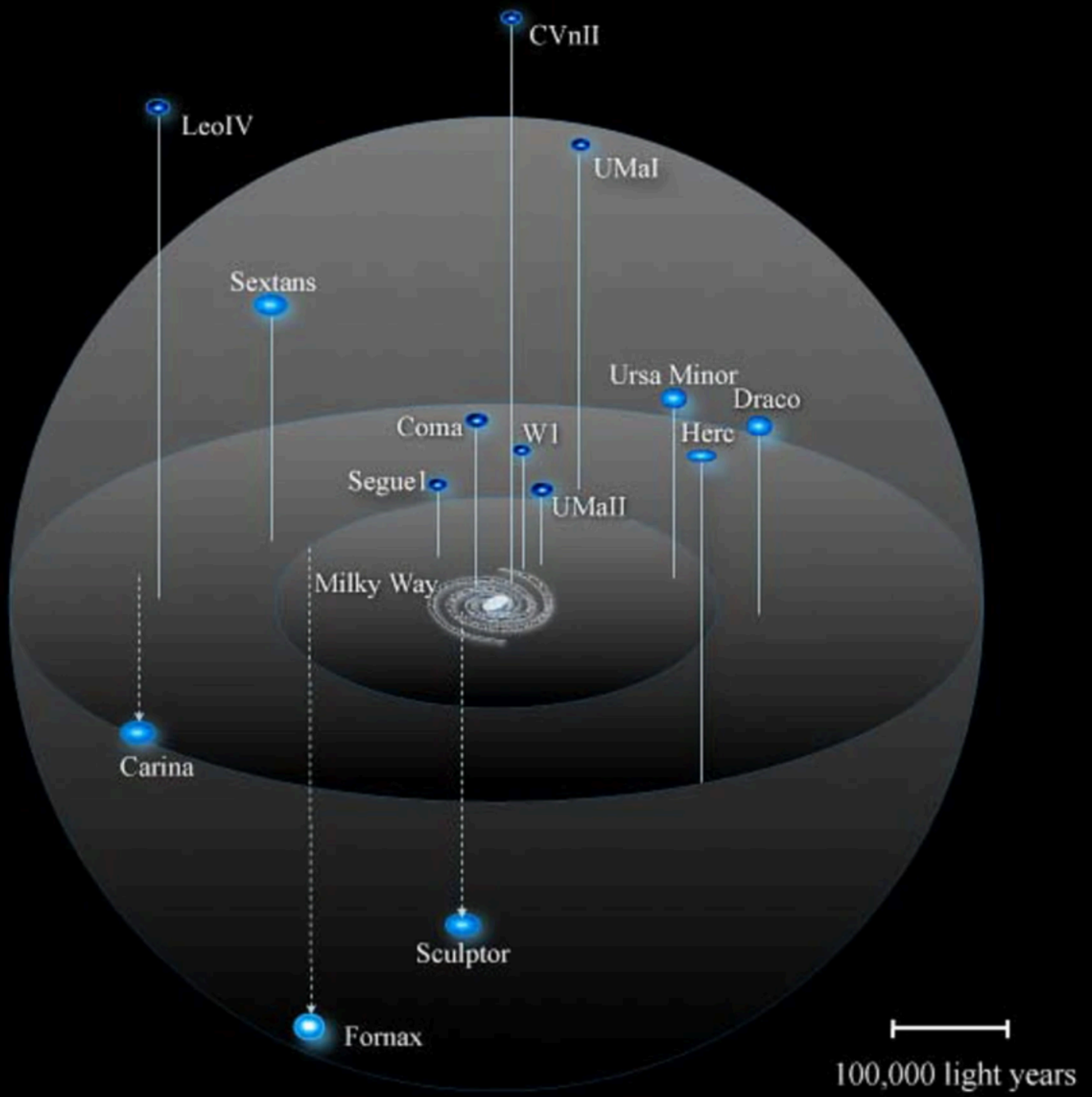
DWARF GALAXIES AROUND THE MILKY WAY

➤ The **Milky Way** has >70 known satellite **dwarf galaxies**, and dozens of **stellar streams**.



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

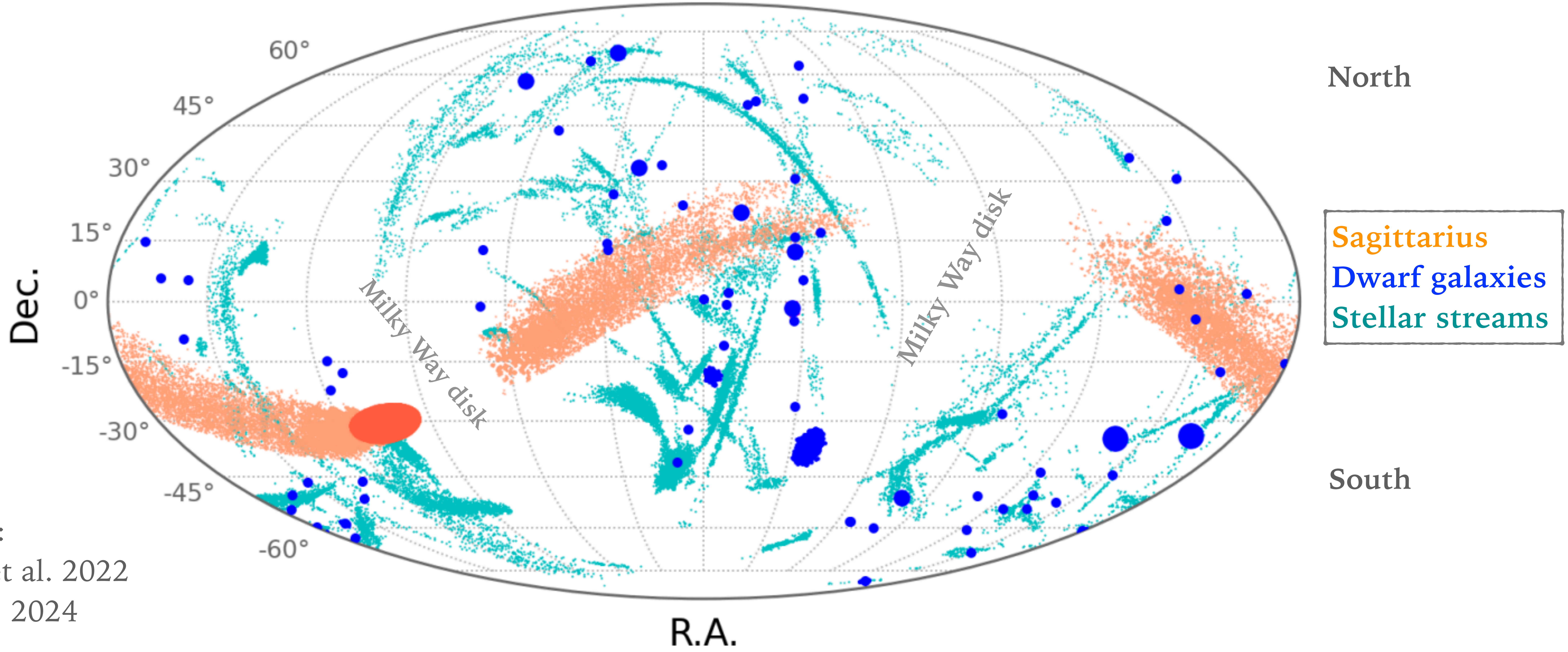
DWARF GALAXIES




GD – 1
Fjörm
Gaia – 1
Sylgr
Kshir
Pal 5
M92
Orphan
ω Cen +
Fimbulthul
Hrid
Galaxy Picture
Credit : ESA/Gaia/DPAC
Stellar Streams
Malhan et al. (2018, 2019)
Ibata et al. (2019, 2021)
NGC 3201
C 7
Gjöll
Phlegethon
NGC 1851
Indus
NGC 1261
Jhelum
Phoenix
Gaia 2

DWARF GALAXIES AROUND THE MILKY WAY

- **Dwarf galaxies:** First galaxies to form, hosts of the first stars, building blocks of the Milky Way.



Data from:
Battaglia et al. 2022
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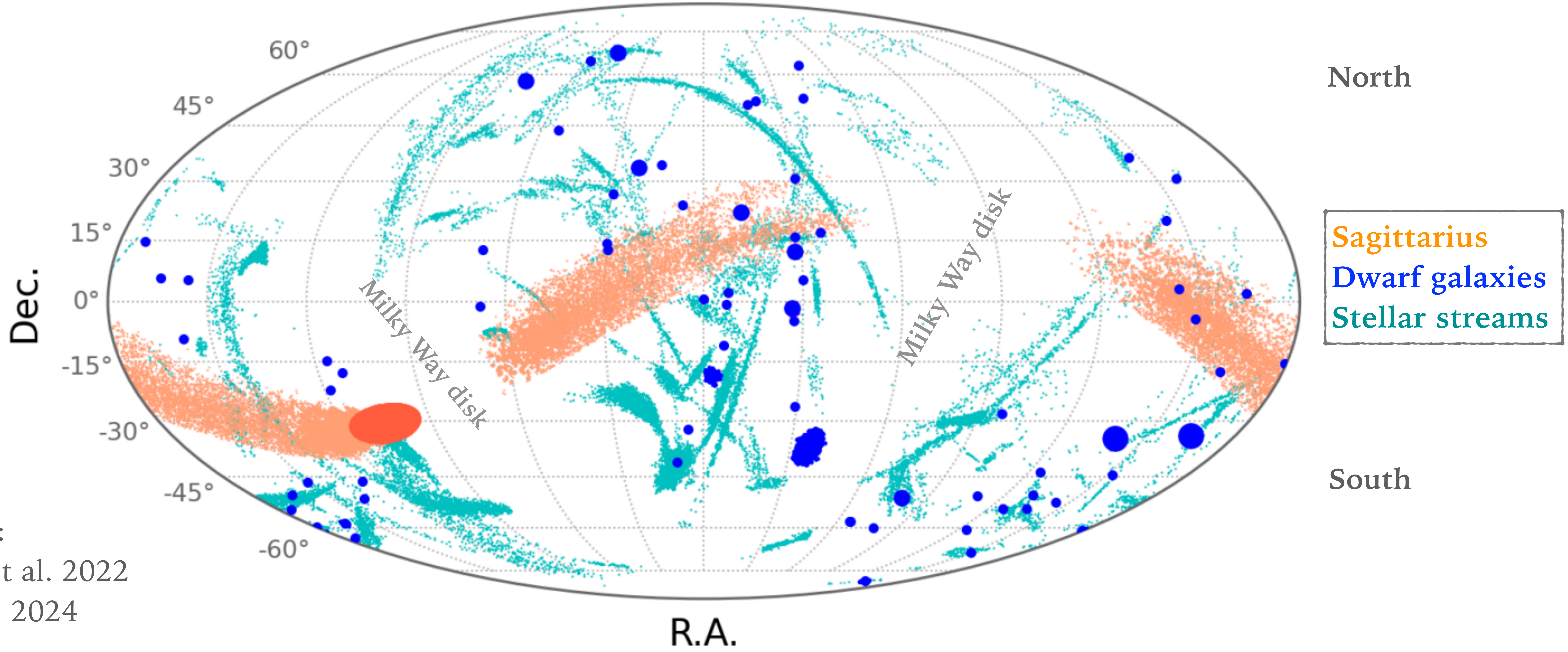
DWARF GALAXIES AROUND THE MILKY WAY

➤ **Stellar streams:** Relics of old systems - dwarf galaxies and stellar clusters - being ripped apart and swallowed by the Milky Way.



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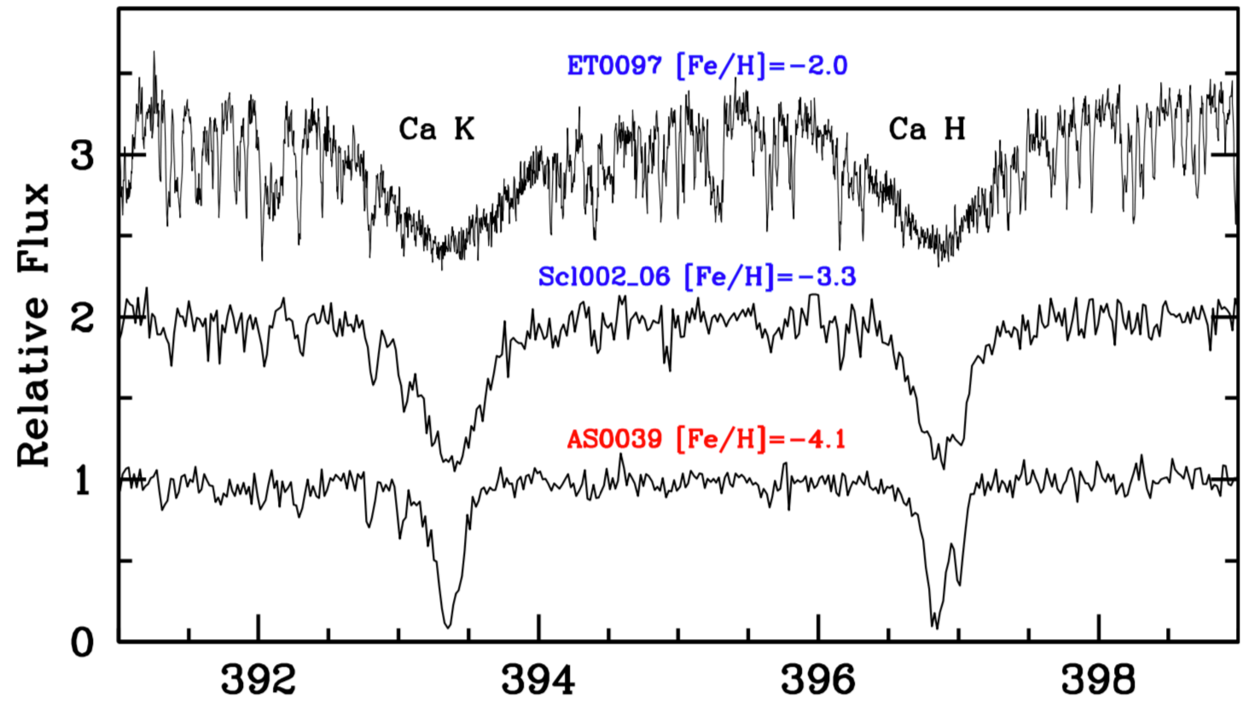
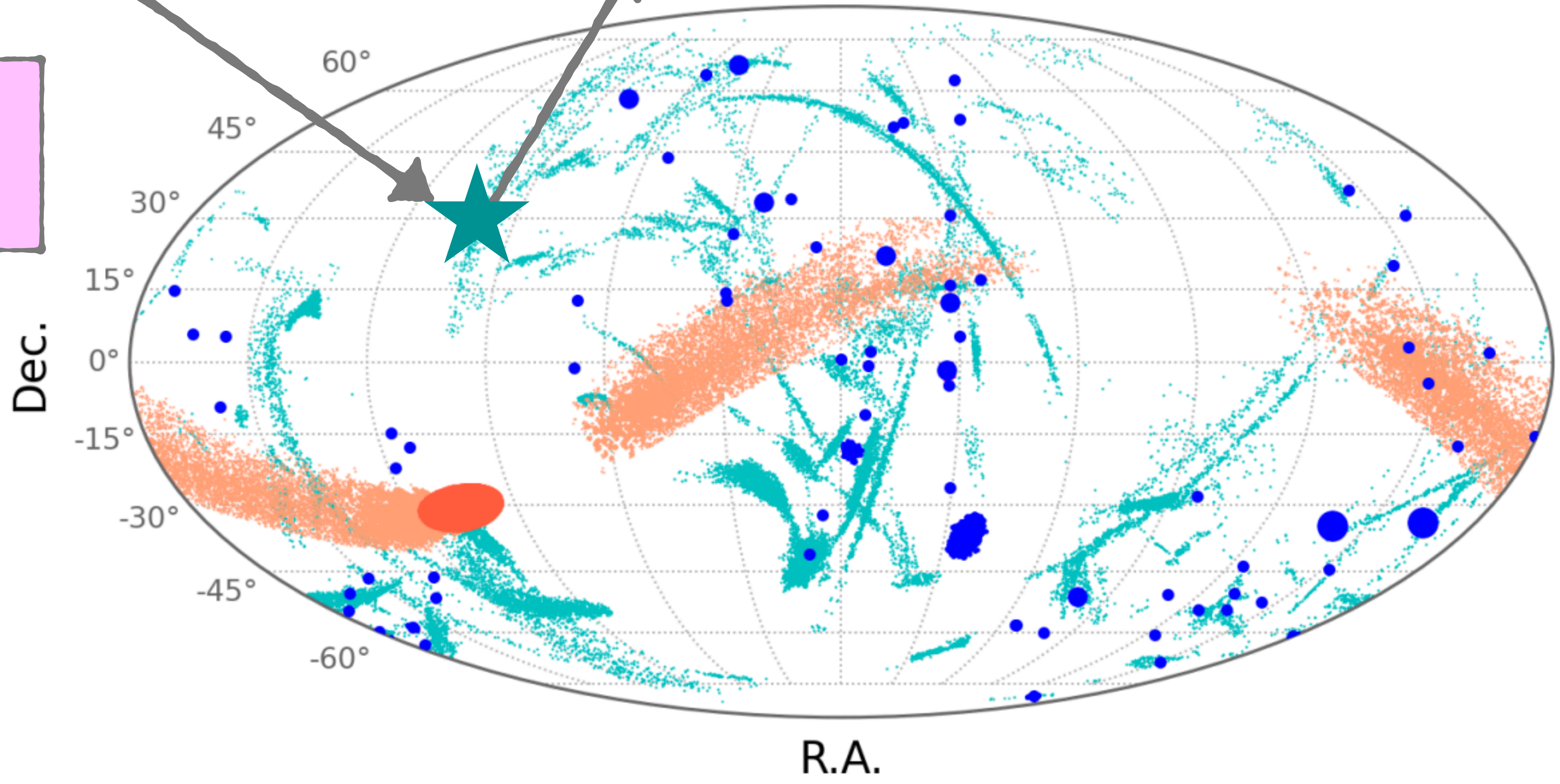
DWARF GALAXIES AROUND THE MILKY WAY

