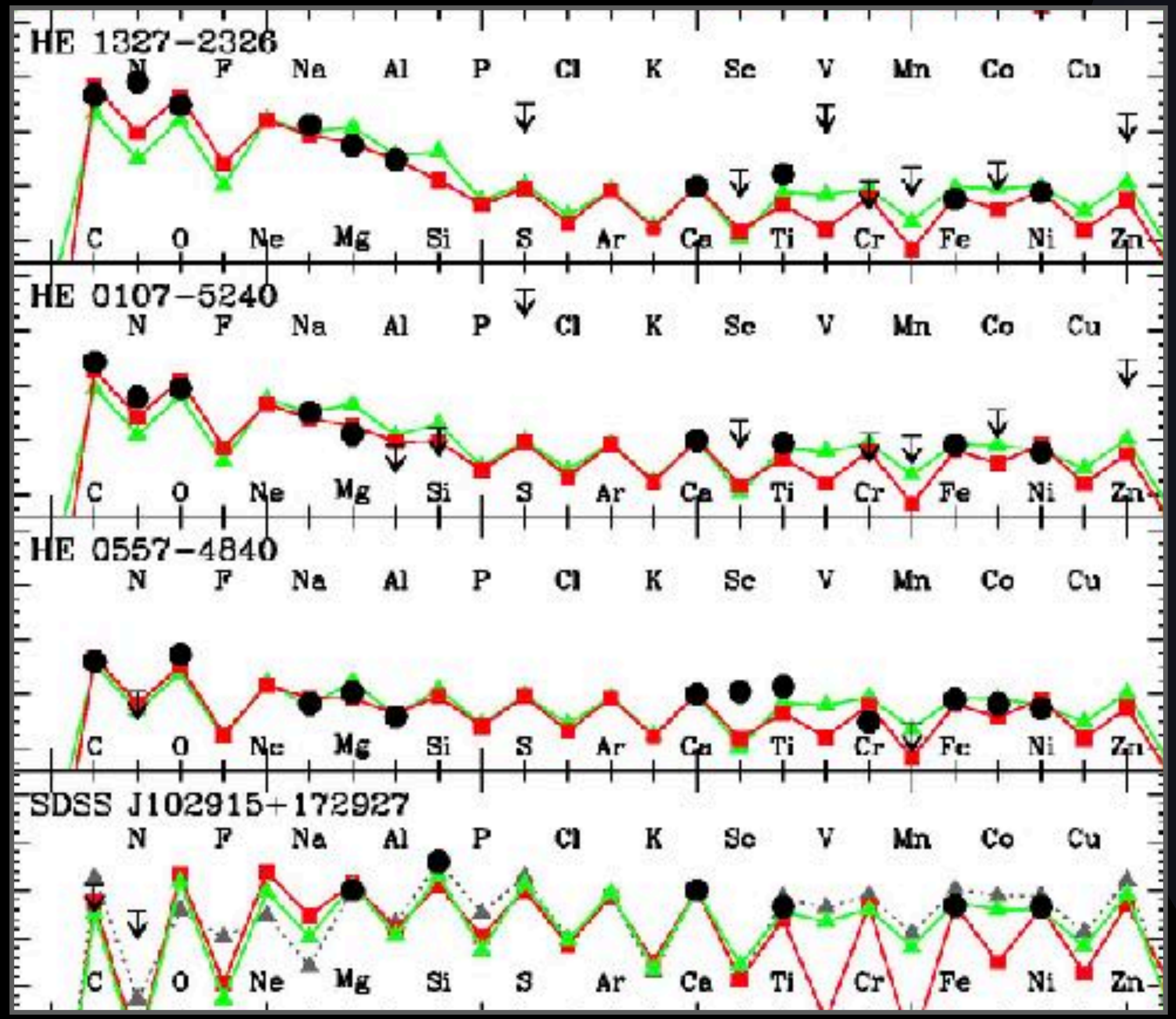
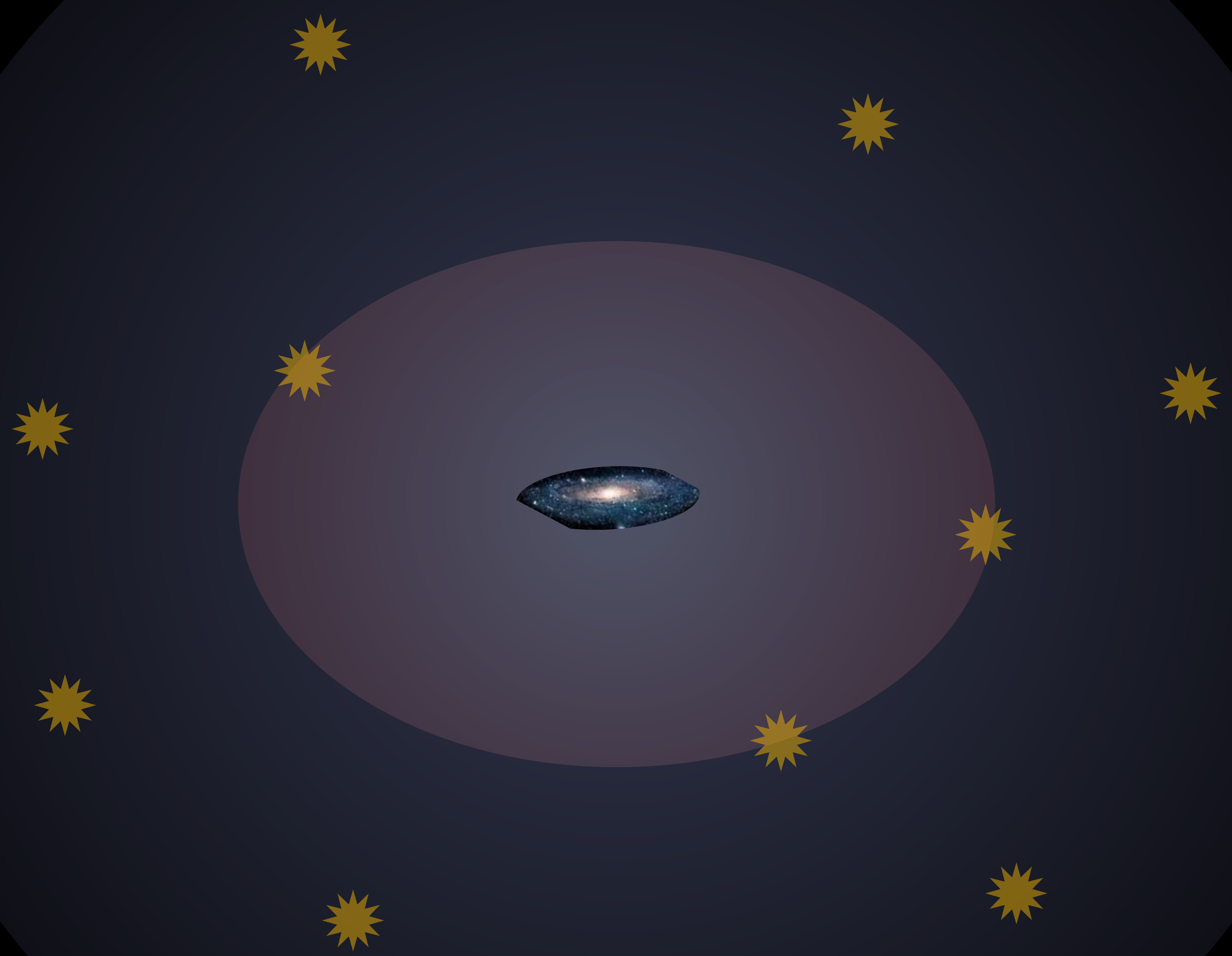
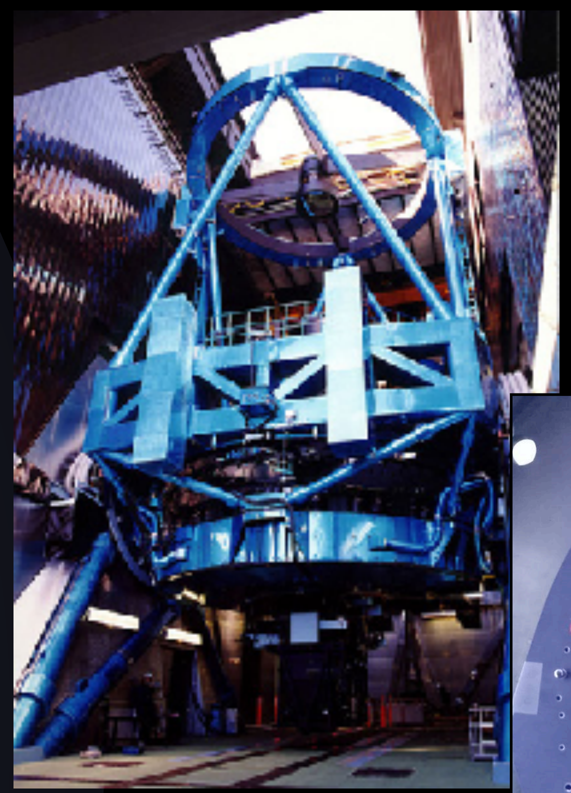
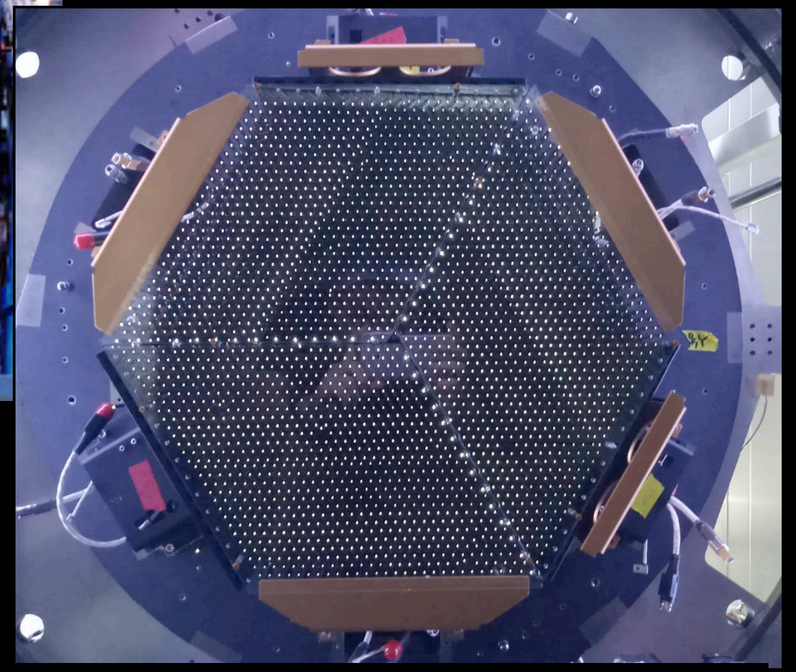
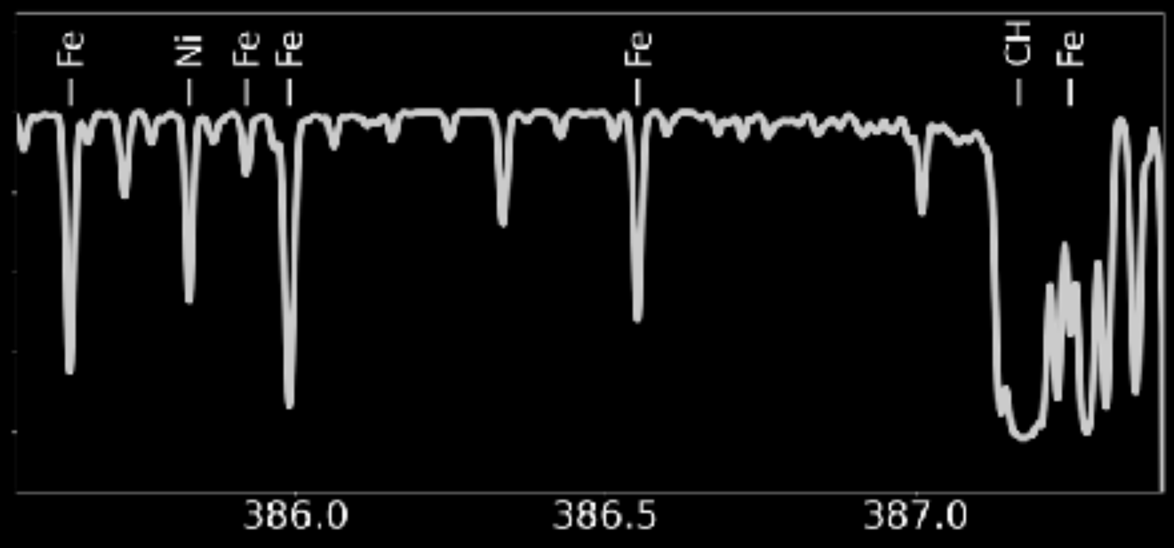
The formation of the Milky Way outer halo with PFS