VLT



Gaia

Positions
Proper motions
Photometry



Spectra

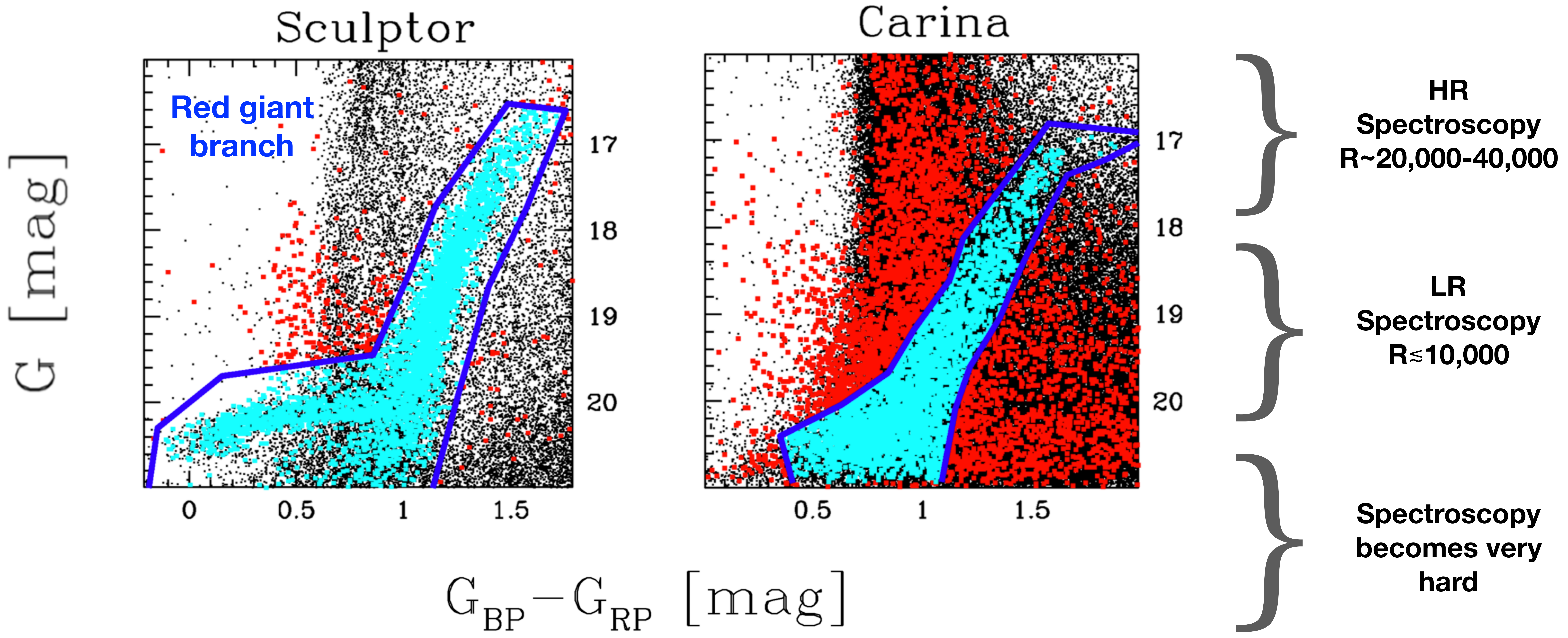
Chemical abundances
Line-of-sight velocities
Stellar ages

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

DWARF GALAXIES: RED GIANT STARS

Gaia Collaboration et al. 2018, Gaia DR2

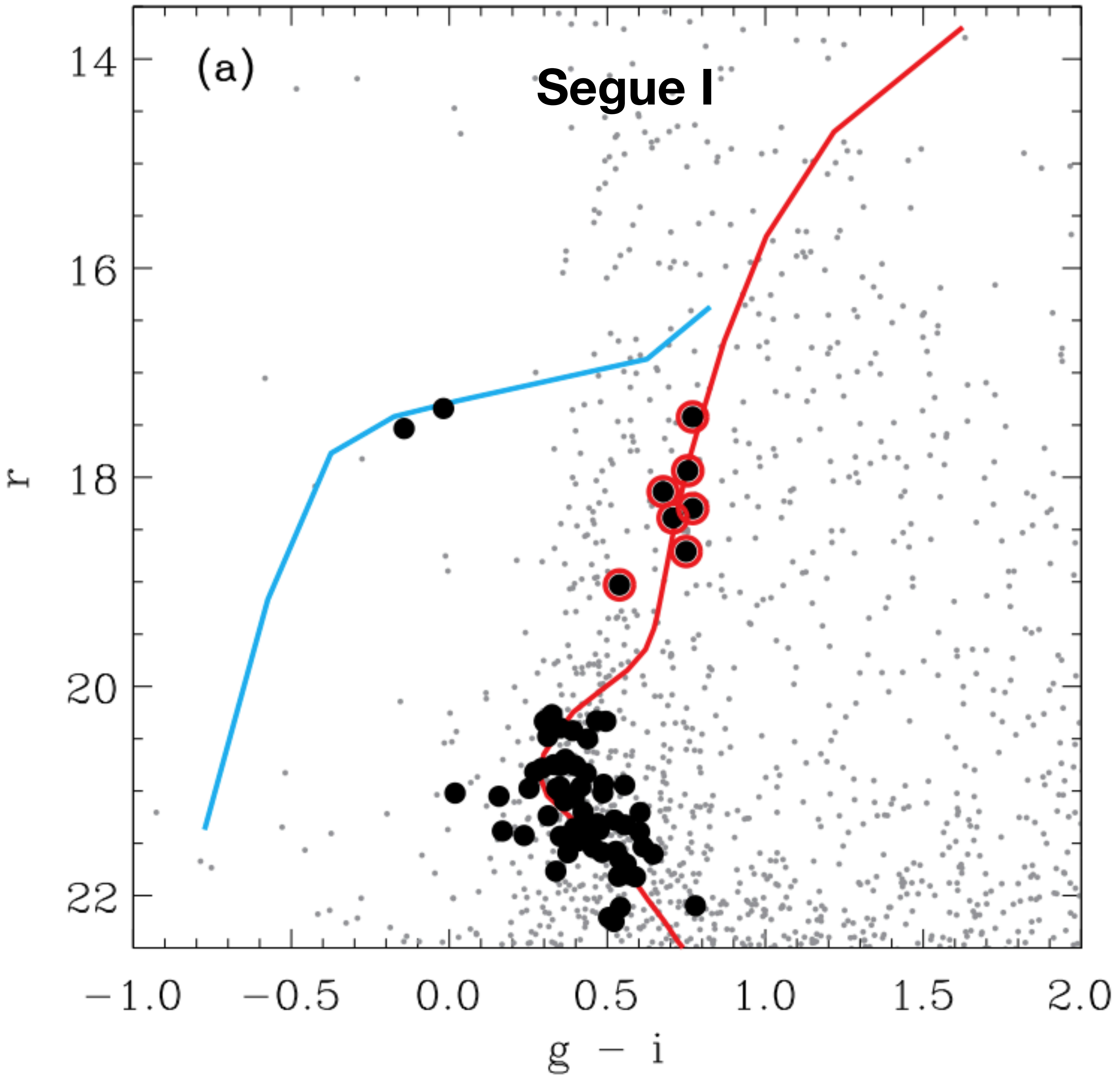
- Two typical dwarf spheroidal galaxies



ULTRA-FAINT DWARF GALAXIES (UFDs)

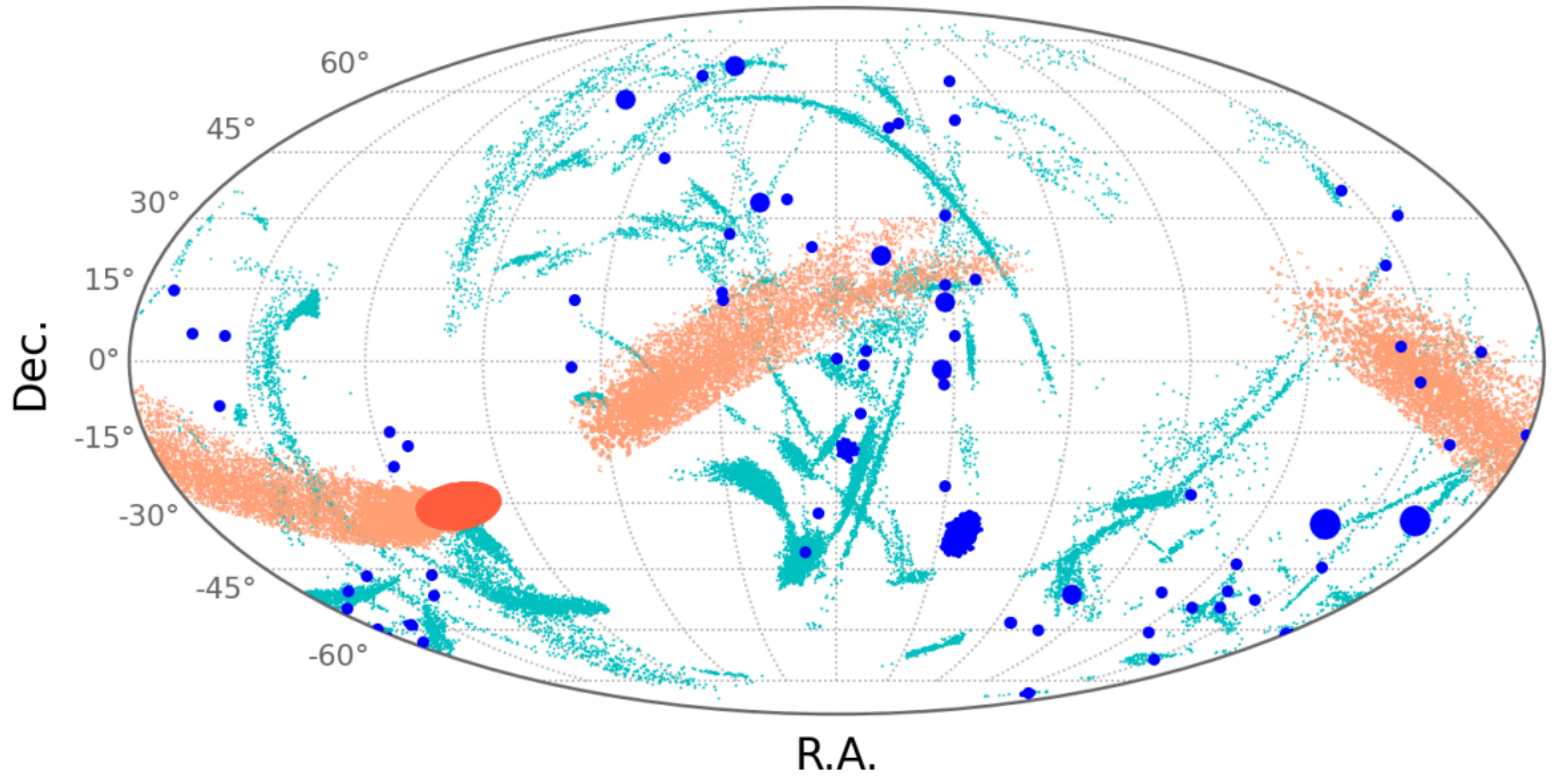
- ➤ The smallest dwarf galaxies are the Ultra Faint dwarf galaxies ($L \leq 10^5 L_\odot$).
- ➤ The smallest one, Segue I, has a stellar mass of $\sim 10^3 M_\odot$, and only 7 stars on its red giant branch.
- ➤ The UFDs typically only have a handful of stars which are feasible to follow up with medium- to high-resolution spectroscopy.

Frebel et al. 2014

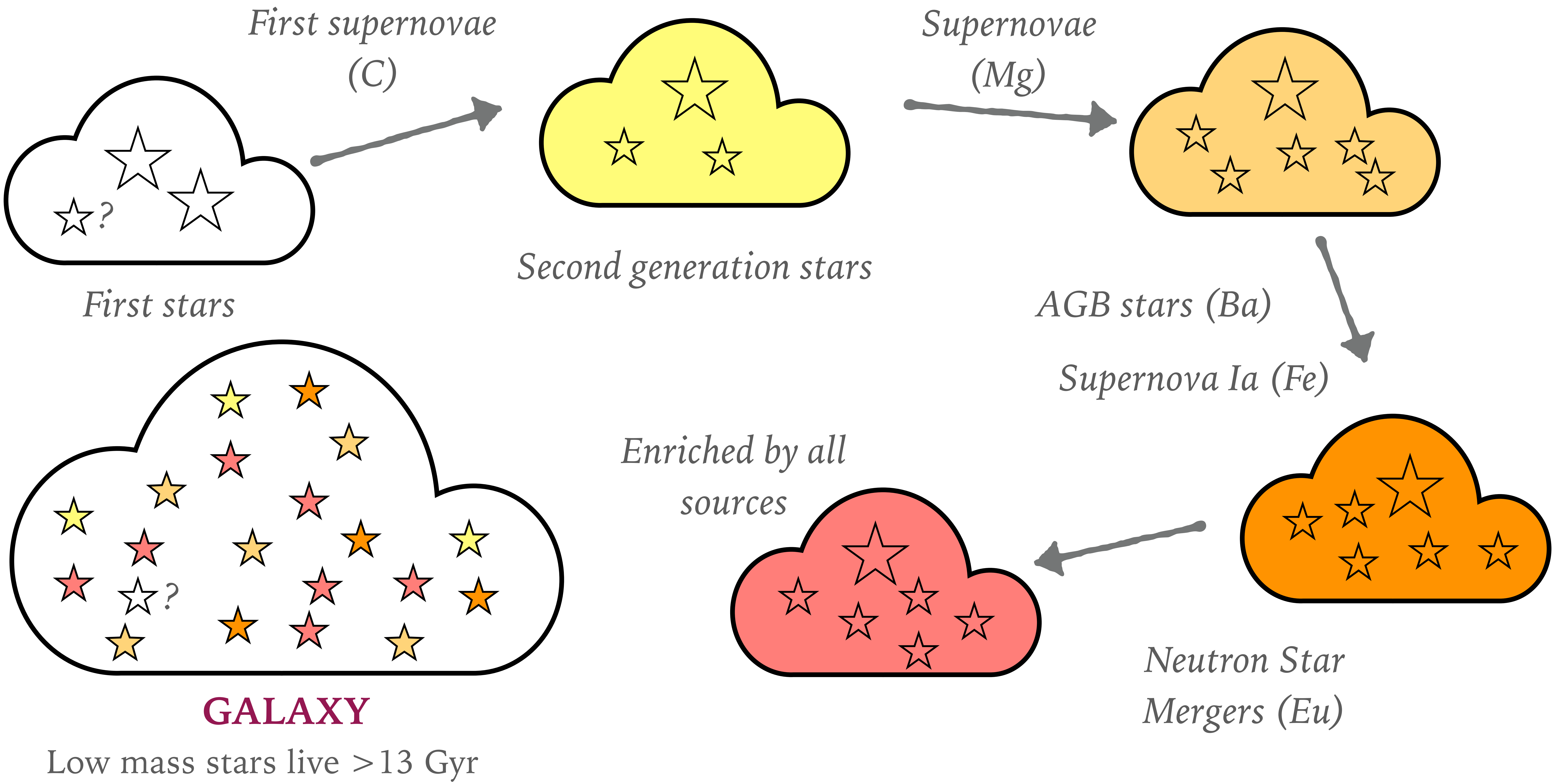


STELLAR ARCHAEOLOGY / GALACTIC ARCHAEOLOGY

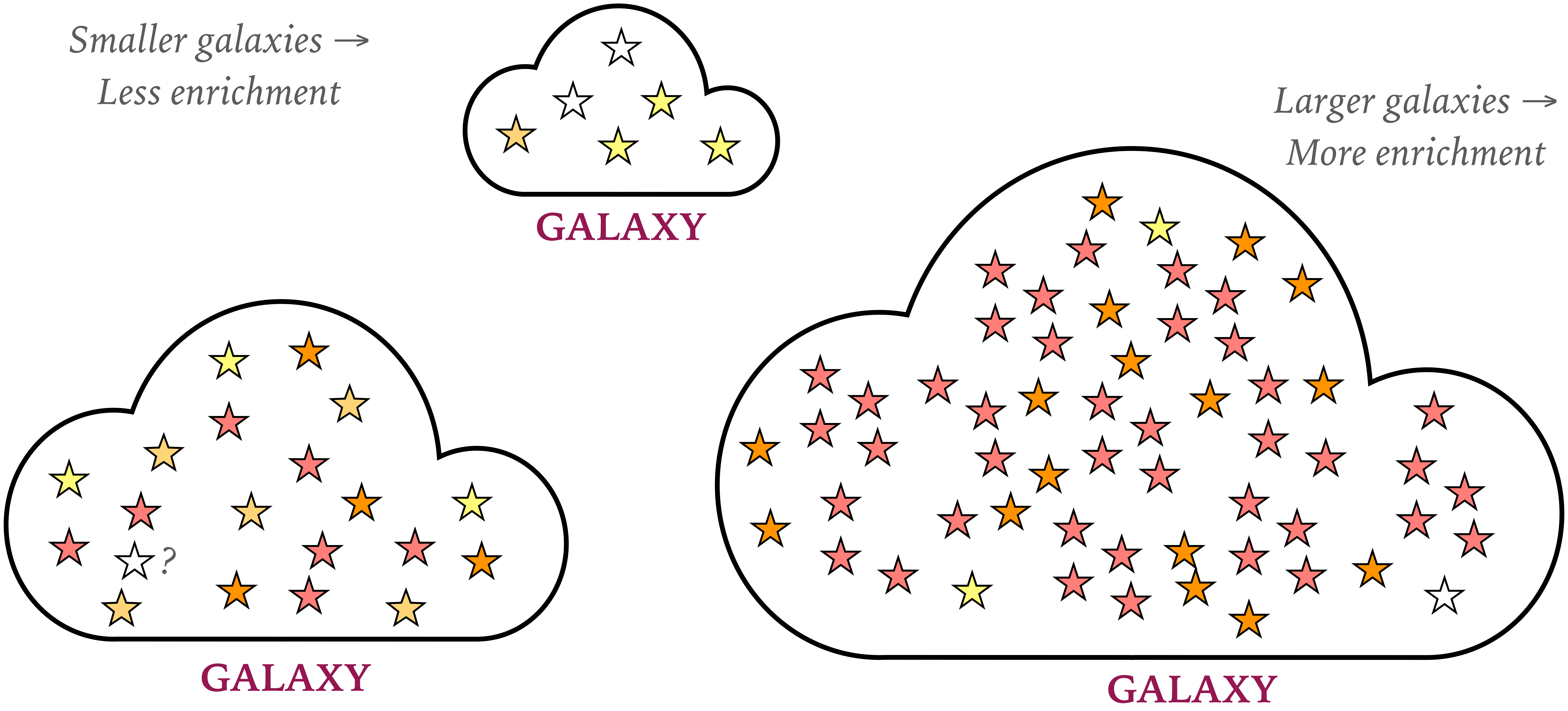
- The purpose of **Galactic archaeology** is to unveil the formation and evolution of our Galaxy by interpreting the observed chemical abundances, stellar ages and kinematics of resolved stellar populations.
- **Hierarchical build-up** of the Milky Way environment
- **Chemical evolution**



CHEMICAL EVOLUTION

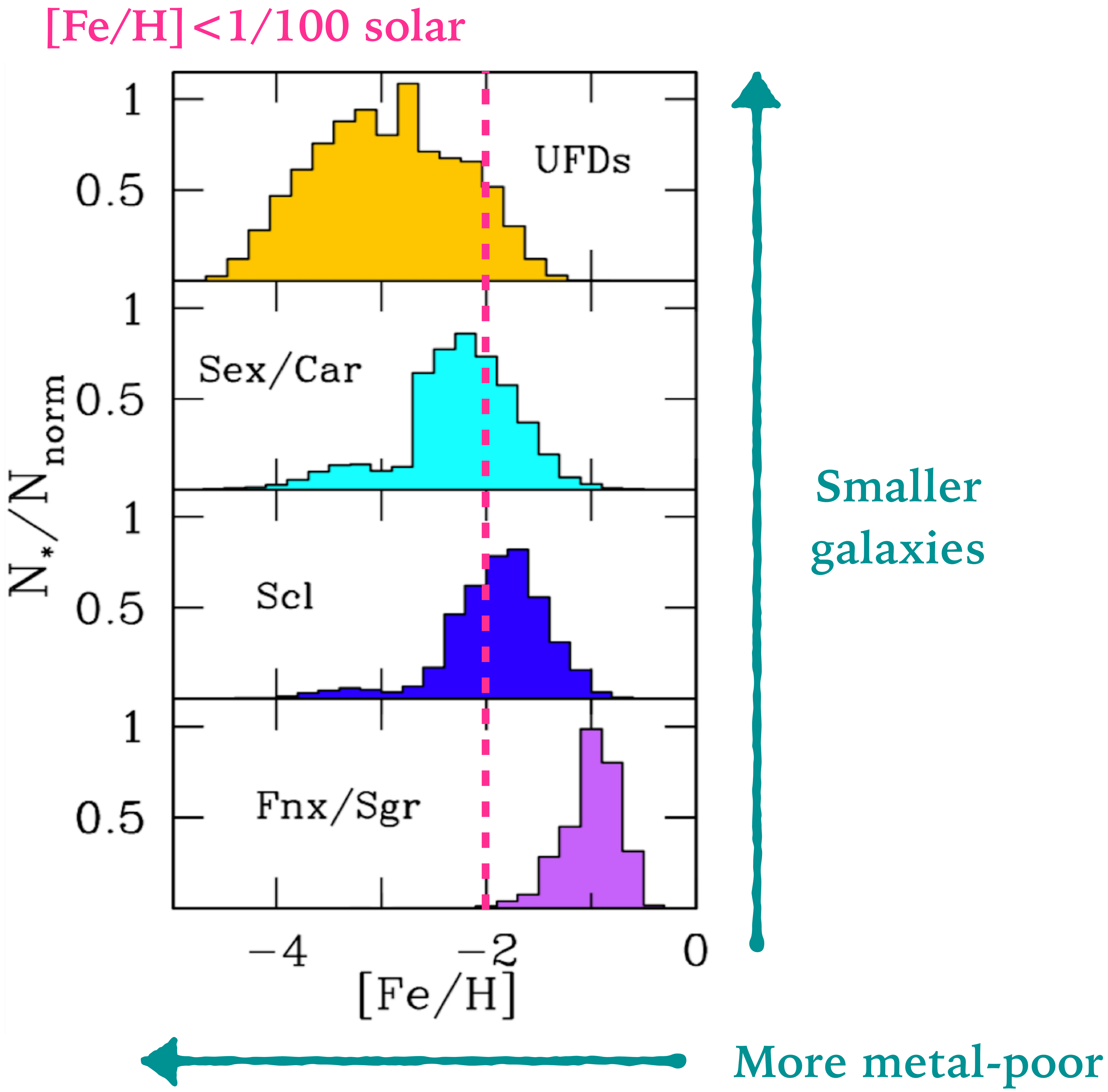


DIFFERENT GALAXIES – DIFFERENT CHEMICAL EVOLUTION



Low mass stars live >13 Gyr

DWARF GALAXIES ARE METAL-POOR

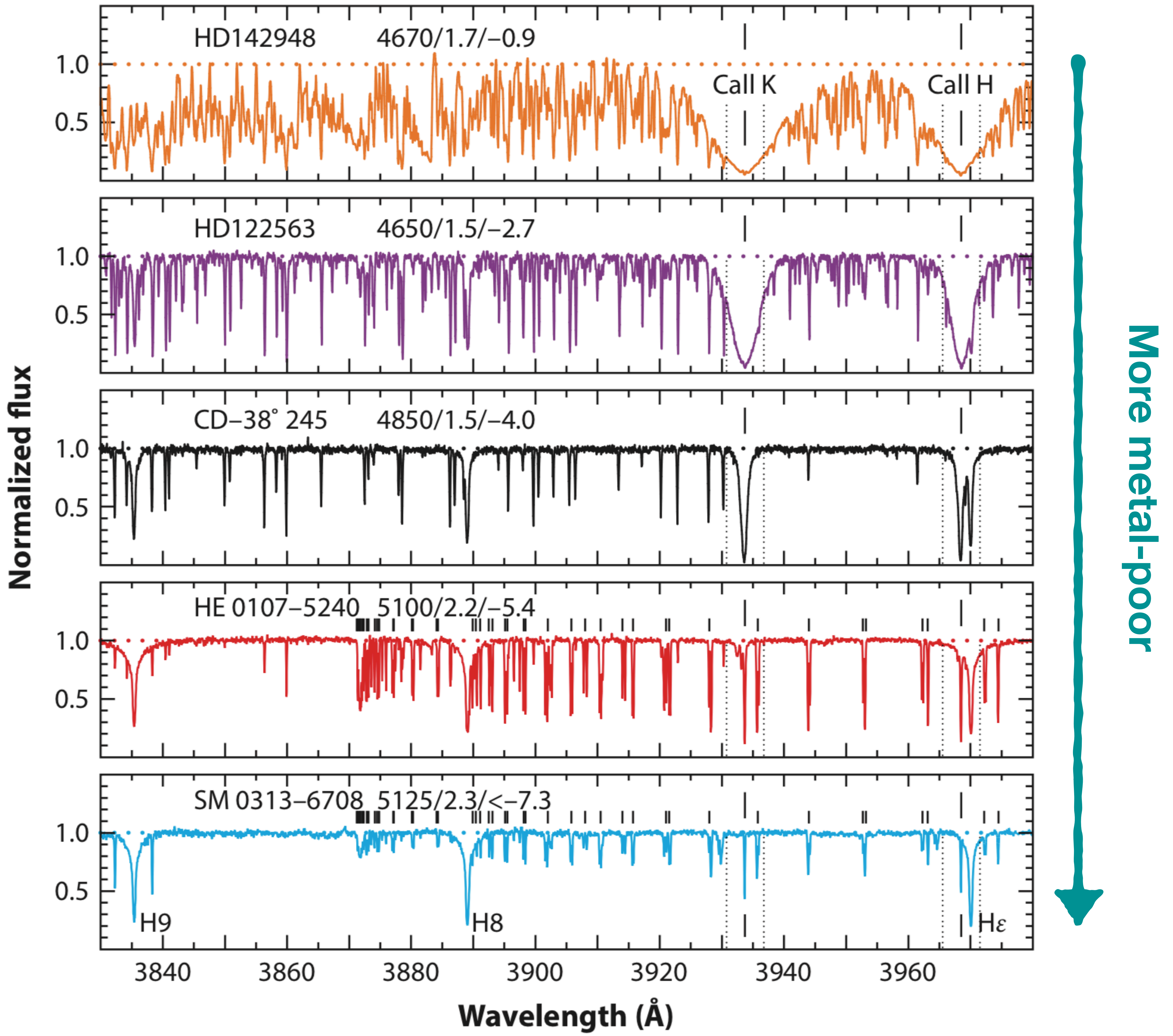


Simulated Metallicity Distribution Functions (MDFs) for different dwarf galaxies (Salvadori, Skúladóttir & Tolstoy 2015).

METAL-POOR SPECTRA

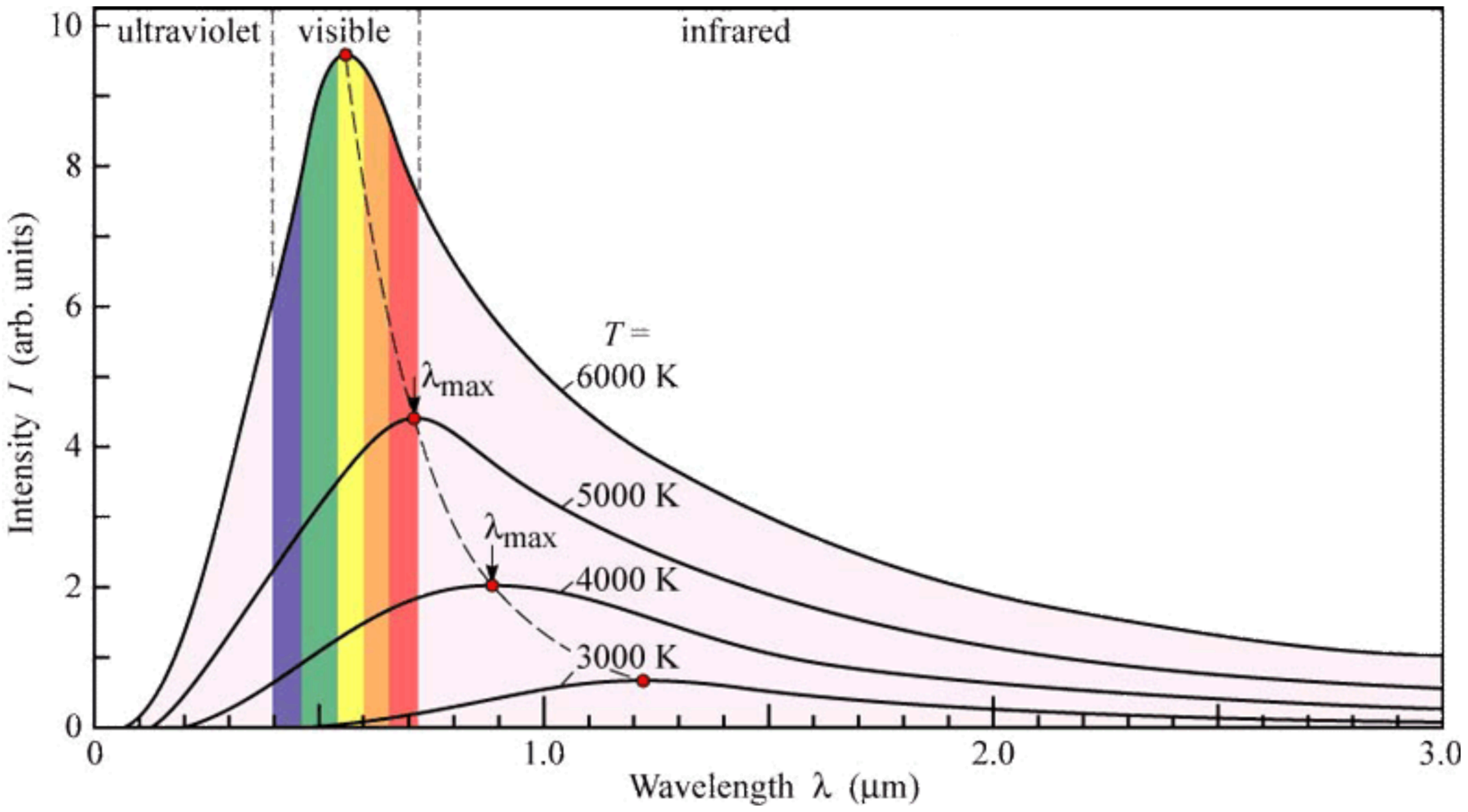
- As stars get more metal-poor
  - The spectra contains fewer detectable lines
  - The lines become weaker and harder to distinguish from the noise.
  - Most of the lines that do remain in the spectrum are in the blue part of the spectrum (≲5000 Å)
- This means that we need higher quality spectra to determine chemical abundances: higher resolution and higher S/N (to recognise weak lines), and blue coverage.

Milky Way Frebel & Norris 2015



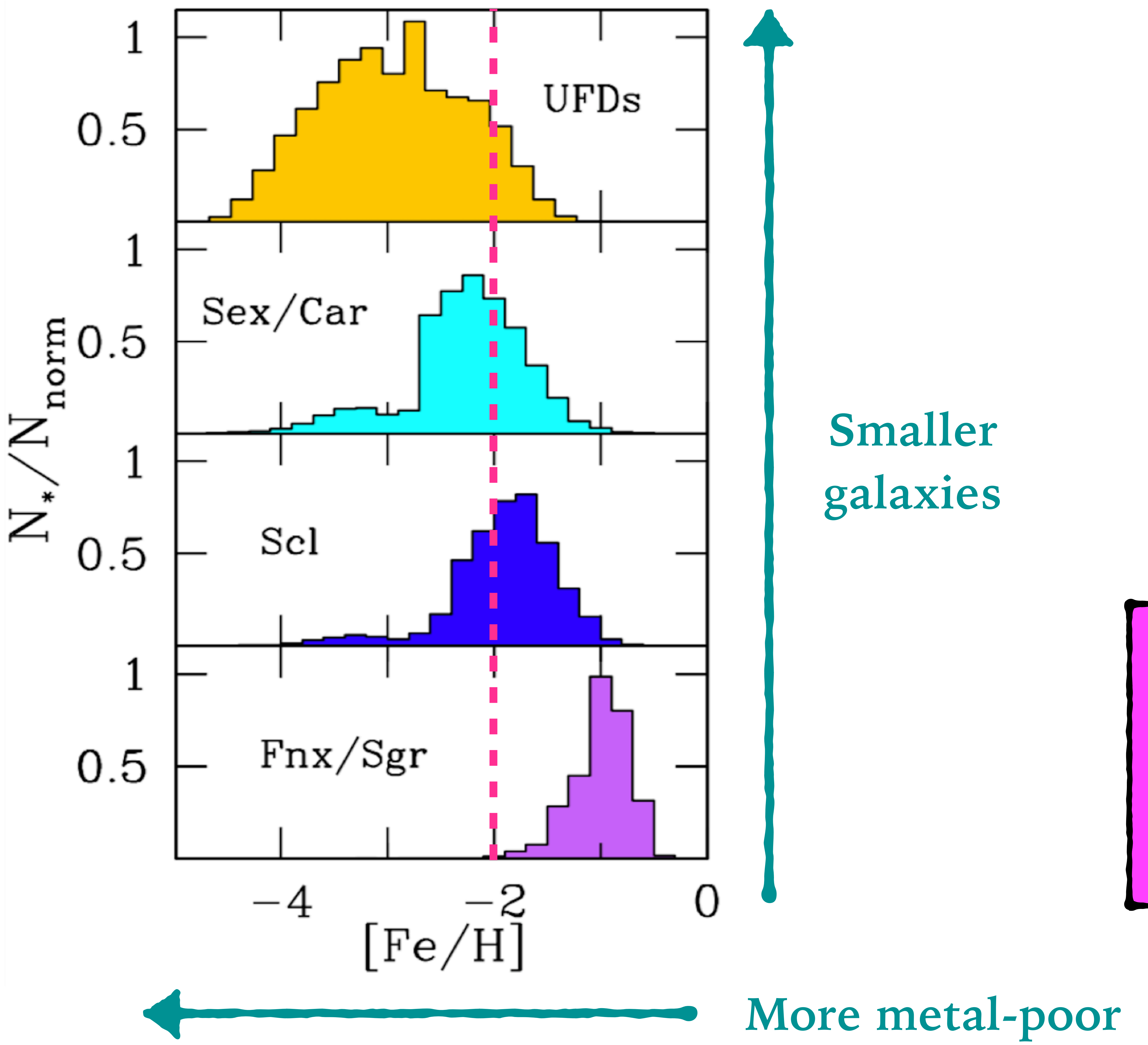
METAL-POOR SPECTRA

- However…
  - Dwarf galaxy and stream stars typically quite faint, so high S/N and high resolution are challenging.
  - We can only target red giant stars (which are faint in the blue)
- …Can be done… (for some stars) … but it is expensive in telescope time.