Miho N. Ishigaki（Subaru Telescope/NAOJ）

FY2023 "What is dark matter? - Comprehensive study of the huge discovery space in dark matter"
March 6-7th, 2024, Yukawa Institute

Collaborators: P. Kuzma, I. Ogami, T. Hartwig, C. Kobayashi, N. Tominaga, K. Nomoto, W. Aoki, M. Chiba, Y. Tarumi, S. Leung, M. Mardini,
PFS Galactic Archaeology science working group, inspiring discussion with many others!

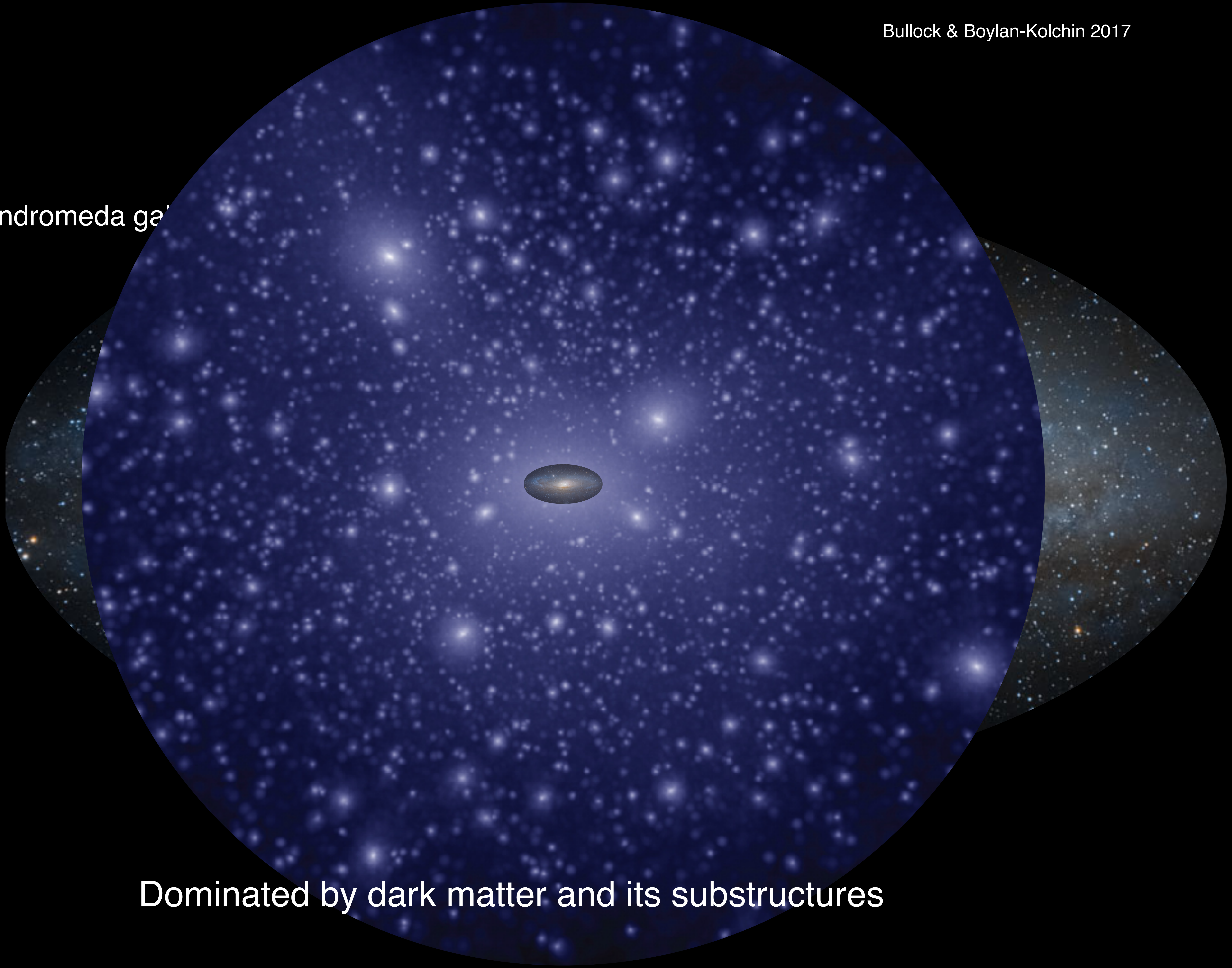
This talk

- The Milky Way's outer halo: a laboratory of dark matter
- The importance of stellar chemical abundance:
    - The timing and characteristics of past merger events
    - Understanding the very first step of the structure formation in the universe

How does the Milky Way Galaxy look like?