DWARF GALAXIES ARE METAL-POOR

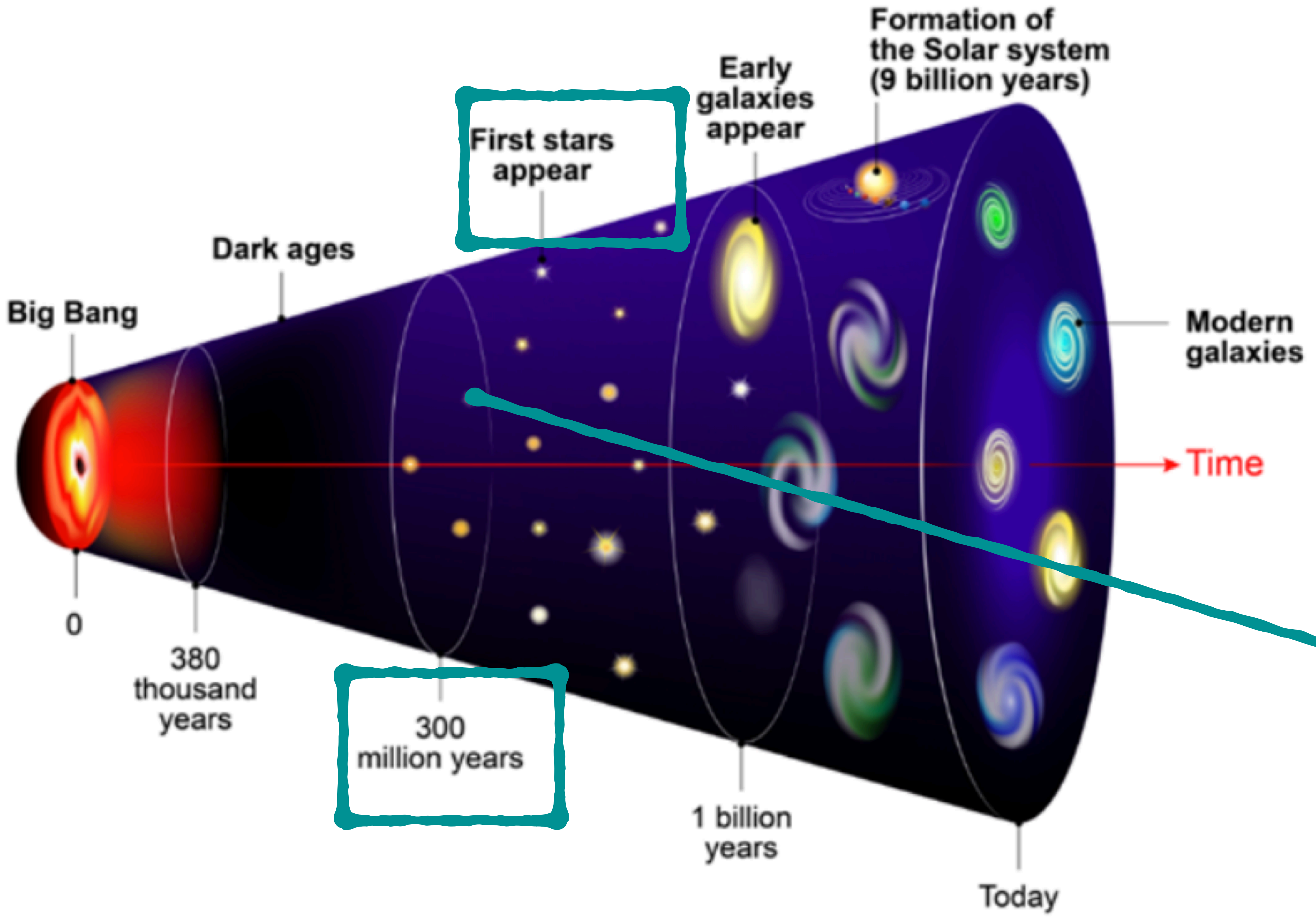
[Fe/H]<1/100 solar



Simulated Metallicity Distribution Functions (MDFs) for different dwarf galaxies (Salvadori, Skúladóttir & Tolstoy 2015).

Very metal-poor stars guard the signature of the First Stars

THE FIRST STARS IN THE UNIVERSE

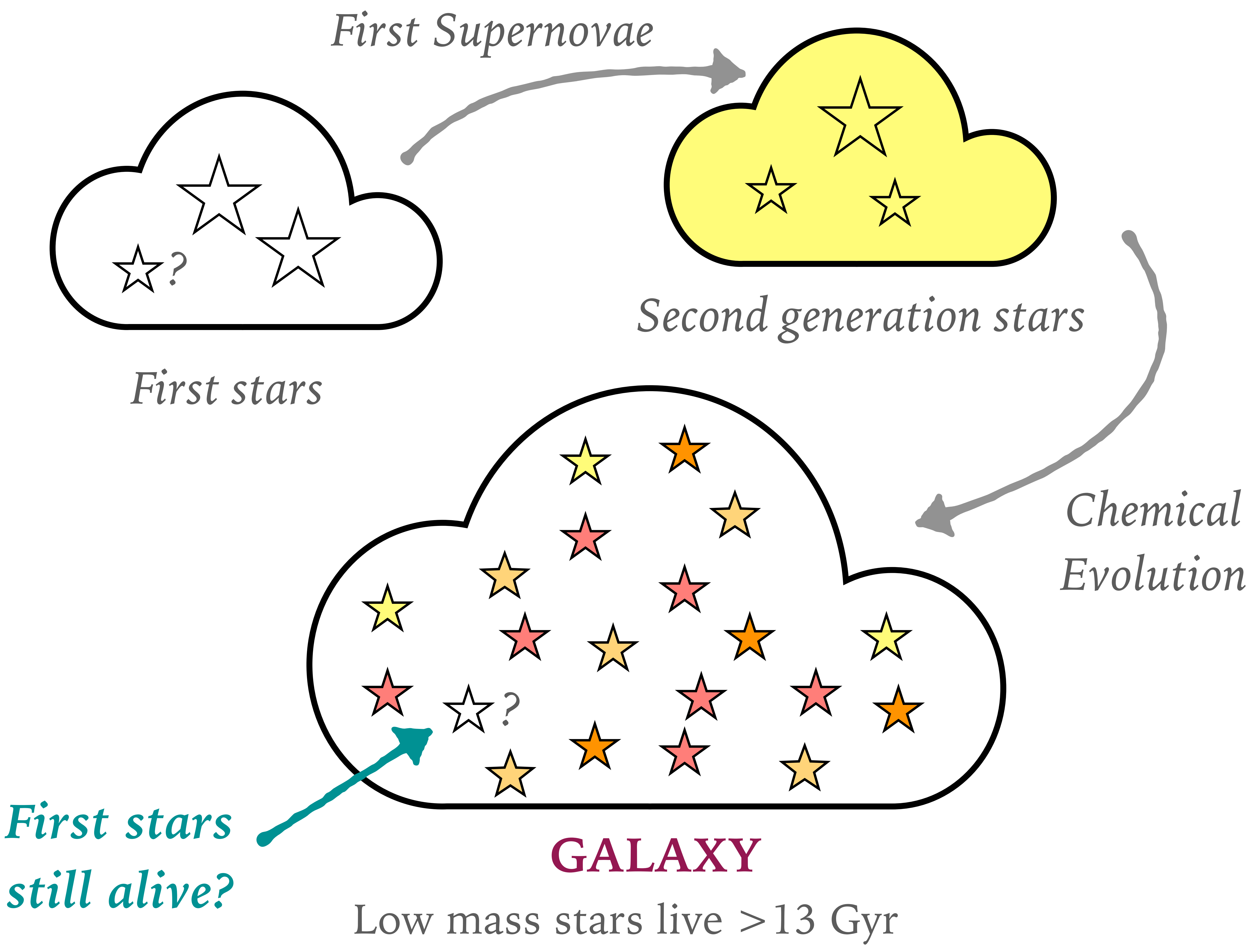


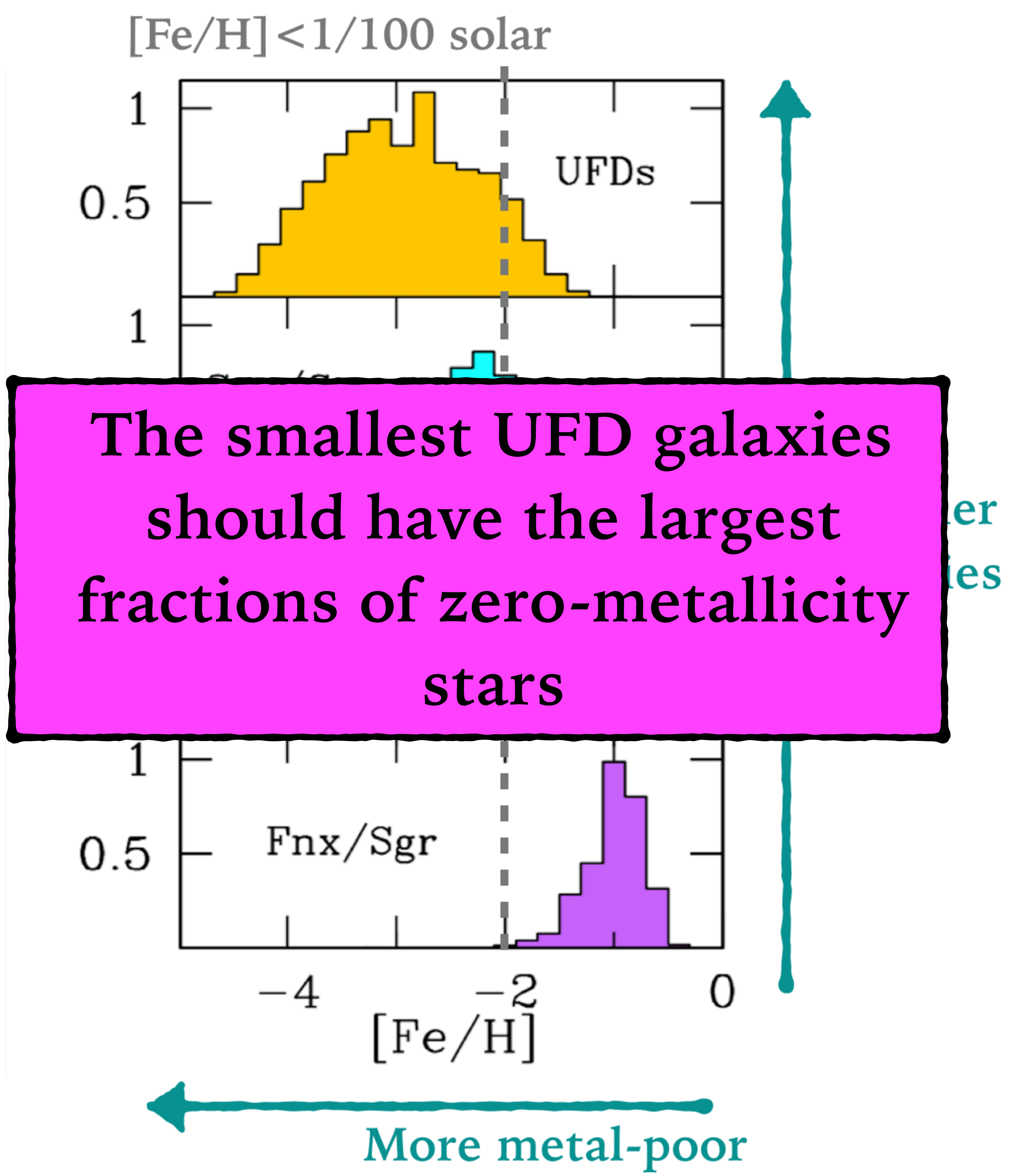
- The First Stars after the Big Bang only made of H and He!
- Likely more massive than stars formed today.
- Stars with $M < 0.8\ M_\odot$ still alive today.
- No metal-free star observed to date!

$M < 0.8\ M_\odot$

Still alive!

SEARCHING FOR THE FIRST STARS

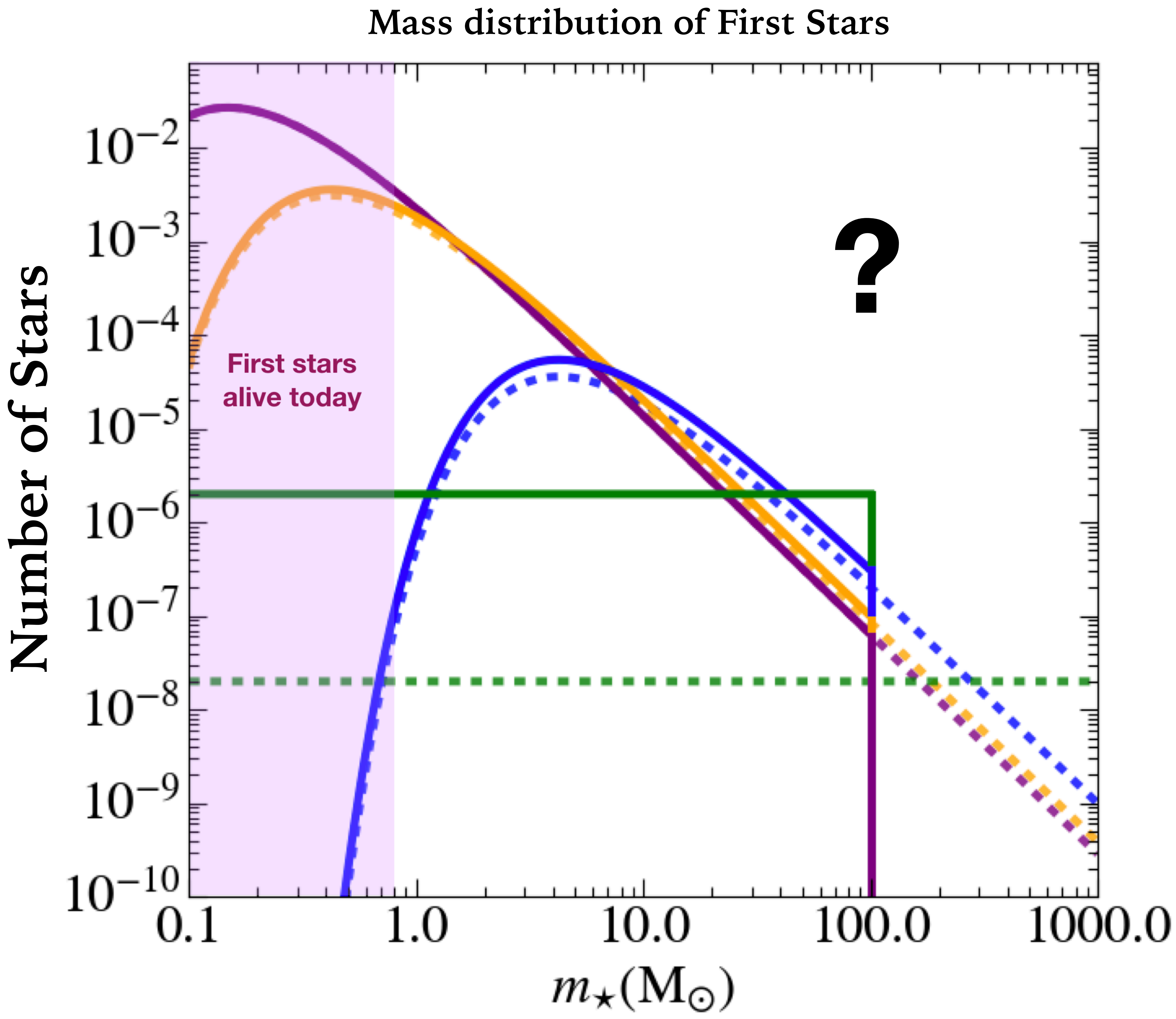




The smallest UFD galaxies should have the largest fractions of zero-metallicity stars

NON-DETECTION OF ZERO-METALLICITY STARS

- ➤ Detailed chemical evolution model of an ultra-faint dwarf galaxies can be used to constrain the mass distribution of the first stars.
- ➤ Different assumption of the mass distribution of the first stars predict different number of surviving first stars (<0.8M$_\odot$)



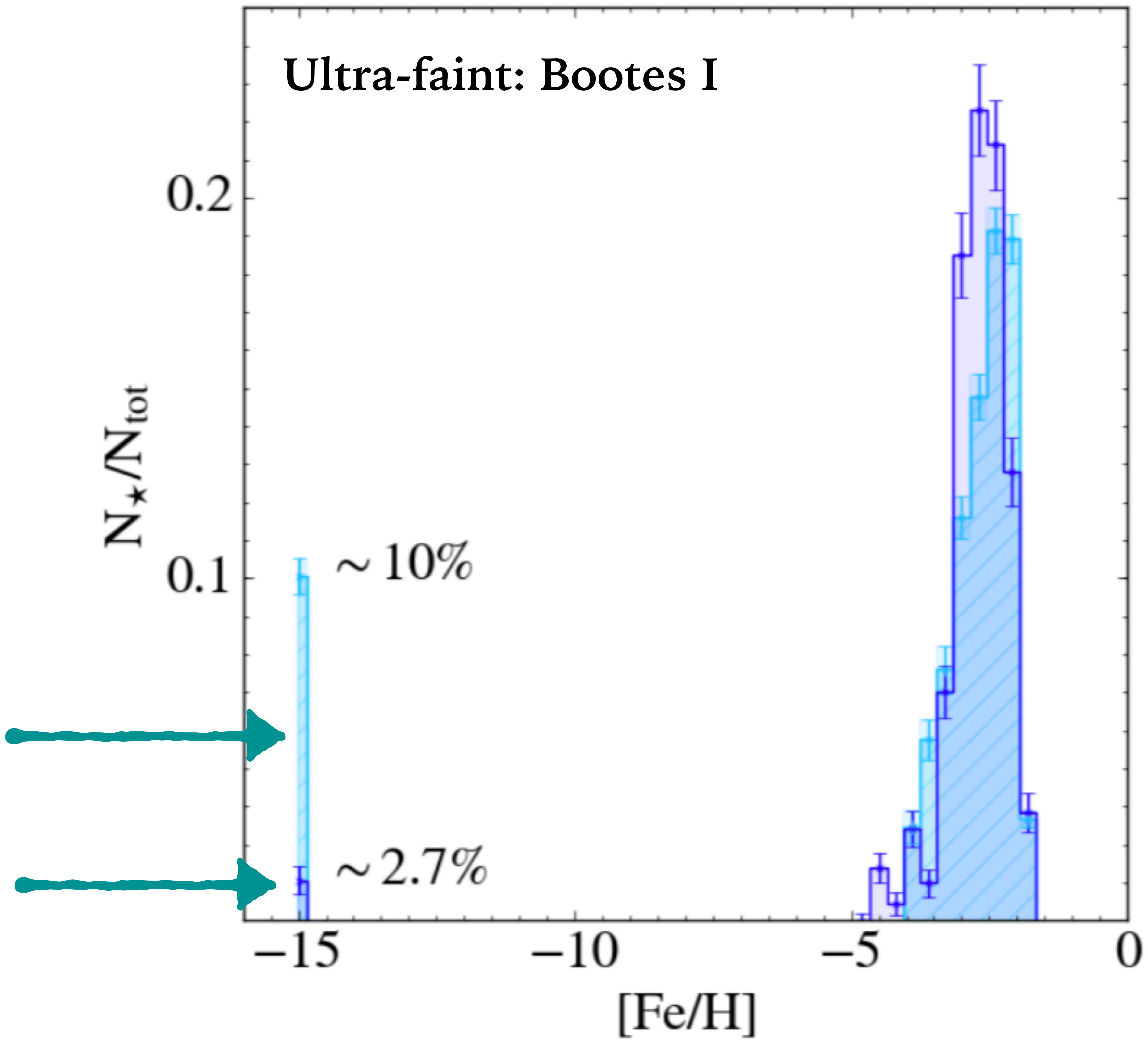
NON-DETECTION OF ZERO-METALLICITY STARS

- **Comparison of model to data:** If the mass distribution of First Stars were the same as present day stars - we would have found them!
- **Results:** First Stars were more massive than present day stars.