Bullock & Boylan-Kolchin 2017

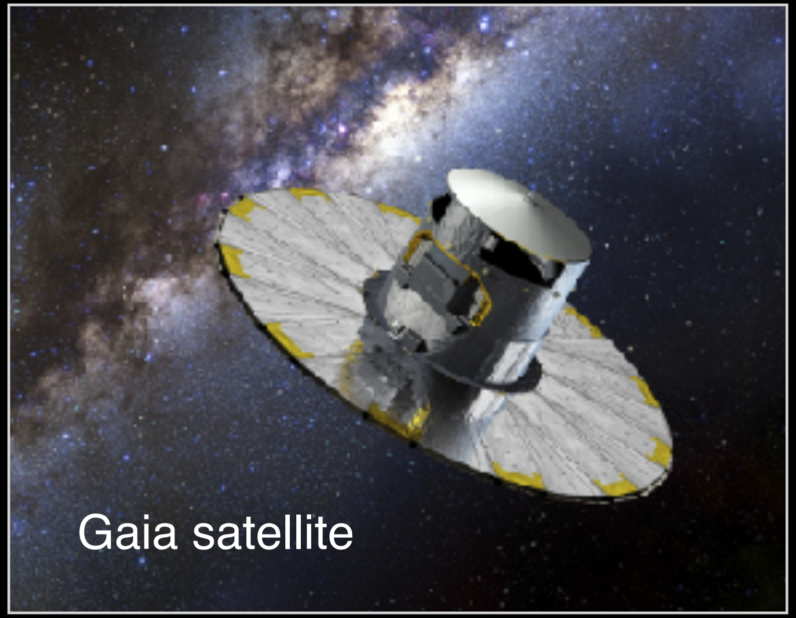
M31(Andromeda ga



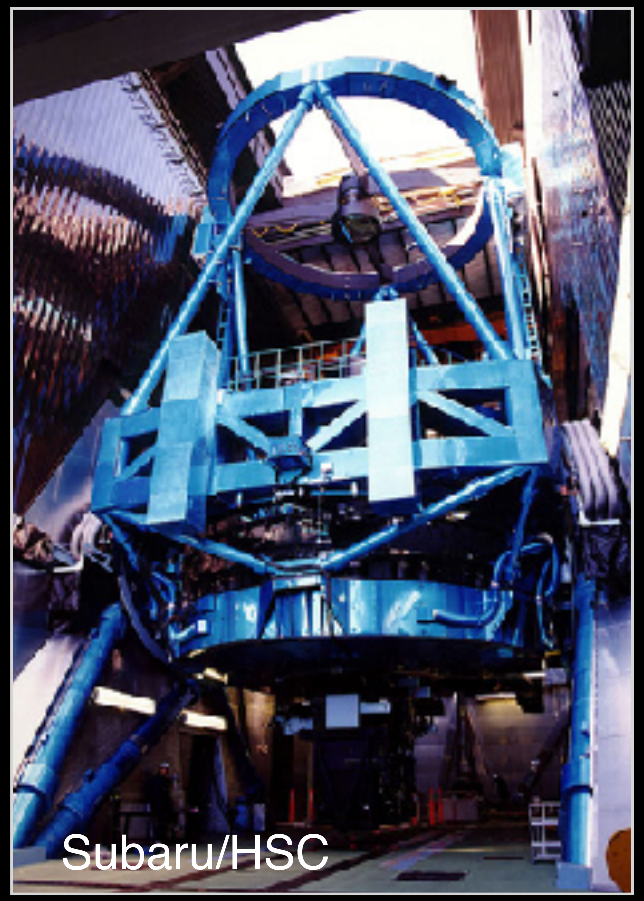
Dominated by dark matter and its substructures

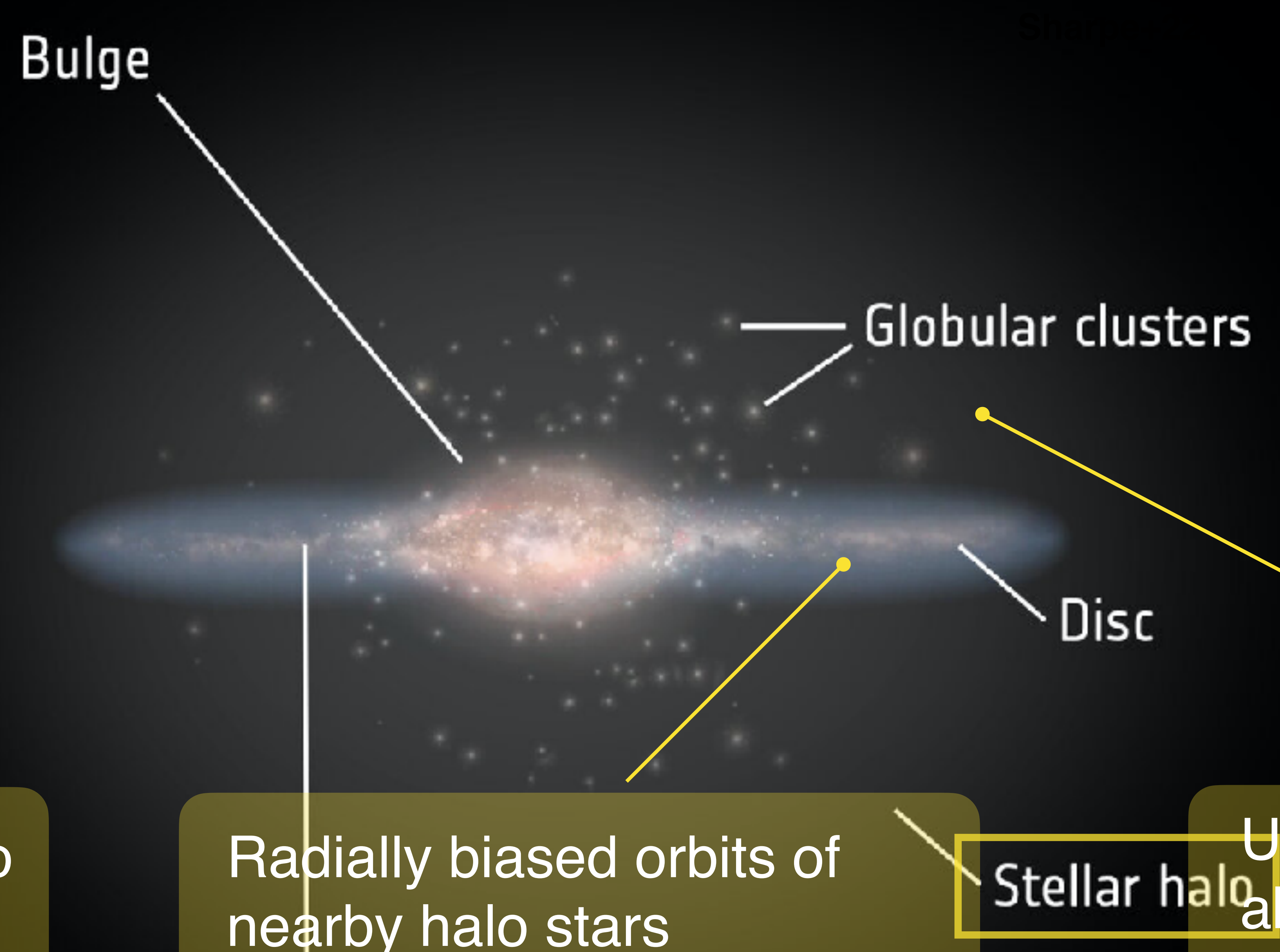
M31: Image Credit & Copyright: Jacob Bers (https://apod.nasa.gov/apod/ap140730.html)