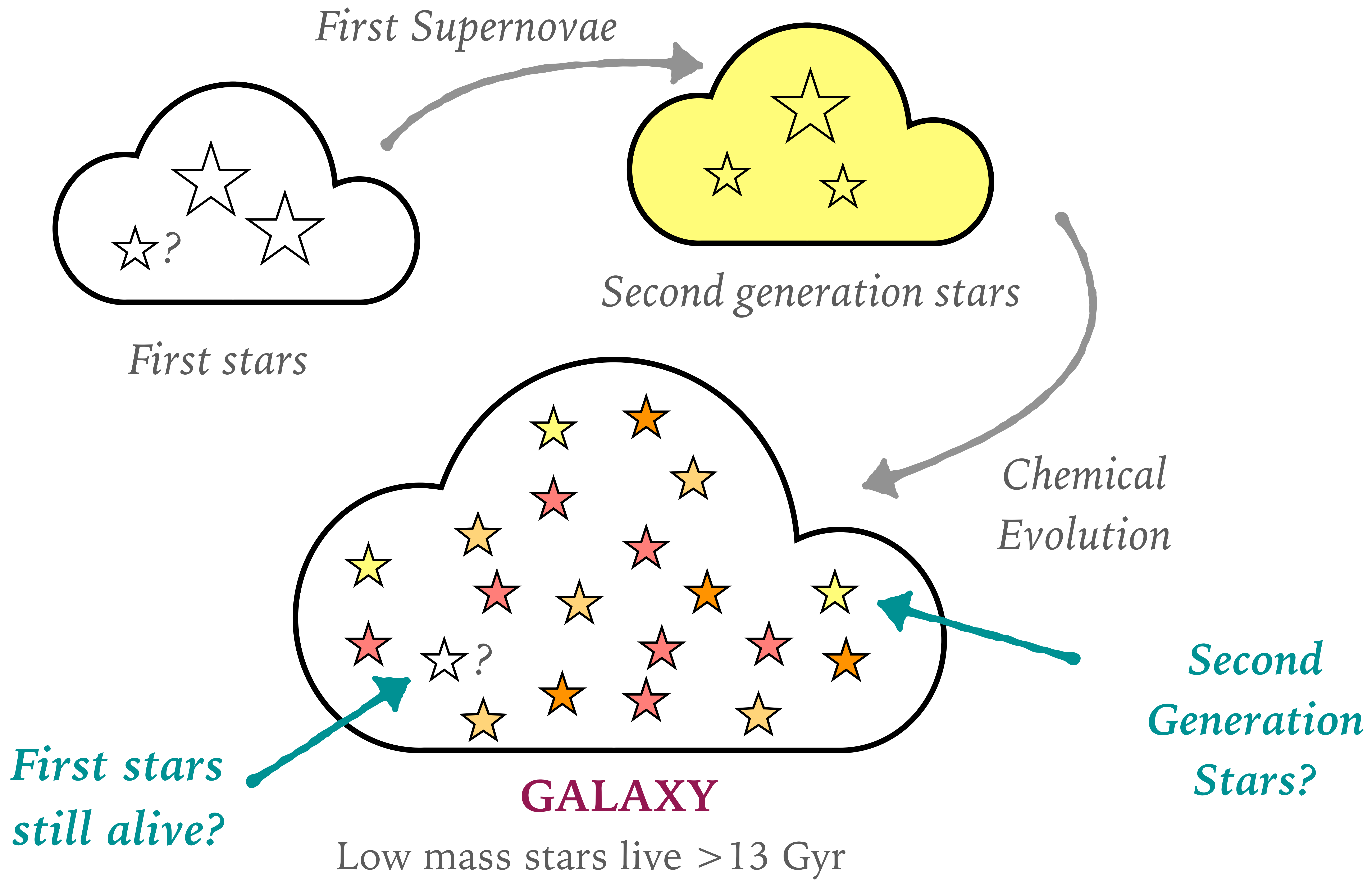
Number game:

For better constraints we need more data

Rossi, Salvadori & Skúladóttir 2021



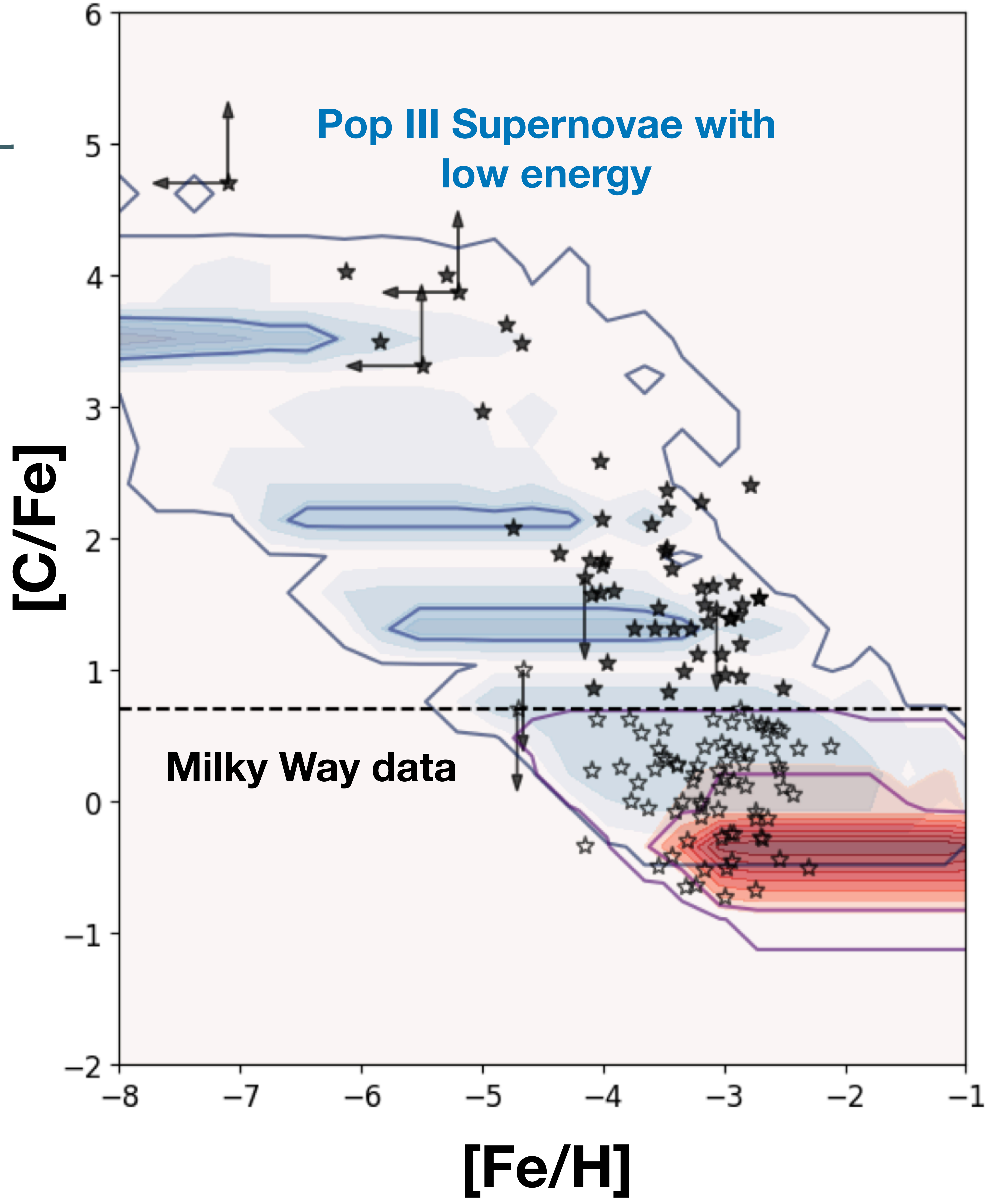
SEARCHING FOR THE FIRST STARS



CEMP: SIGNATURES OF THE FIRST STARS

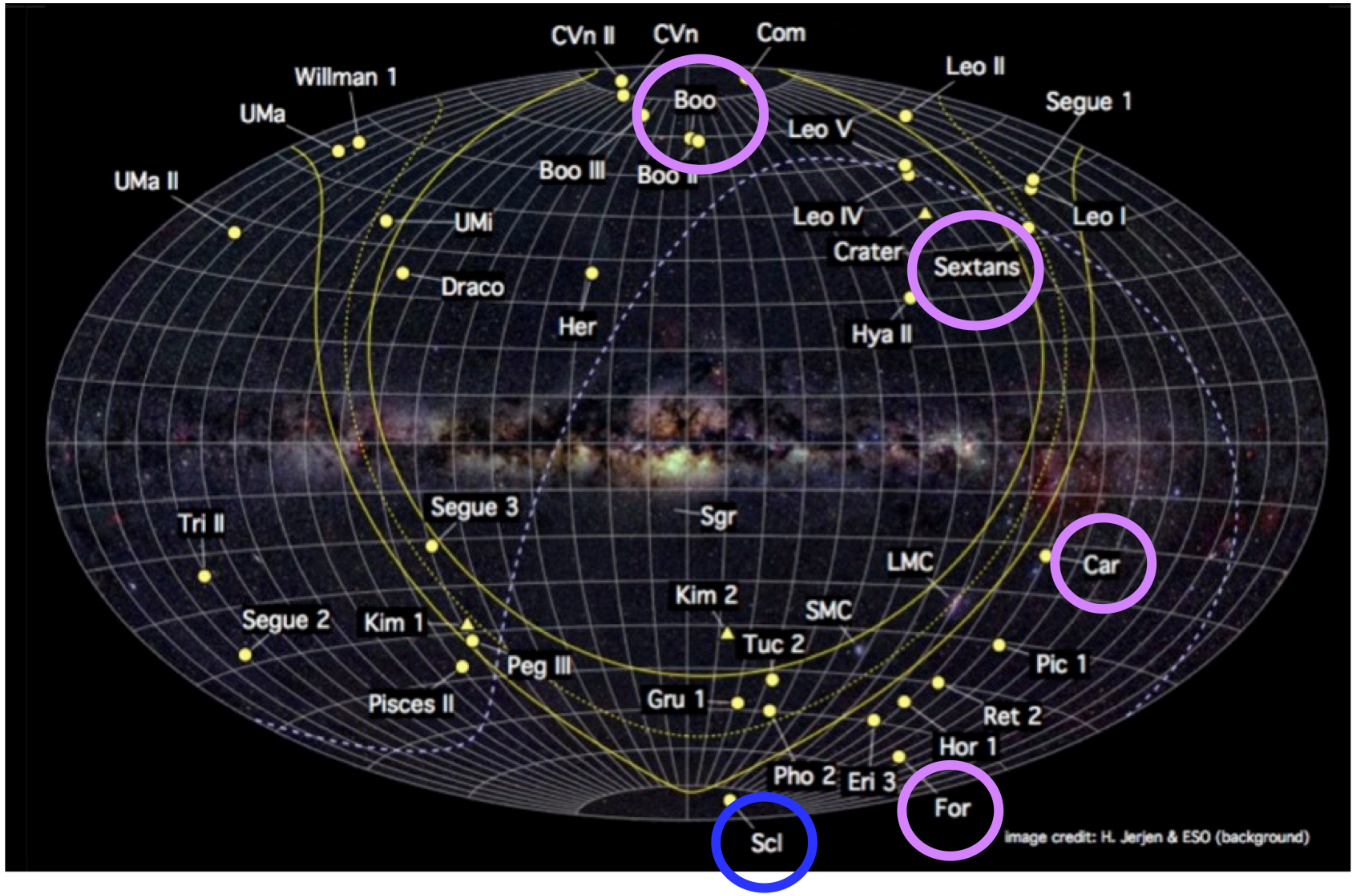
CEMP stars:
Carbon-enhanced
metal-poor stars

Vanni, Salvadori & Skúladóttir 2023



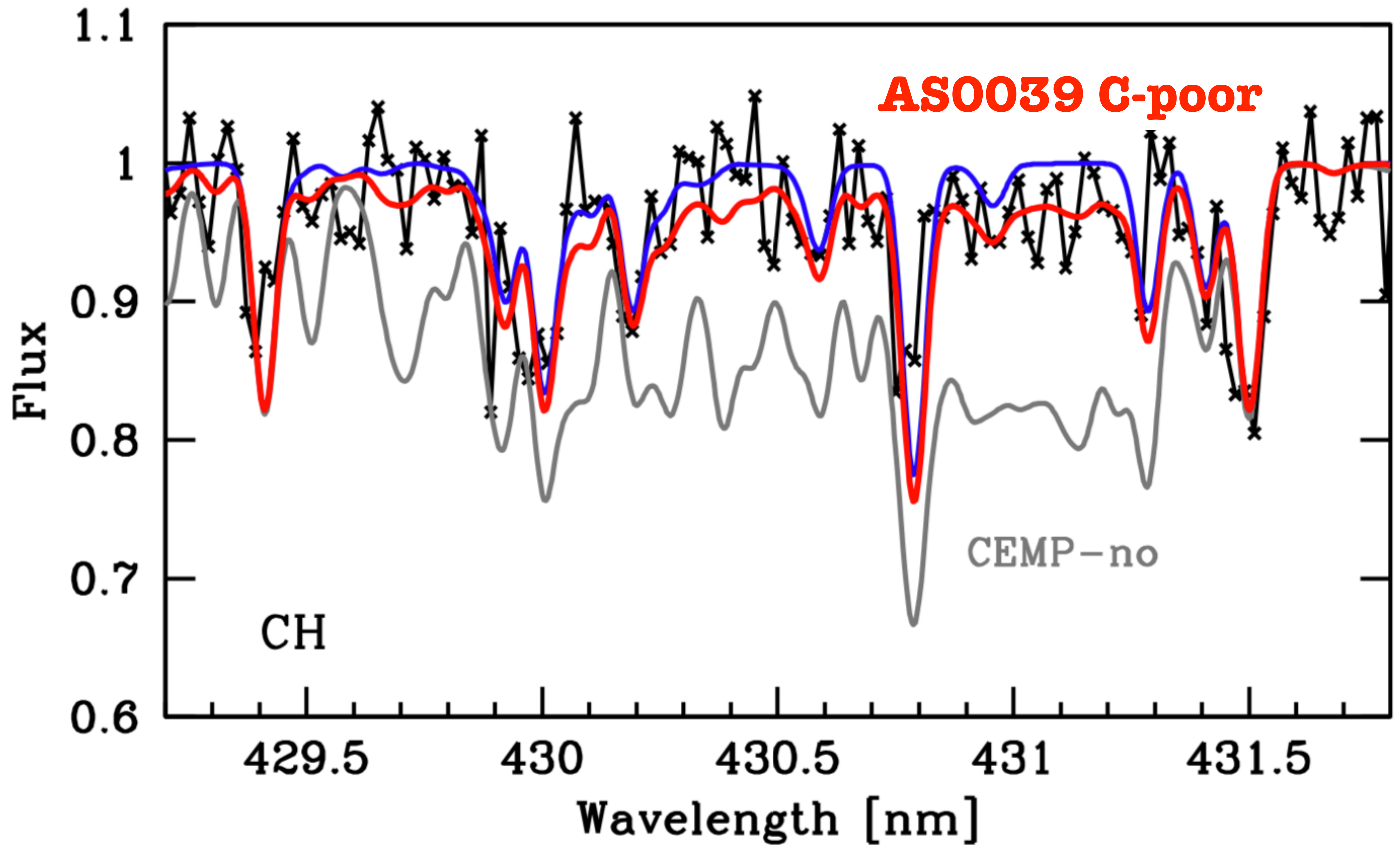
SEARCH FOR METAL-POOR STARS

- Survey of radial velocities and [Fe/H] - few thousand stars .
  (First paper out: Tolstoy et al. 2023)
- Most metal-poor star in our sample found in **Sculptor!**

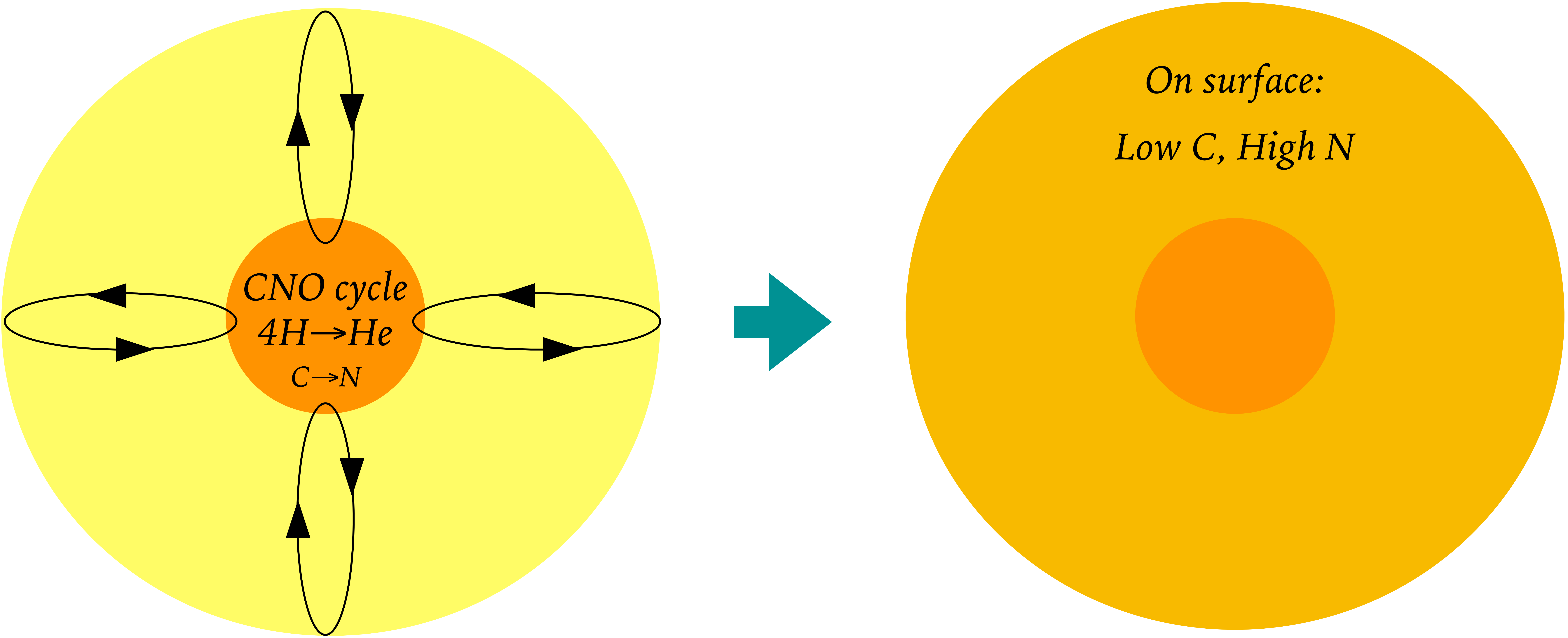


AS0039: C-NORMAL AND ULTRA METAL-POOR

- **Ultra metal-poor** [Fe/H]=-4
  - Not just C-“normal”, but **C-poor:**
    - A(C)=3.60 → **Lowest C measured in any star**
    - **[C/Fe]=-0.3** (LTE, when corrected for **internal mixing**)



CARBON: EFFECTS OF MIXING ON THE RGB



Highly simplified!

Not to scale!

This dredge-up has to be corrected for, to obtain the C-abundance that the star was born with (Placco et al. 2014)

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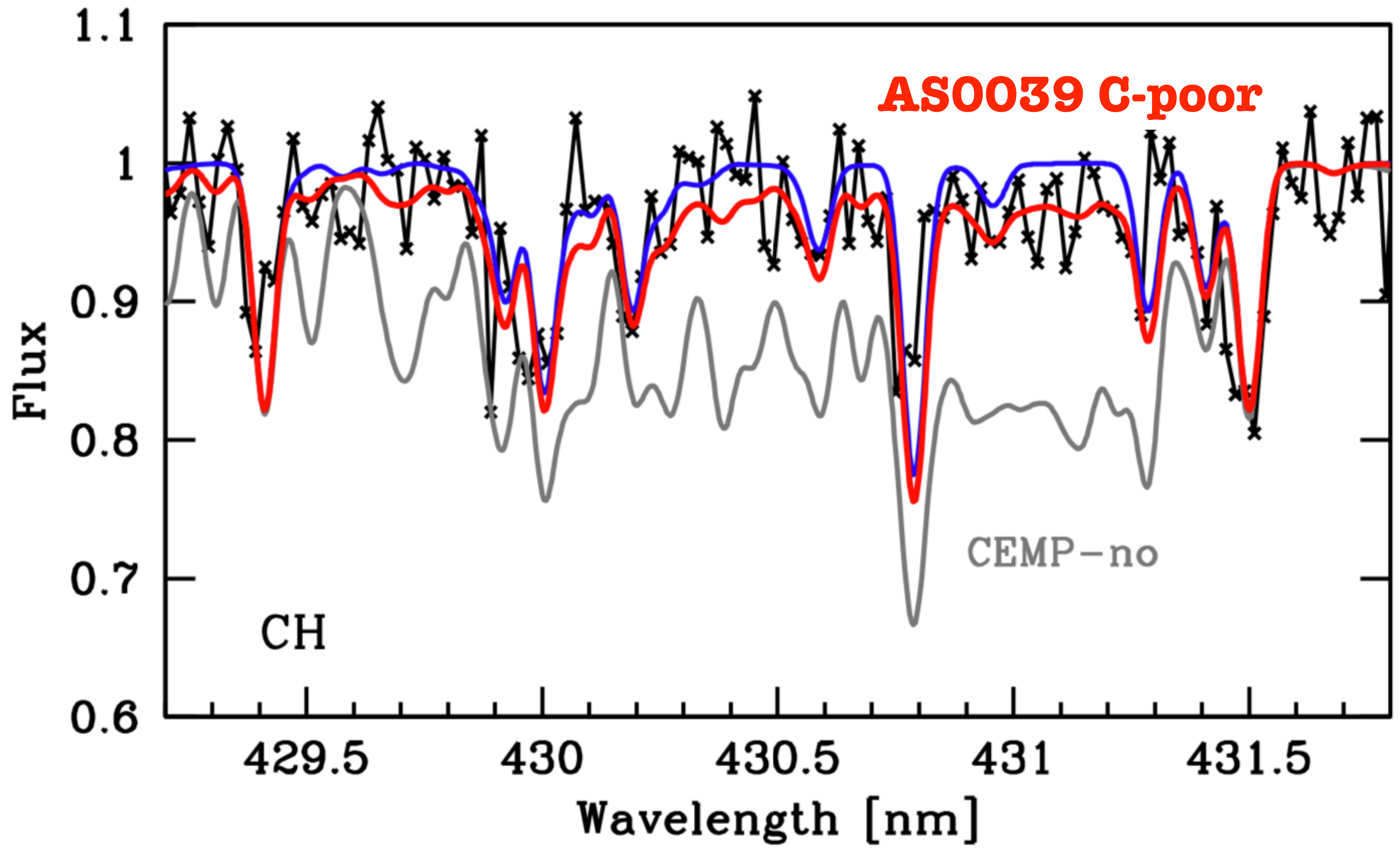
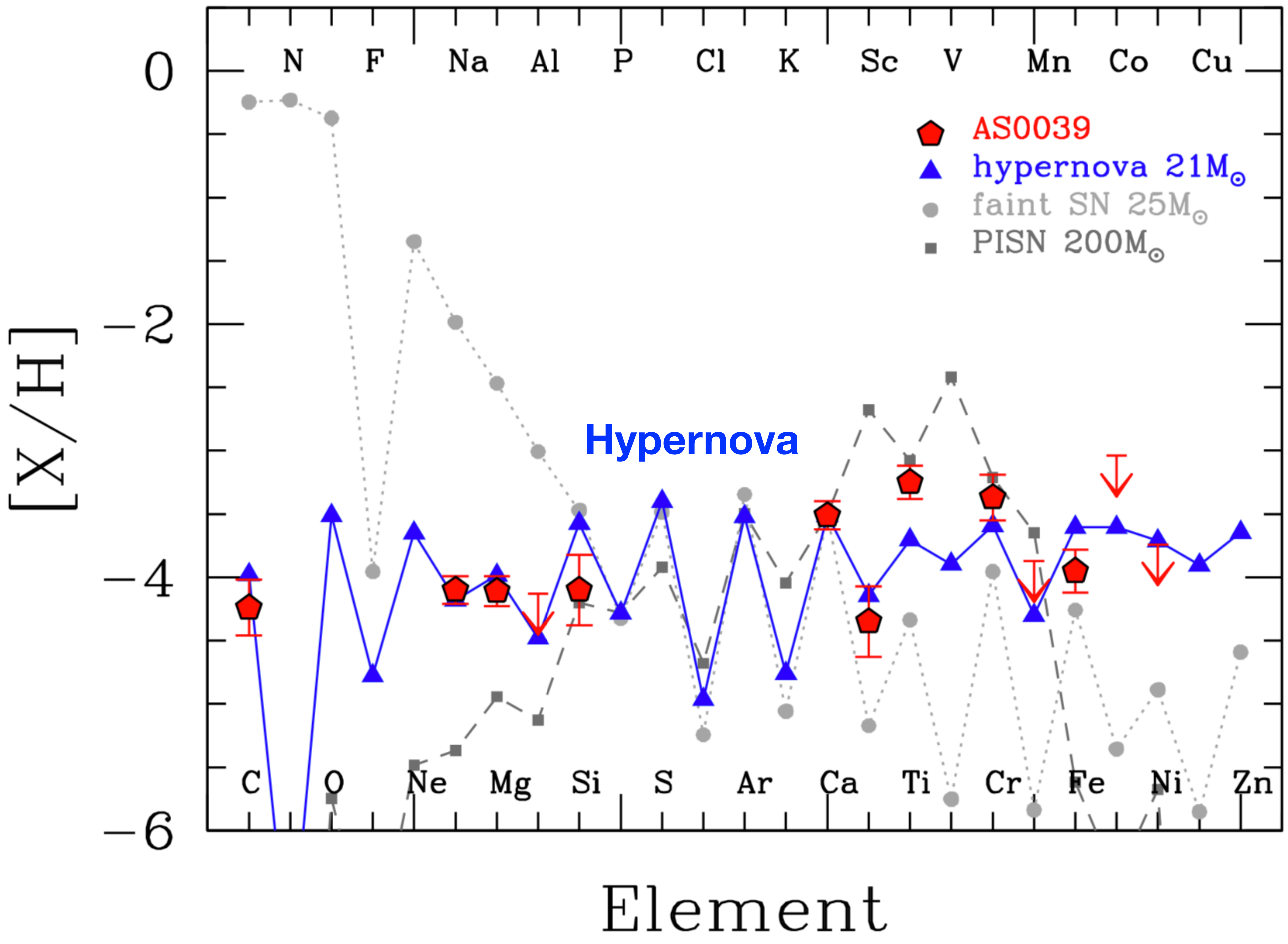
  - Not just C-“normal”, but **C-poor:**
    - A(C)=3.60 → Lowest C measured in any star
    - **[C/Fe]=-0.3** (LTE, when corrected for internal mixing)
- Lowest metallicity measured in any star outside of the Milky Way!



BEST FIT: ZERO-METALLICITY HYPERNOVA!

Skúladóttir et al. 2021



Constraints on the ***energy distribution*** *of the First stars.*

Yields: Heger & Woosley 2002; 2010, Iwamoto et al. 2005

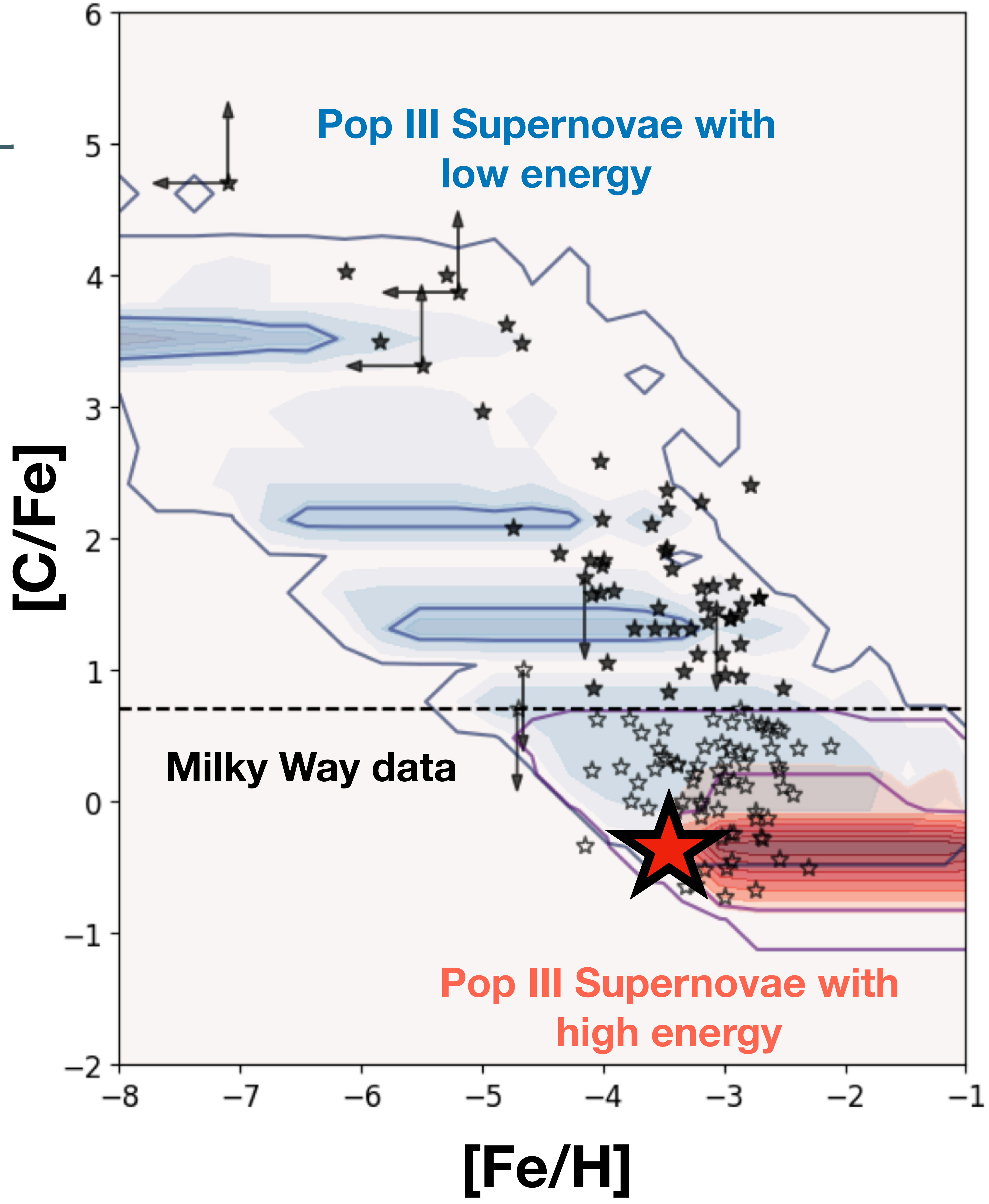
See also: Placco et al. 2021

SIGNATURES OF THE FIRST STARS

CEMP stars: Descendants of low energy PopIII Supernovae

Decendants of high-energy PopIII Supernovae

Vanni, Salvadori & Skúladóttir 2023

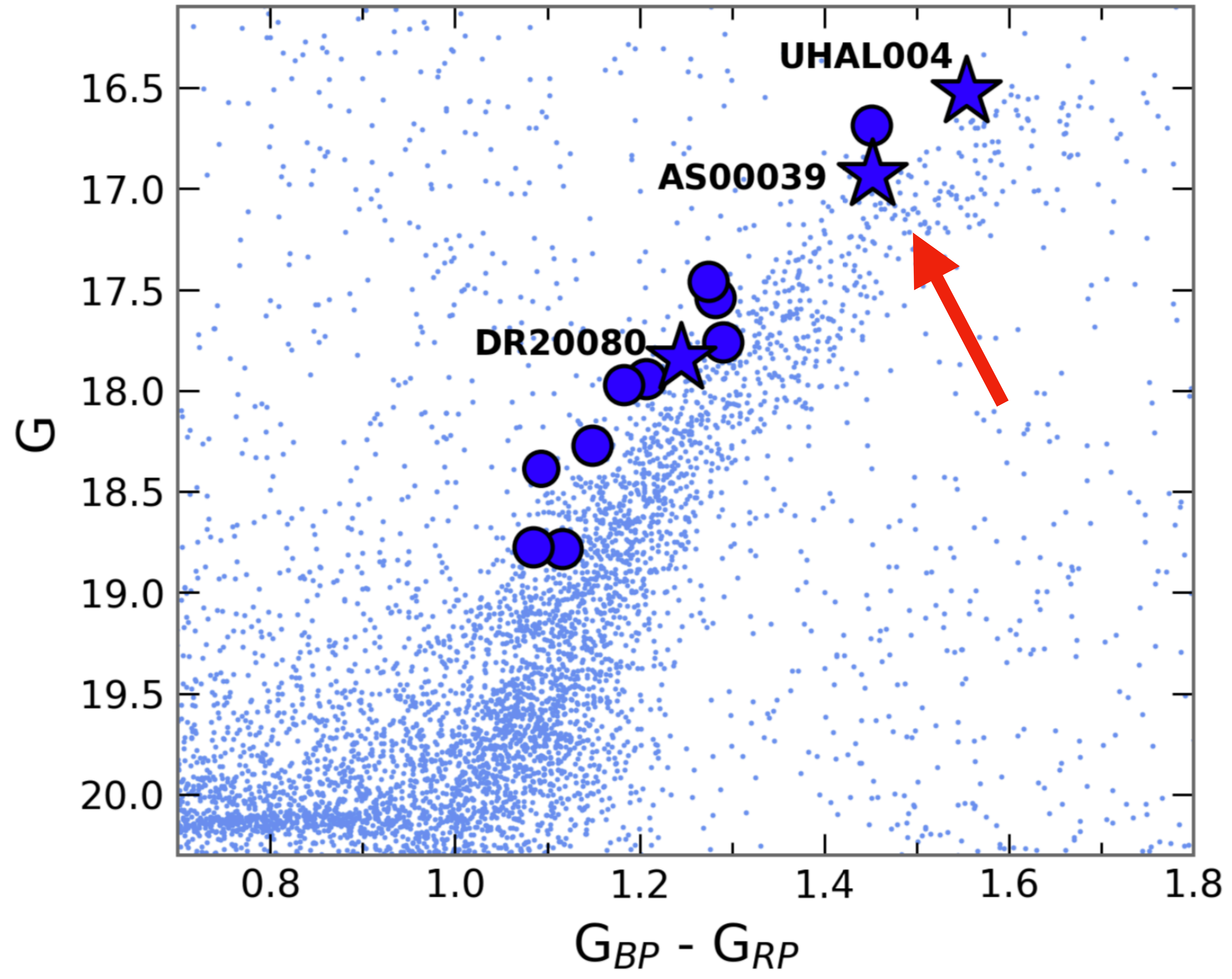


BETTER DATA – NEW RESULT?