The new view of the Galaxy's stellar halo

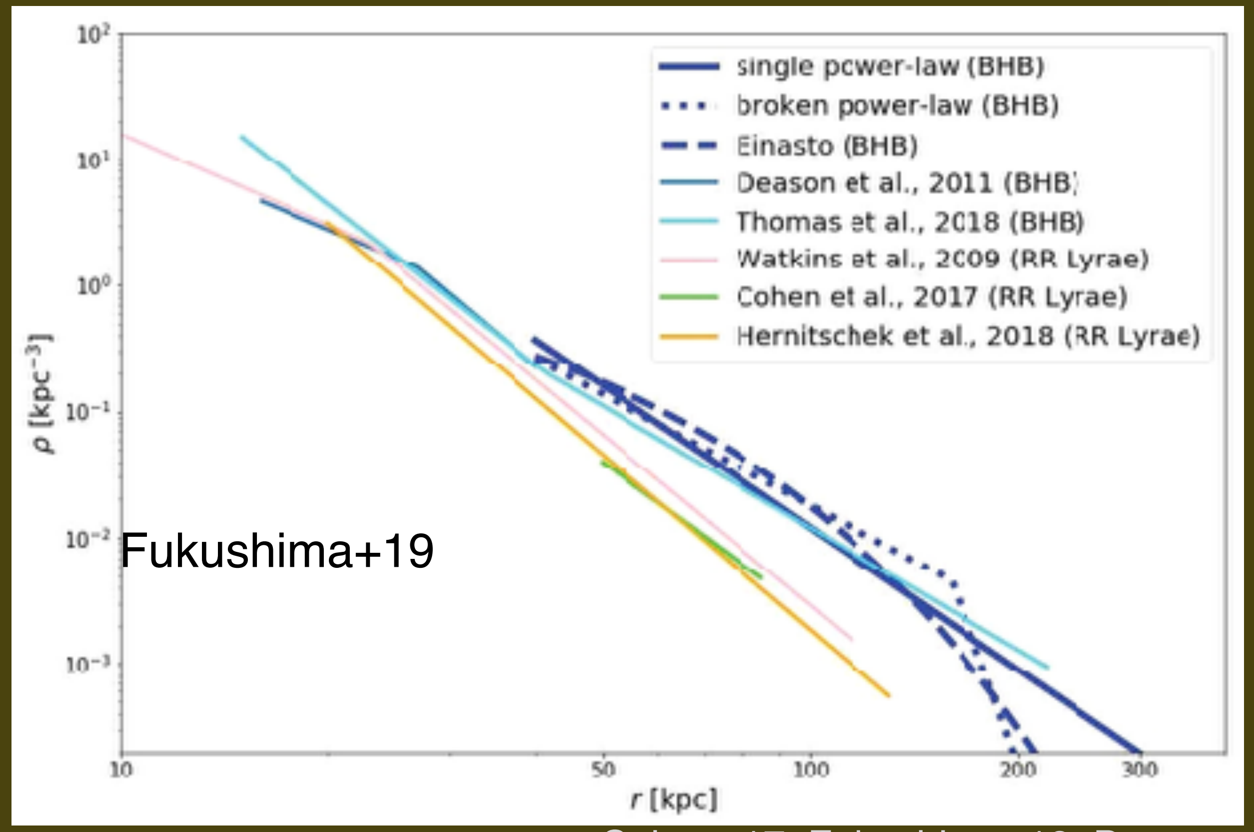


Gaia + Wide-field imaging surveys



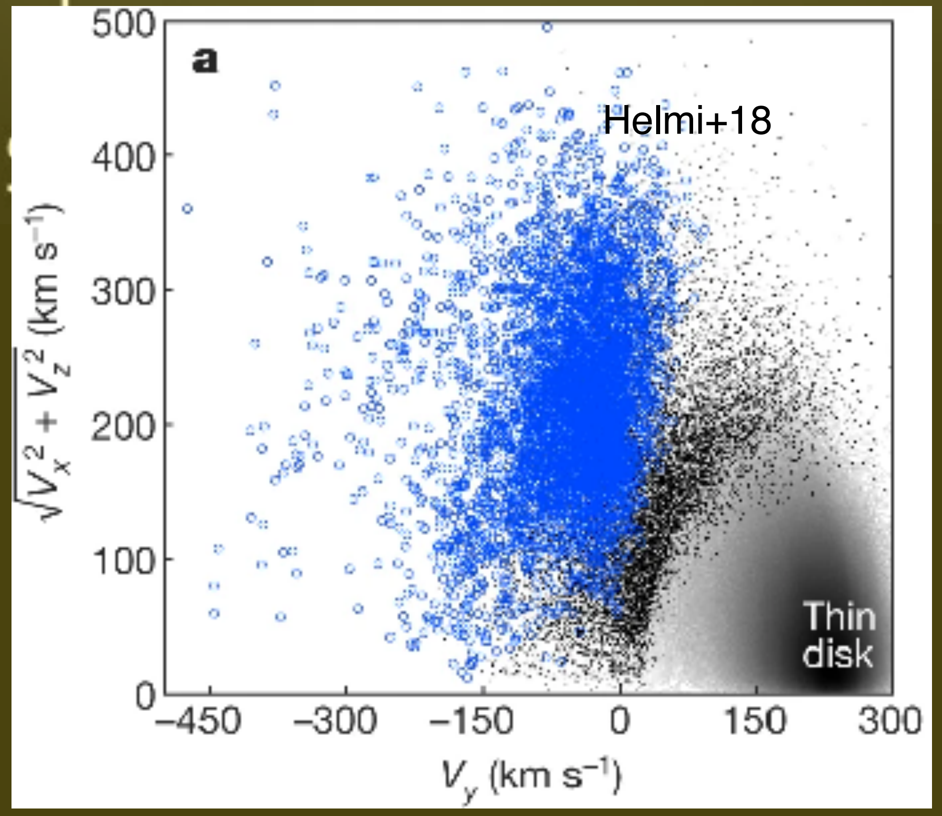


The density profile of stellar halo out to ~ 300 kpc



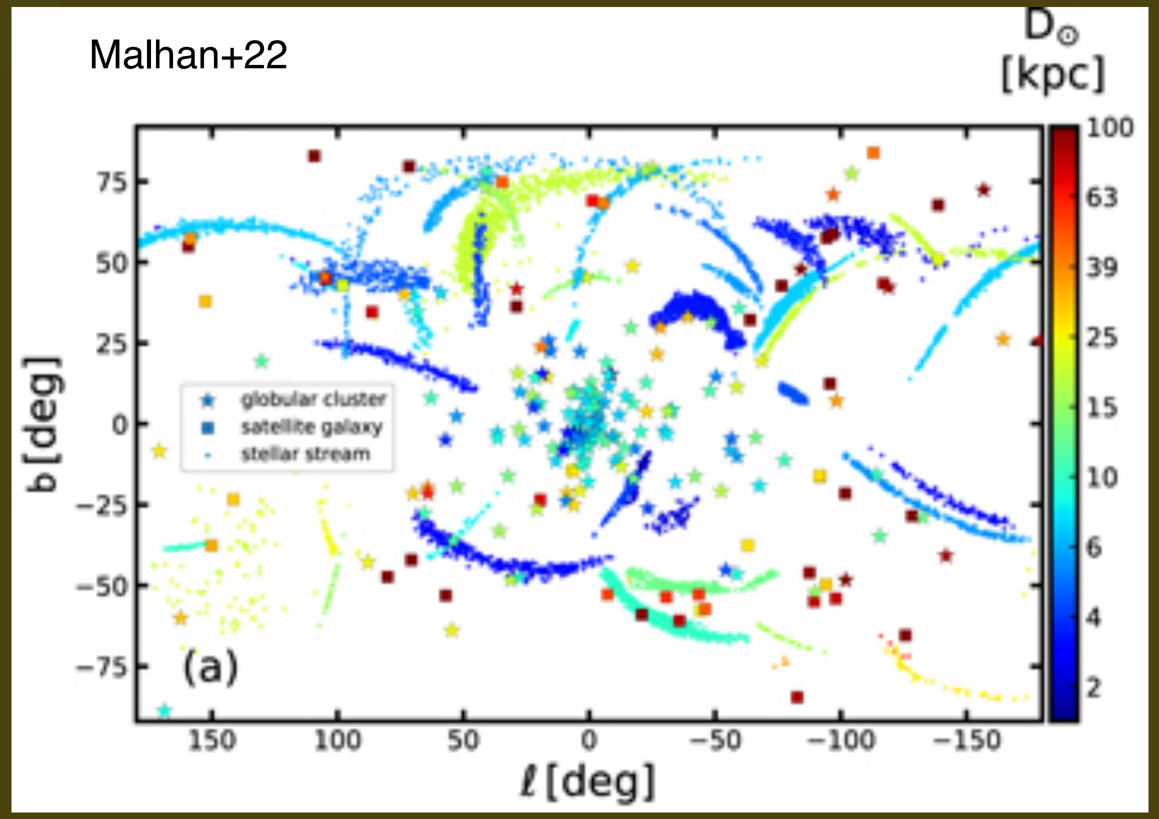
Cohen+17, Fukushima+18, Deason+19

Radially biased orbits of nearby halo stars



Helmi+18, Belokurov+18

Ultra-faint dwarf satellites and abundant stellar streams



Ibata+20, Naidu+20, Malhan+22

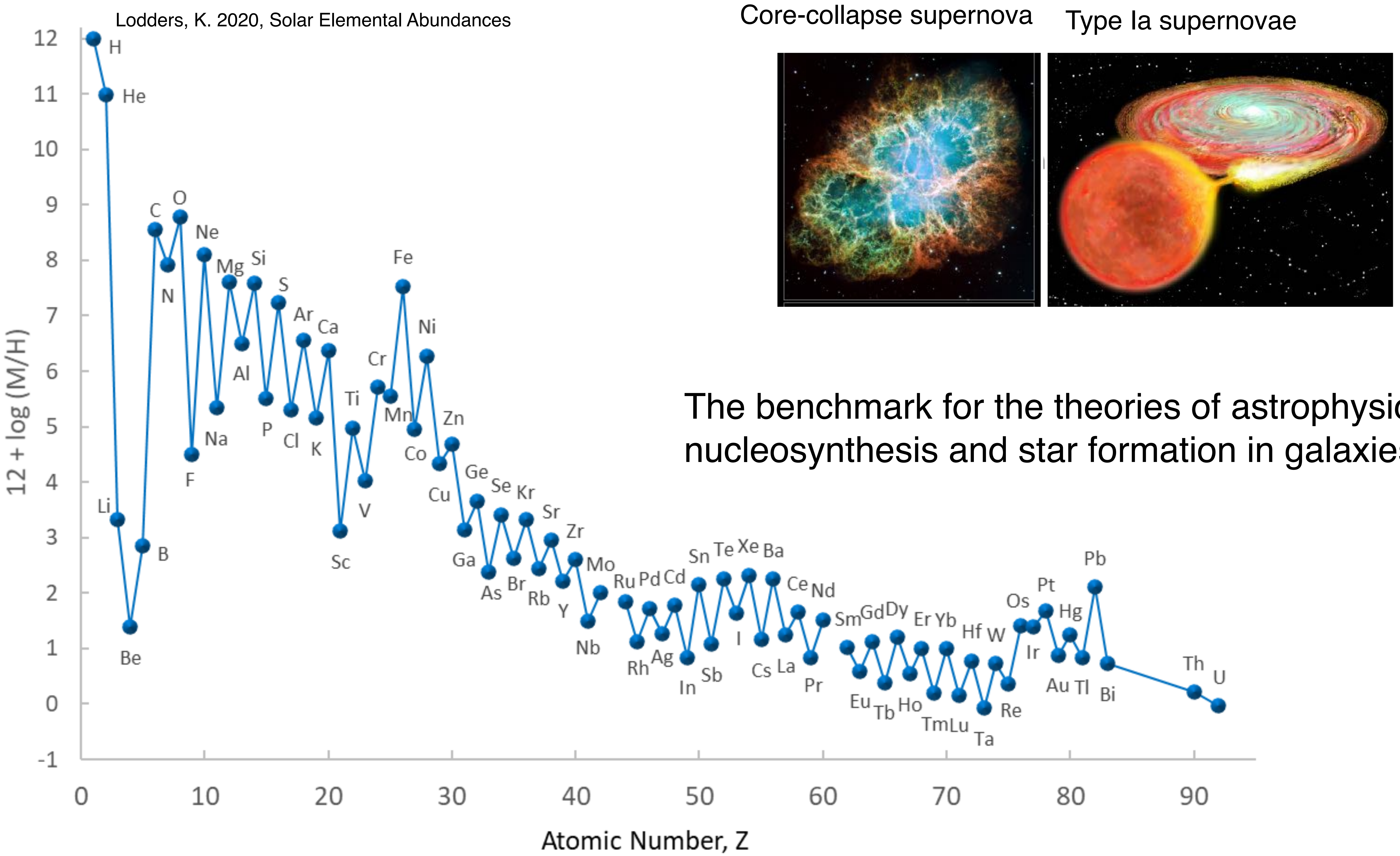
Next steps?

Quantitative comparisons between observations vs cosmological simulations at different phases of Galaxy formation

- ✦ The non-spherical shape, e.g., triaxial, or a more complicated structure for the dark matter halo (e.g., the interaction with the Large Magellanic Cloud)
- ✦ The timing and the mass distribution of dwarf galaxy mergers in the past
- ✦ The very first stage of the structure formation, the nature of the first stars (Population III/Pop III stars)

Stellar chemical abundances provide crucial information

Stellar chemical abundances as a probe of the Milky Way formation



The benchmark for the theories of astrophysical nucleosynthesis and star formation in galaxies

Next steps?

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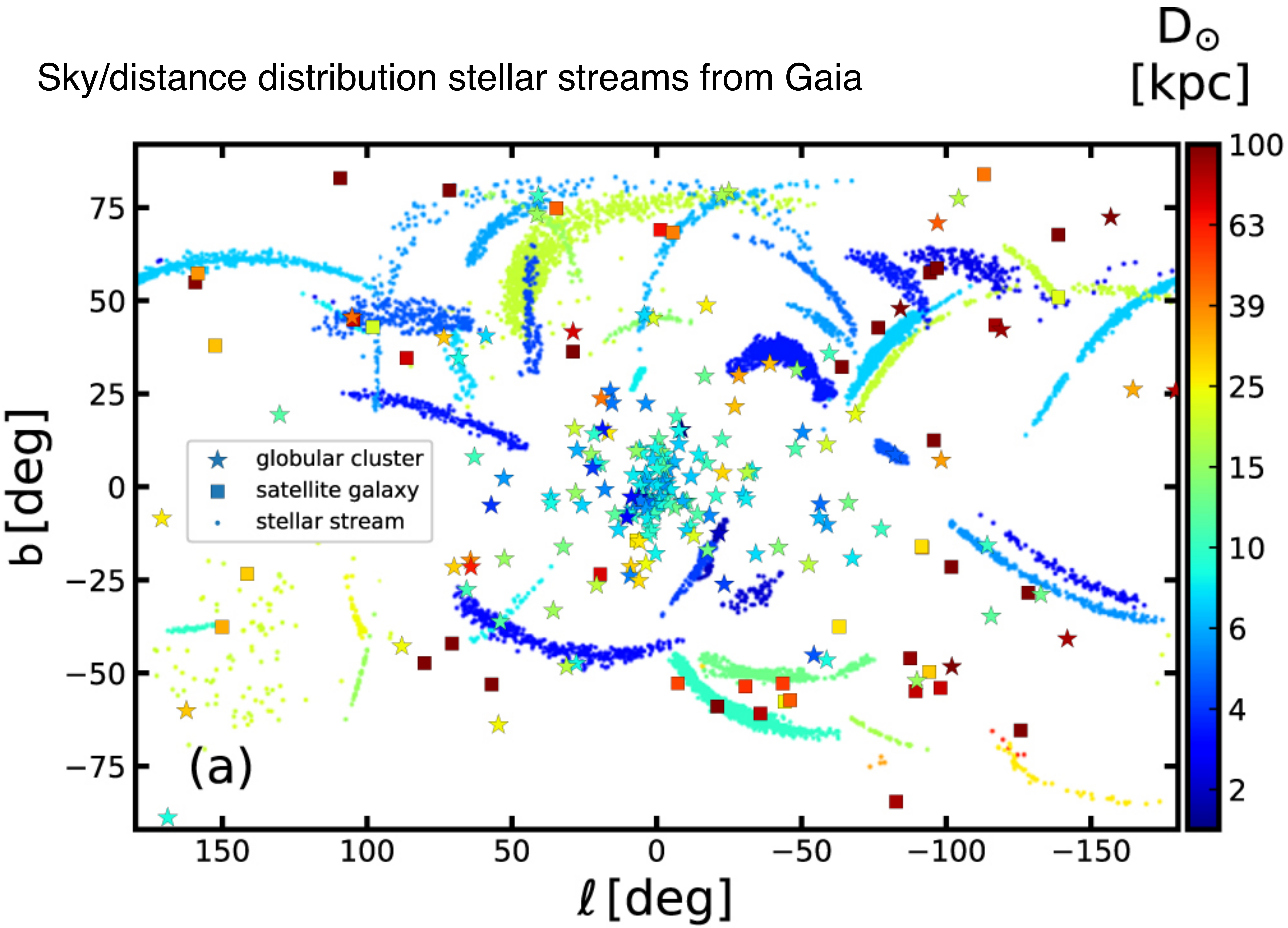
Stellar chemical abundances provide crucial information