Data	*Progenitor*
X-Shooter spectra (R~5,000-9,000) →	**Zero-metallicity Hypernova 21 M⊙**
UVES spectra (R~20,000-40,000) →	**?**

More elements!

Sculptor CMD



Skúladóttir et al. 2024

BETTER DATA – NEW RESULT?

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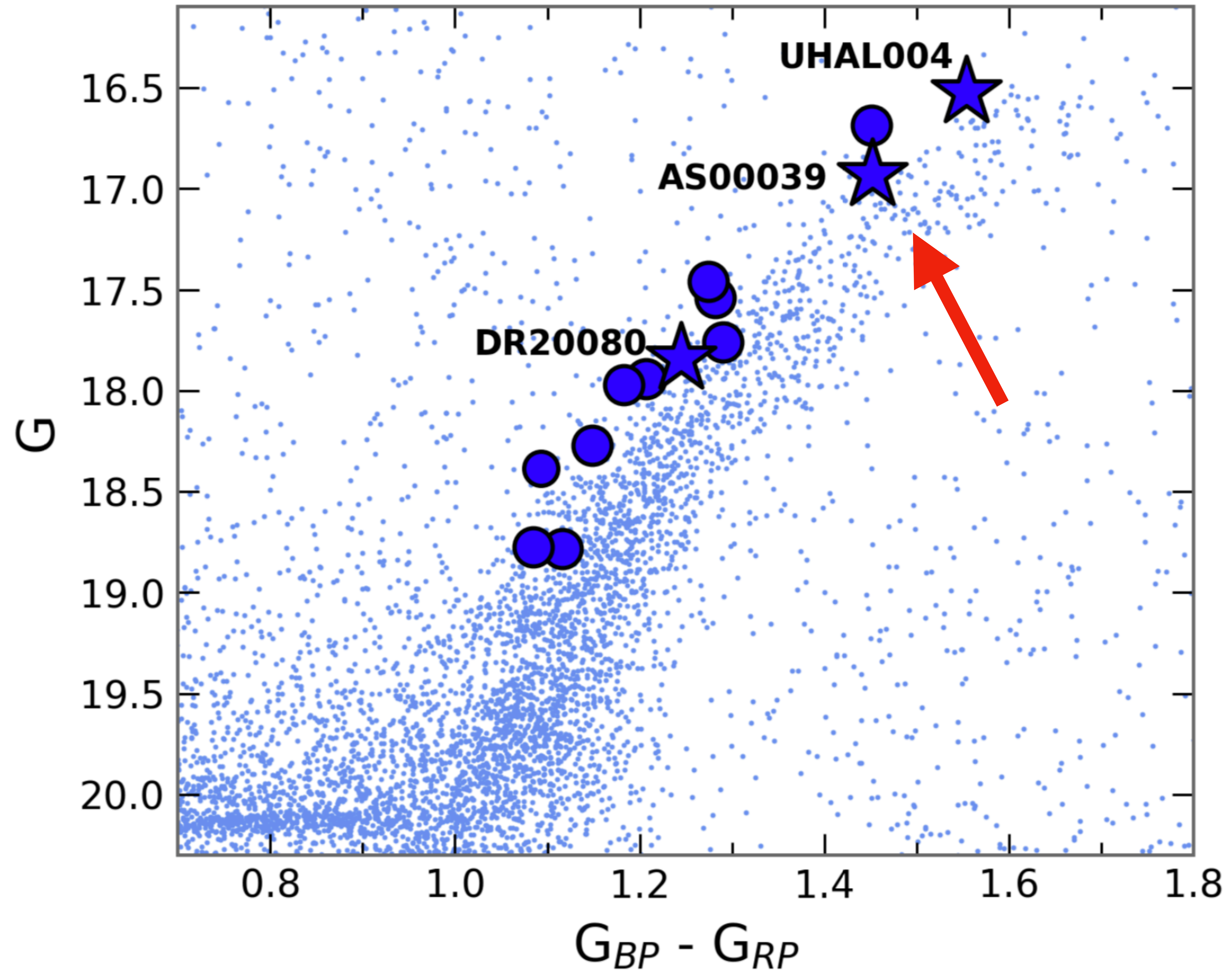
X-Shooter spectra (R~5,000-9,000)	→	**Zero-metallicity Hypernova 21 M⊙**
UVES spectra (R~20,000-40,000)	→	**Zero-metallicity Hypernova 20 M⊙**

More elements!

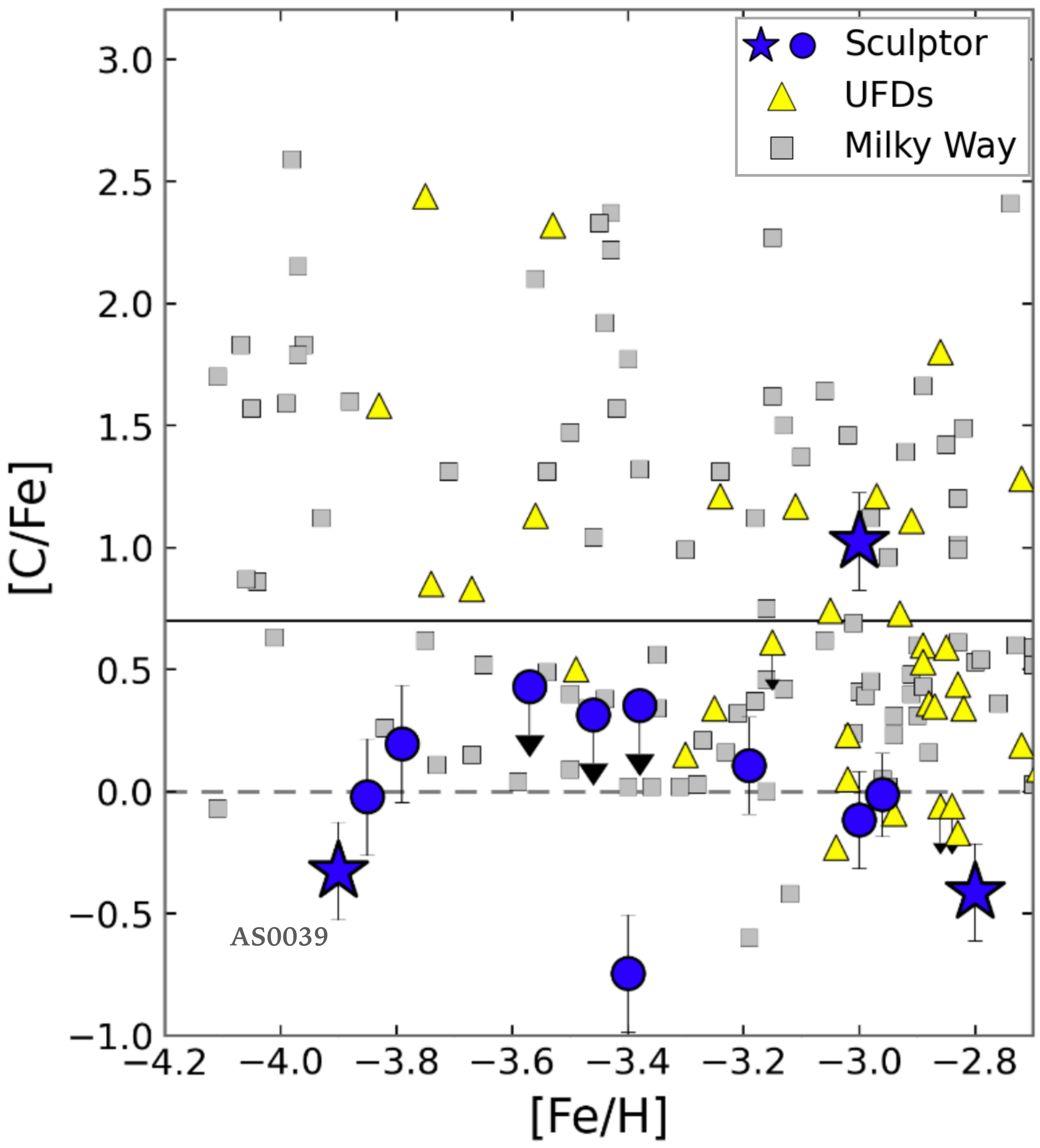
Sculptor CMD



Skúladóttir et al. 2024

CARBON IN SCULPTOR

Skúladóttir et al. 2024a

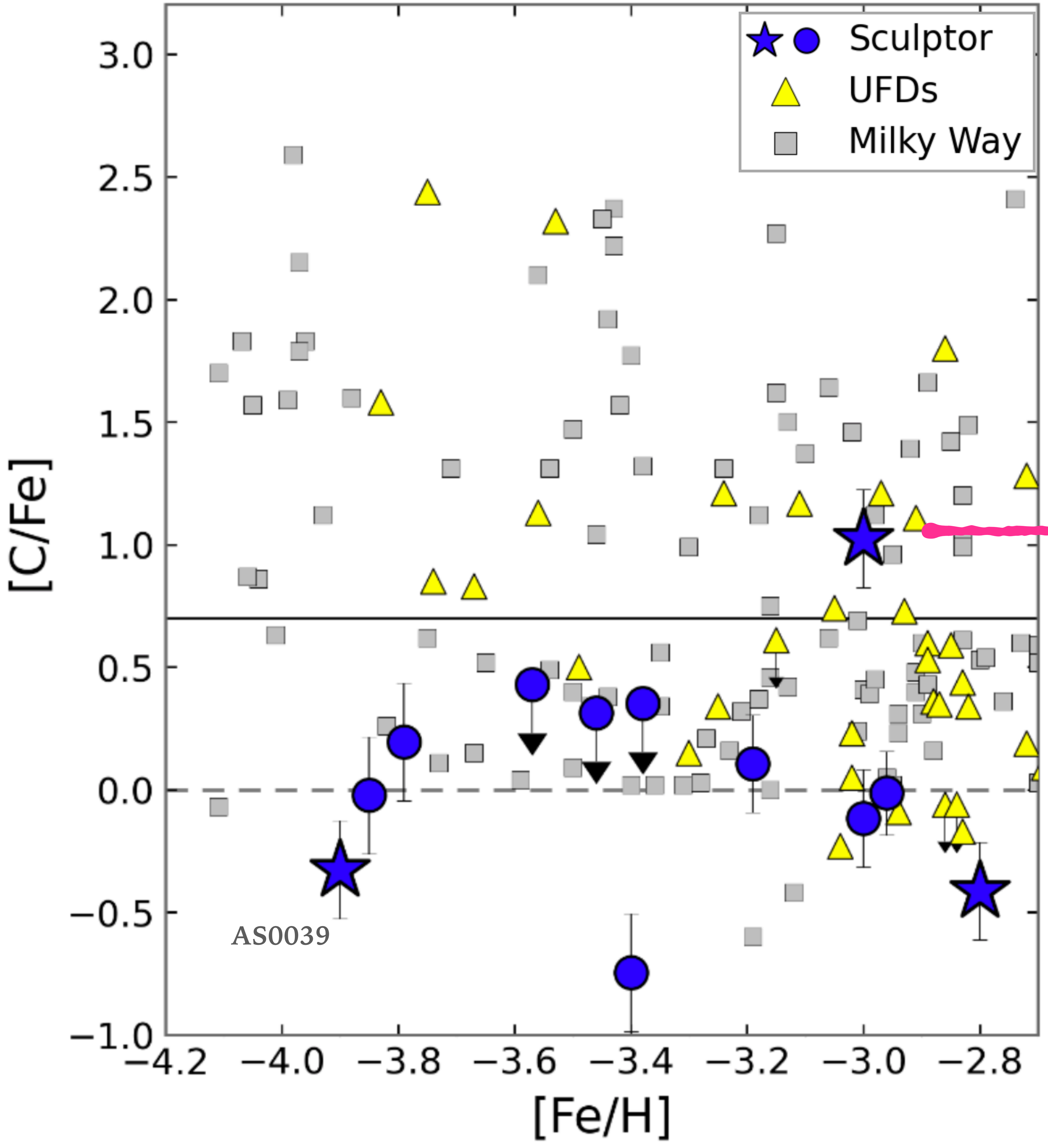


Sculptor: Three new spectra (star symbols) & Reanalysis of literature data (circles)

See also: Tafelmeyer et al. 2010, Frebel et al. 2010, Starkenburg et al. 2013, Simon et al. 2015, Jablonka et al. 2015

CARBON IN SCULPTOR

Skúladóttir et al. 2024a

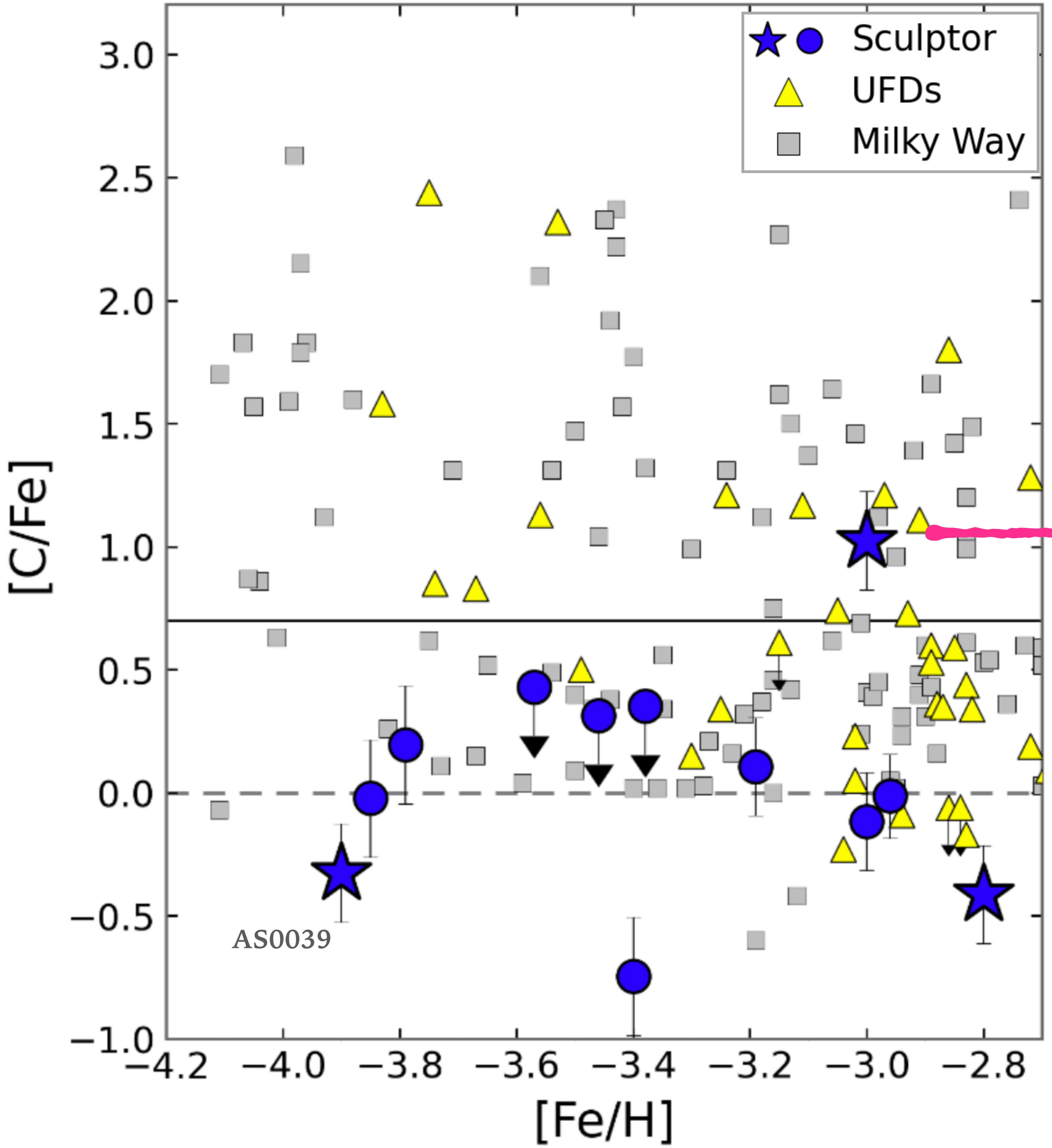


New CEMP-no star

CARBON IN SCULPTOR

Skúladóttir et al. 2024a

Why not more?