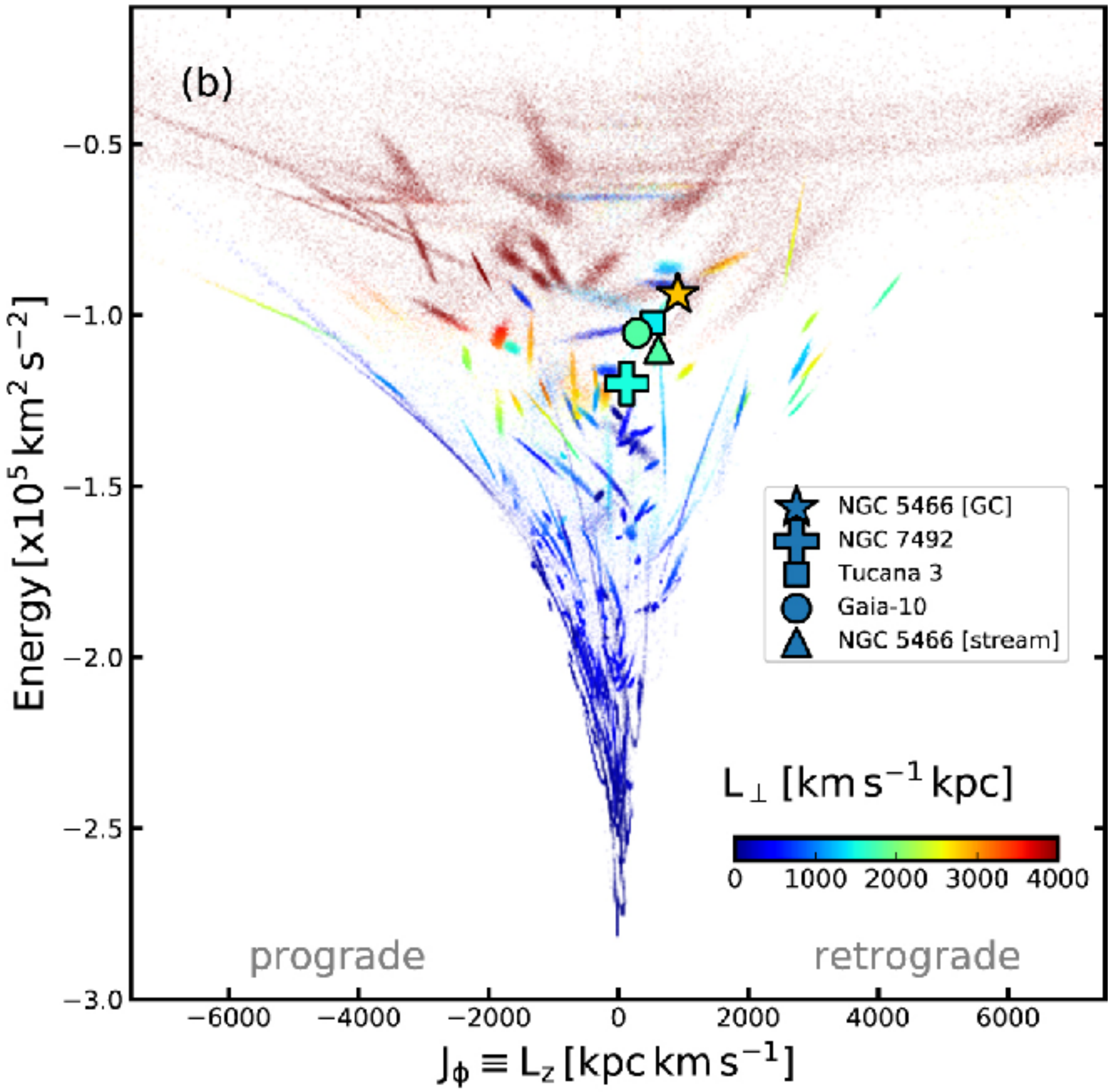
“Chemical tagging” helps to associate globular clusters with past accretion events

Malhan+22

Sky/distance distribution stellar streams from Gaia

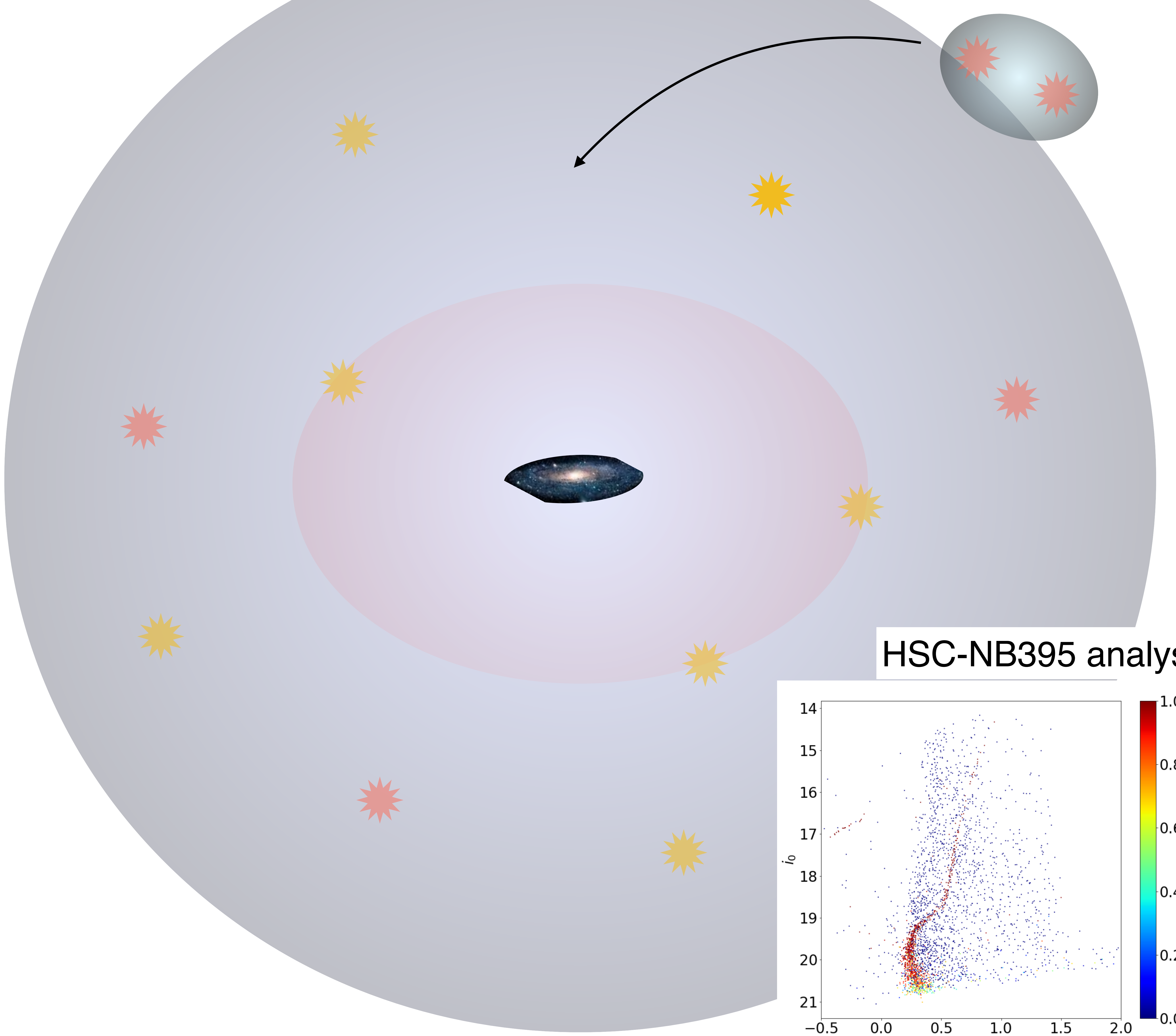


Energy vs angular momentum

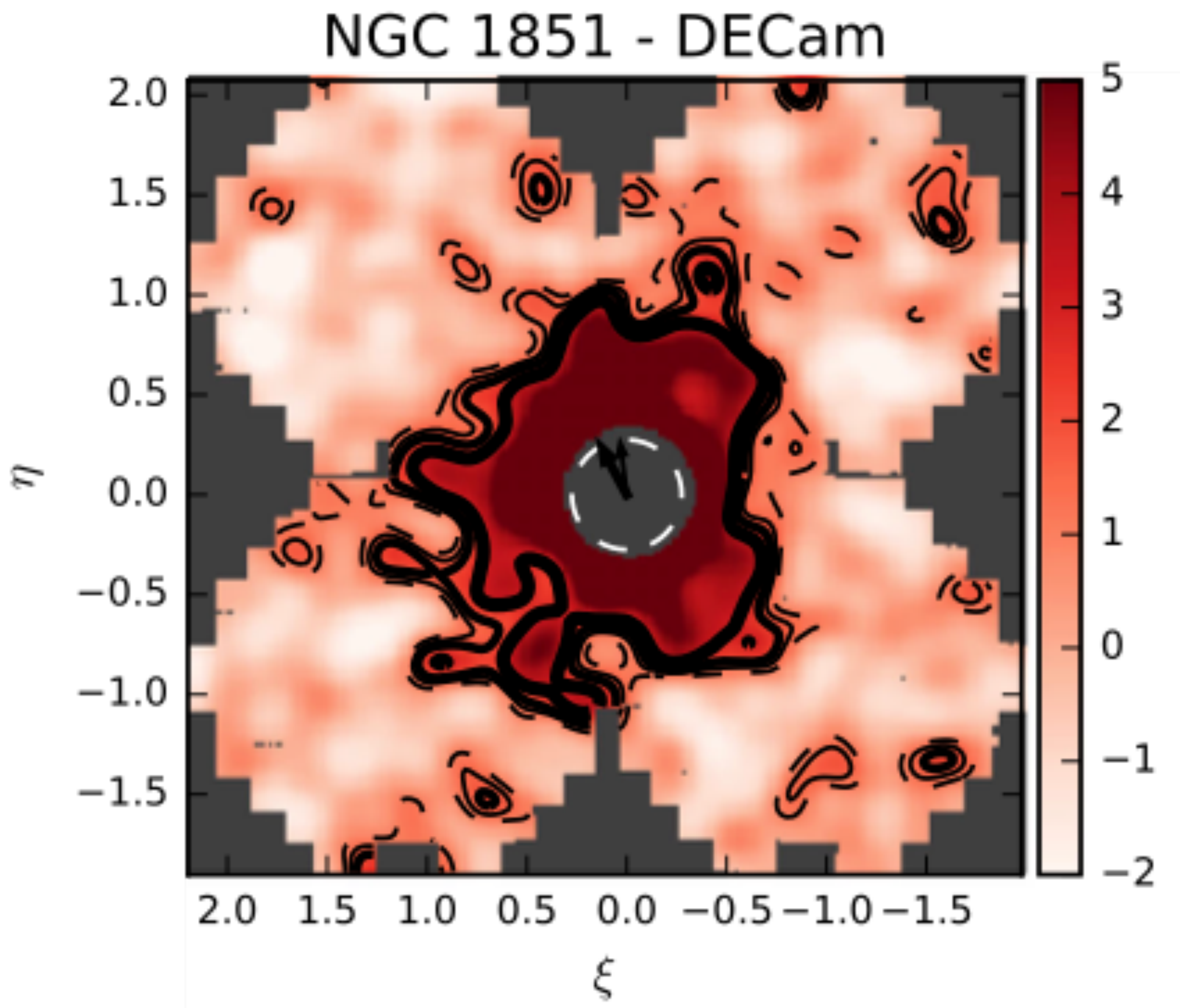


Extra-tidal structures in globular clusters using the metallicity-sensitive narrow-band filter

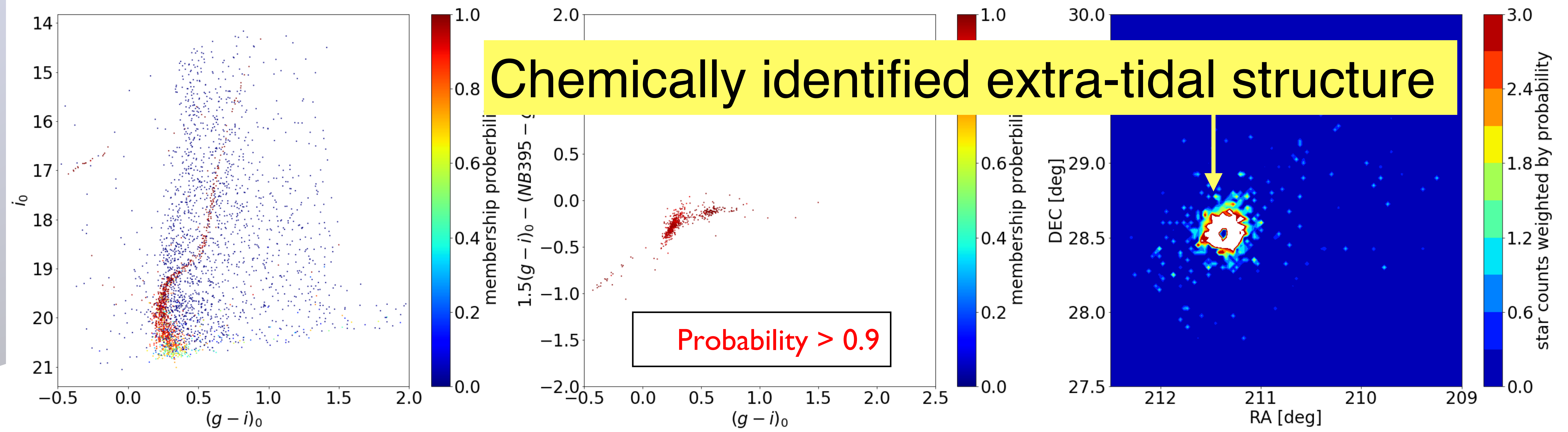
Globular clusters in the Milky Way halo



by P. Kuzma (NAOJ/JSPS fellow),
2018, MNRAS, 473, 2881



HSC-NB395 analysis of a globular cluster NGC 5466 by I. Ogami (Sokendai)



Next steps?

Quantitative comparison between observations vs cosmological simulations at different phases of Galaxy formation

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- ✦ The timing and the mass distribution of dwarf galaxy mergers in the past
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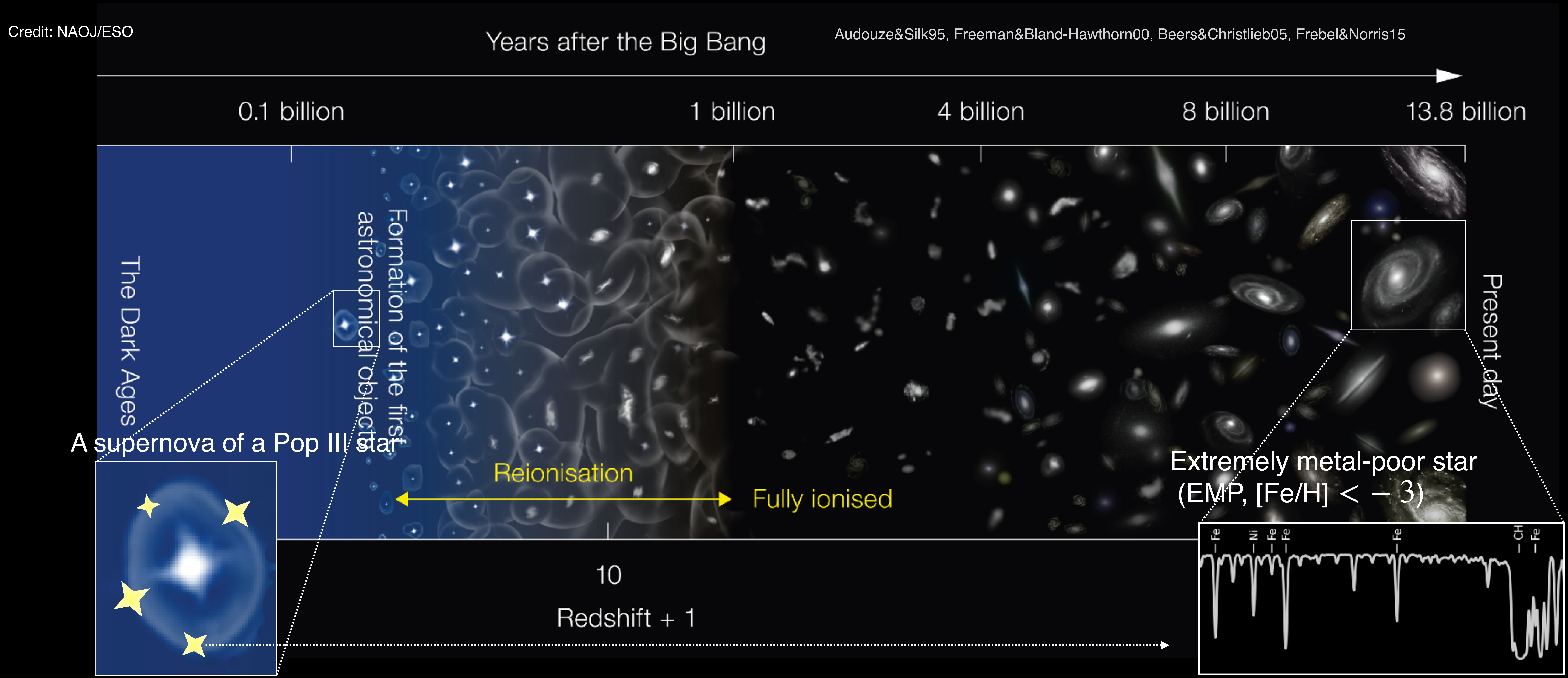
Stellar chemical abundances provide crucial information

How can we study the first stage of the cosmic structure formation?