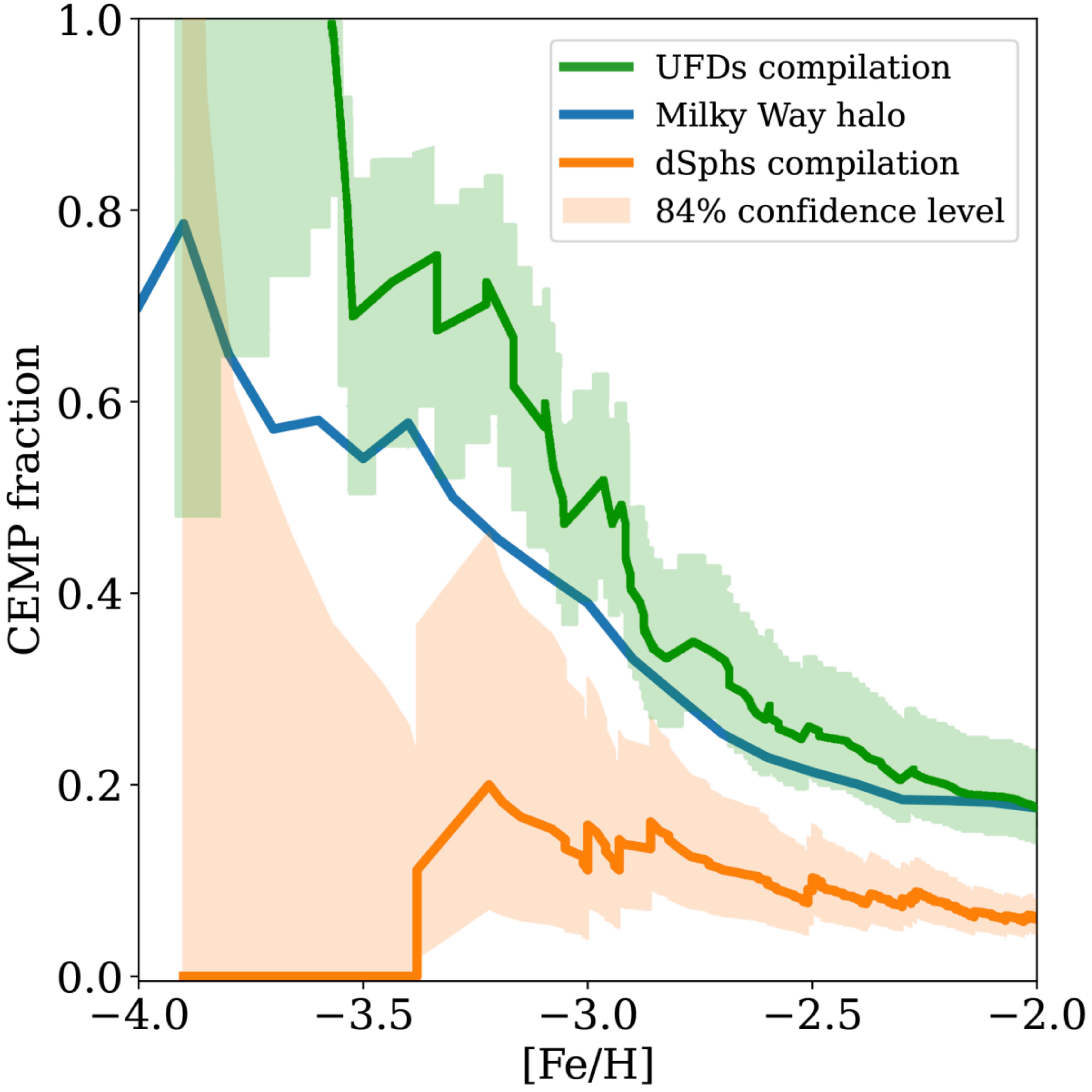


New CEMP-no star

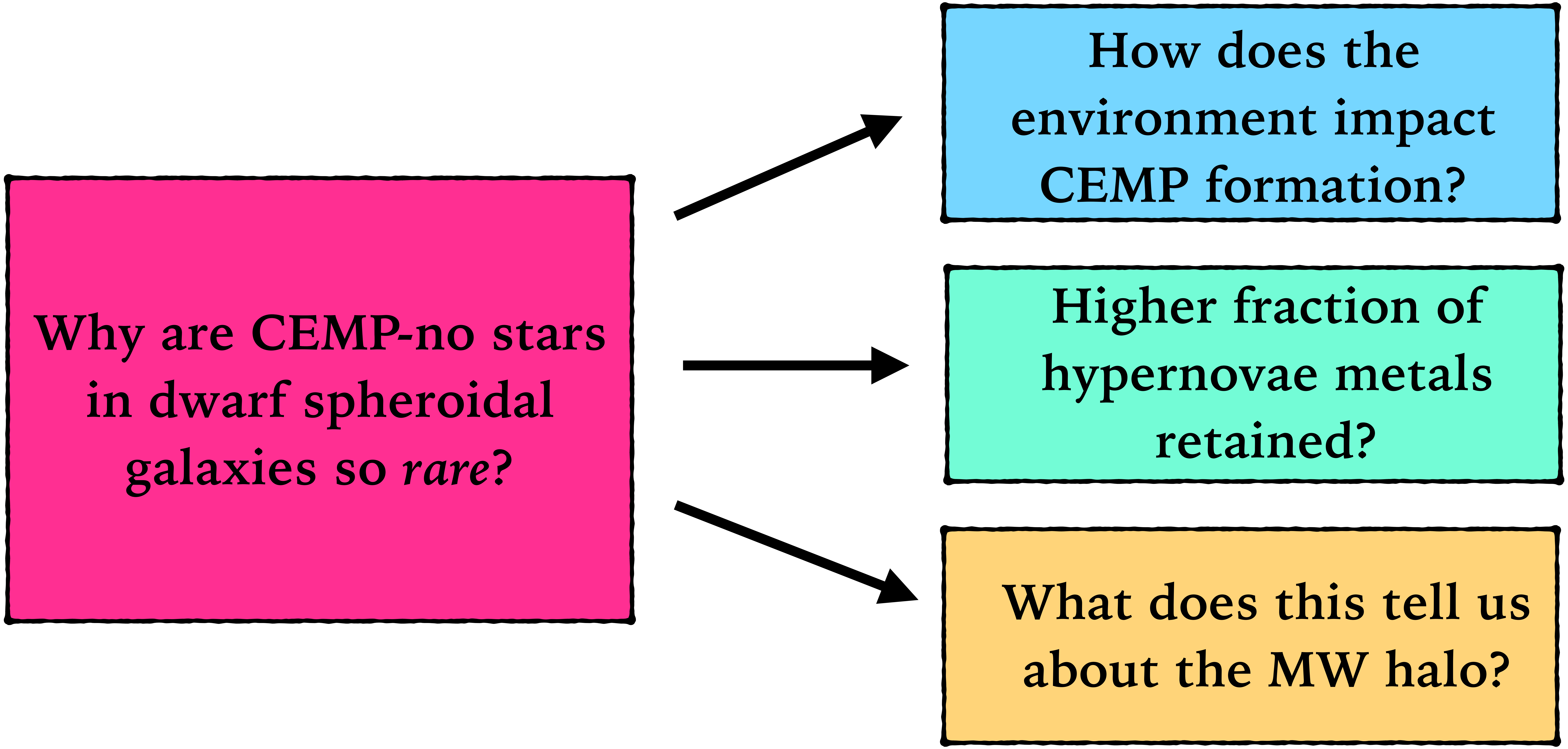
CARBON IN DWARF GALAXIES

- Clear lack of CEMP-no stars in dwarf spheroidal galaxies!
- But… but we expect the dSph to be the building blocks of the Milky Way halo! (e.g. Deason et al. 2016)

Lucchesi et al. 2024

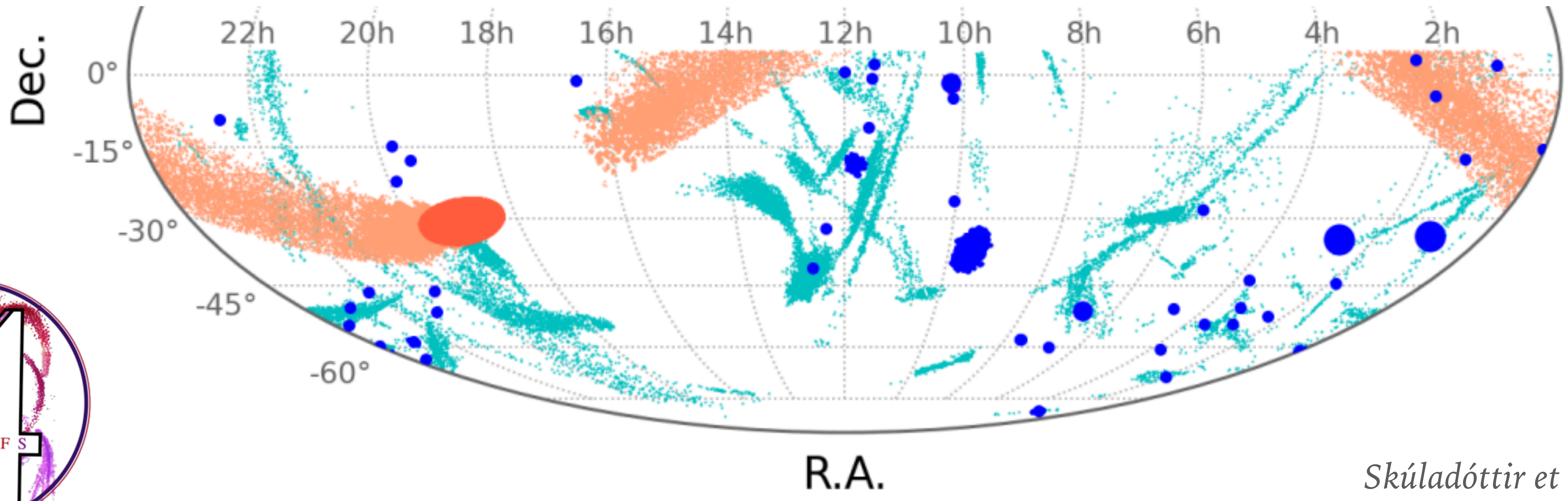


OPEN QUESTIONS



NEW ERA WITH 4DWARFS

- **4DWARFS - Survey of Dwarf Galaxies and their Stellar streams PI: Skúladóttir - 520 000 fibre hours**. Community survey, selected in 2021, after a 2 year competitive process.
- 4DWARFS is a part of the 4MOST **5 year** spectroscopic survey of the Southern sky, with first light in **early 2025**.

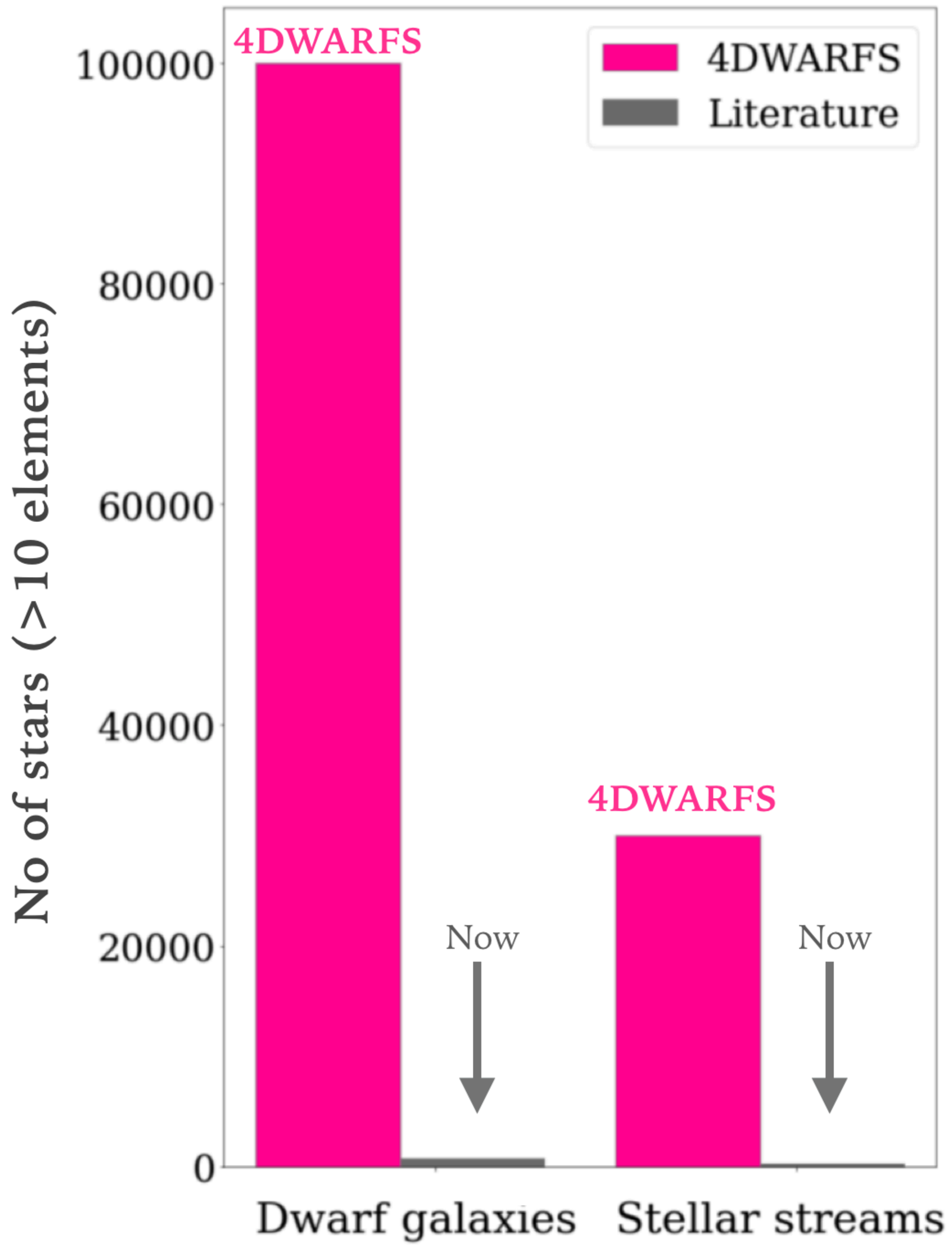


Skúladóttir et al. 2023a (4DWARFS)

NEW ERA WITH 4DWARFS

- High quality **radial velocities**, **chemical abundances** and **stellar ages**.
- Large discovery space of unexpected findings.

Skúladóttir et al. 2023 (4DWARFS)



KEY SCIENTIFIC QUESTIONS

Skúladóttir et al. 2023 (4DWARFS)

What are the properties of the first stars?

How are the chemical elements created and distributed?

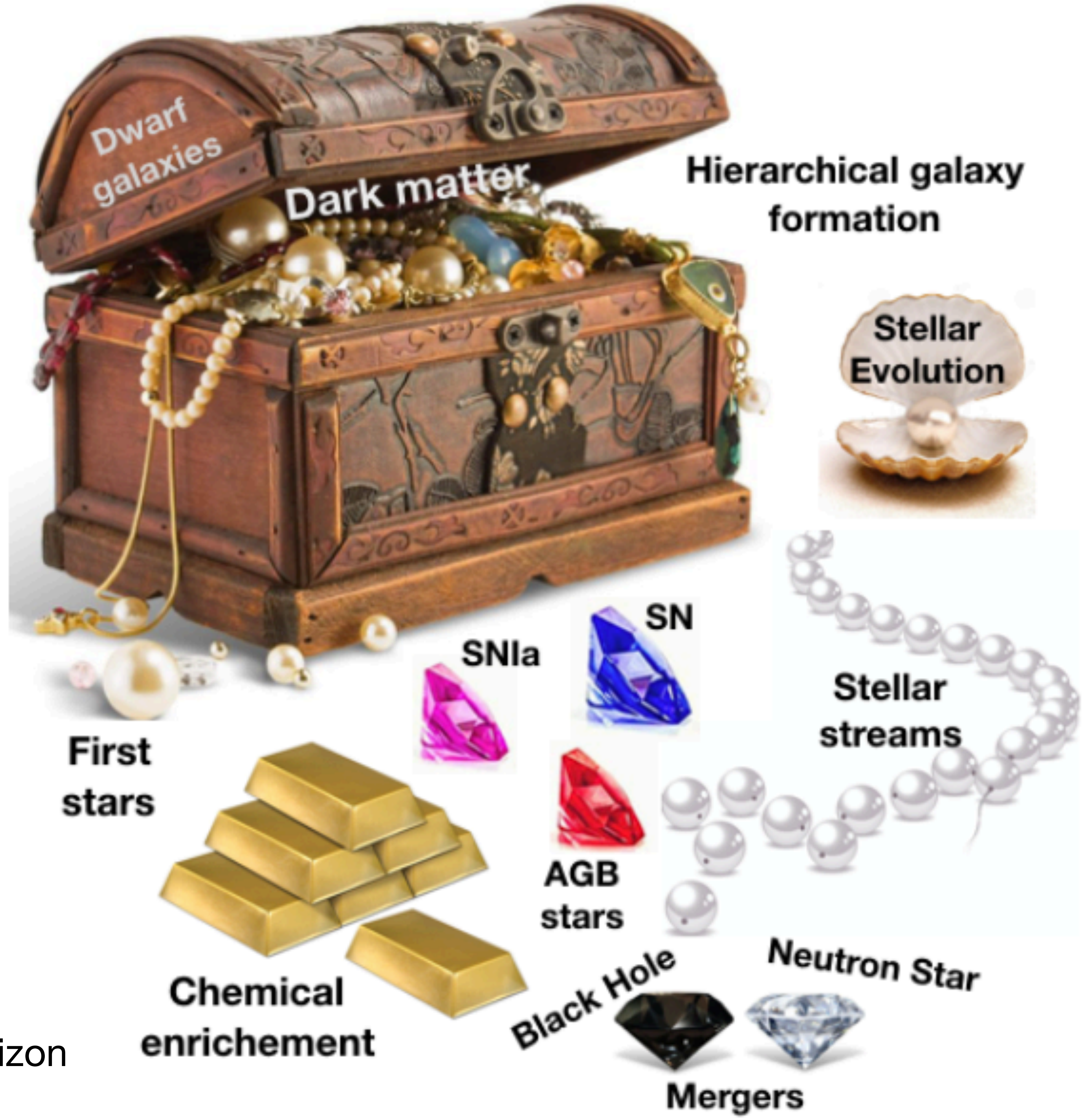
What are the dynamical properties of dwarf galaxies?

What are the small-scale limits of hierarchical galaxy formation?

CONCLUSIONS

- Spectroscopy of individual stars in dwarf galaxies and their stellar streams is challenging, but rewarding.
- Dwarf galaxies are metal-poor and excellent for studying the impact of the first stars in the Universe
  - The first stars were more massive
  - Evidence for zero-metallicity hypernova
- The origin of our Milky Way halo is far from solved.
- Spectra are coming!

Logo by Martina Rossi



This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (TREASURES - grant agreement No. 101117455).