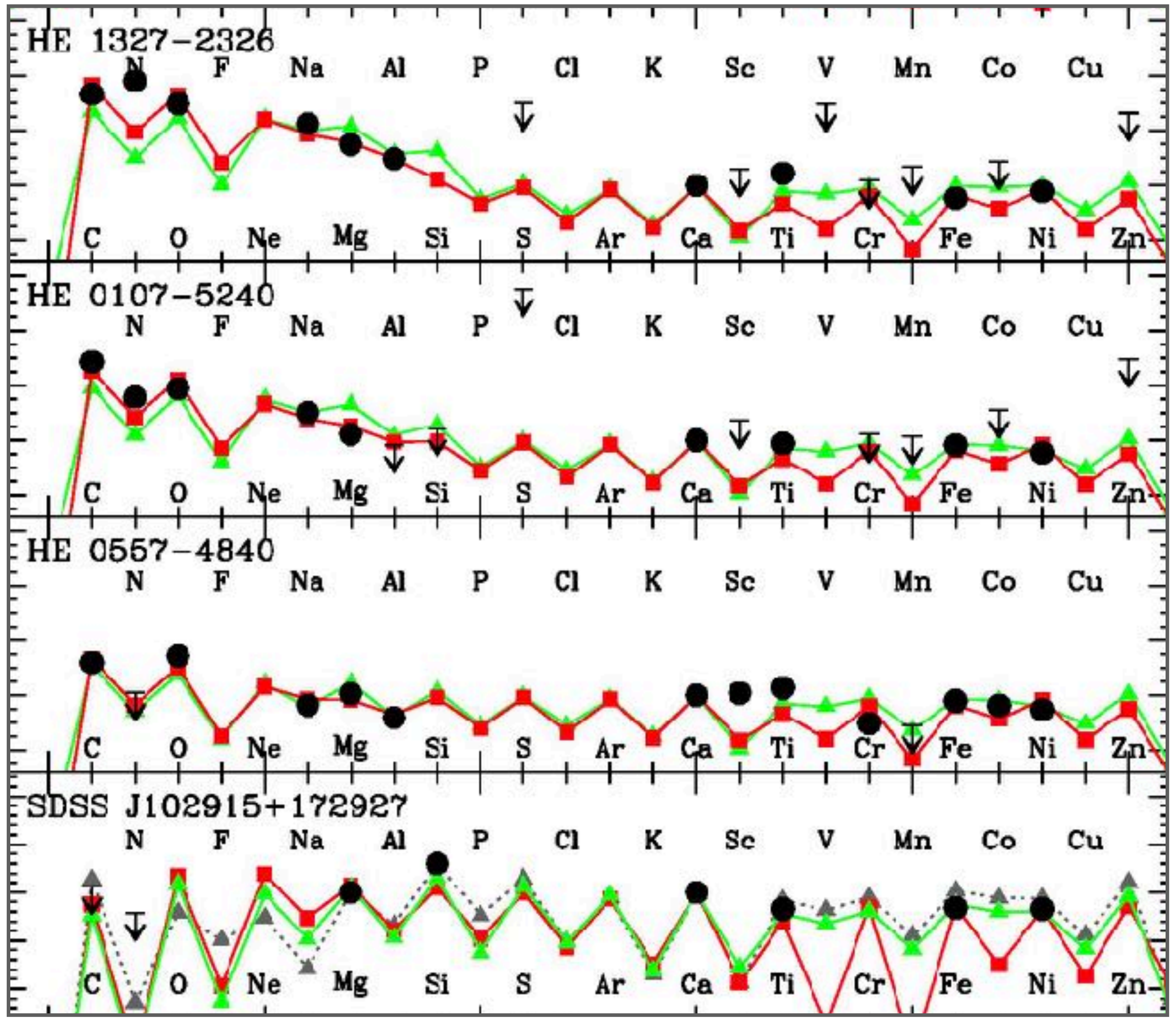


Chemical enrichment by multiple first star's supernovae

The limitation in traditional approach

- The assumption that a single Pop III star's supernova enriches the subsequent generation of stars
- Free parameters in the models (mass, explosion energy, geometry, fallback, mixing)

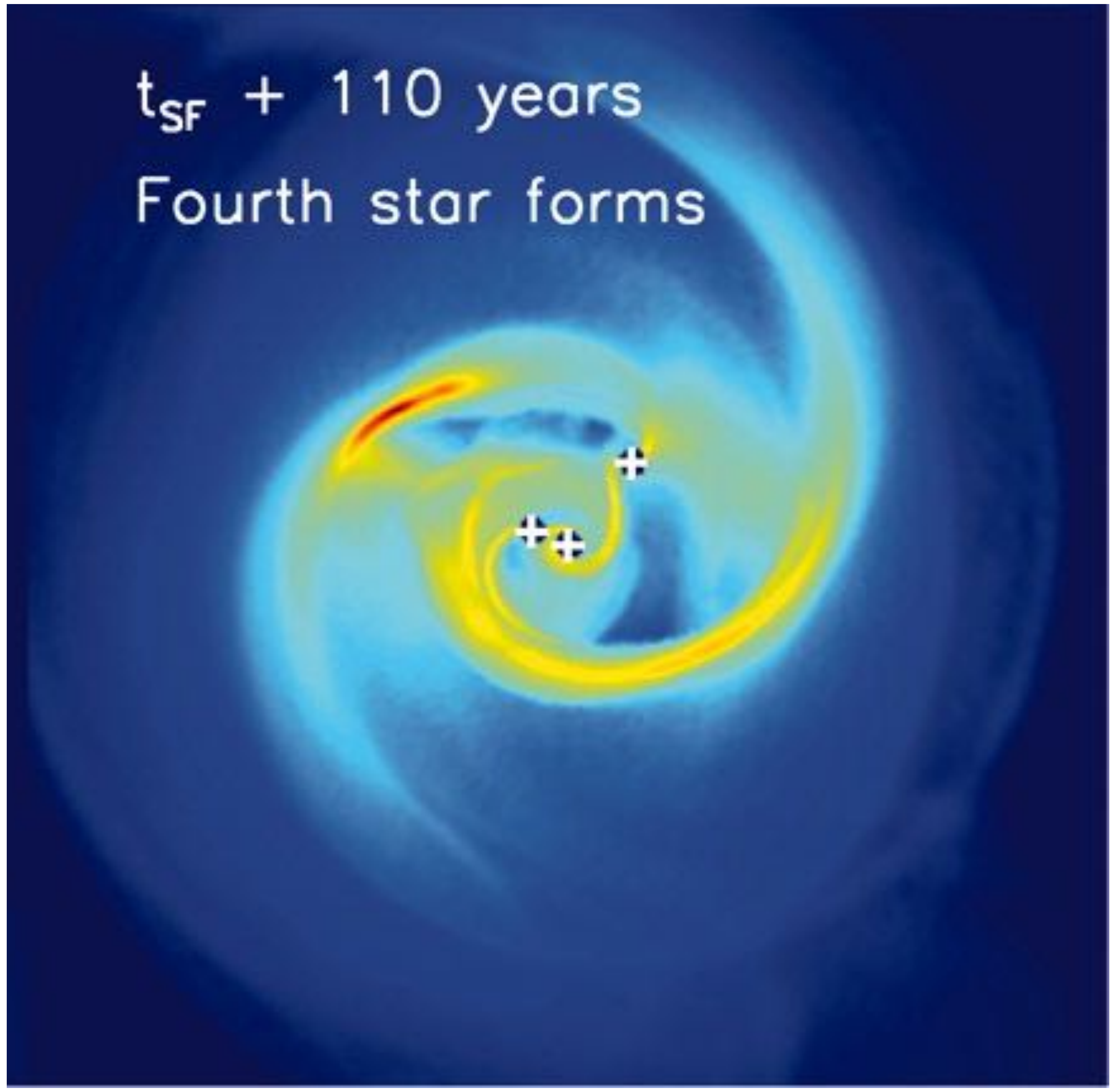
MI, Tominaga, Kobayashi, & Nomoto 2014



Cosmological simulations predicts…

The first stars form in binaries/clusters

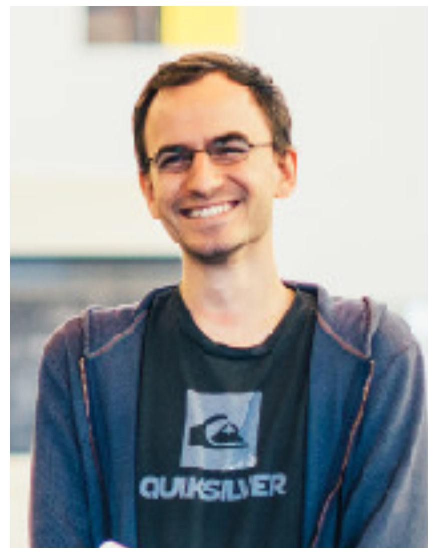
Clark+11, Greif+15, Hirano & Bromm+17, Susa+19, Sharda+20, Sugimura+20



The assumption about the mono-enrichment may bias the inference on the nature of the Pop III stars

Discriminating mono- vs multi-enriched metal-poor stars with machine learning

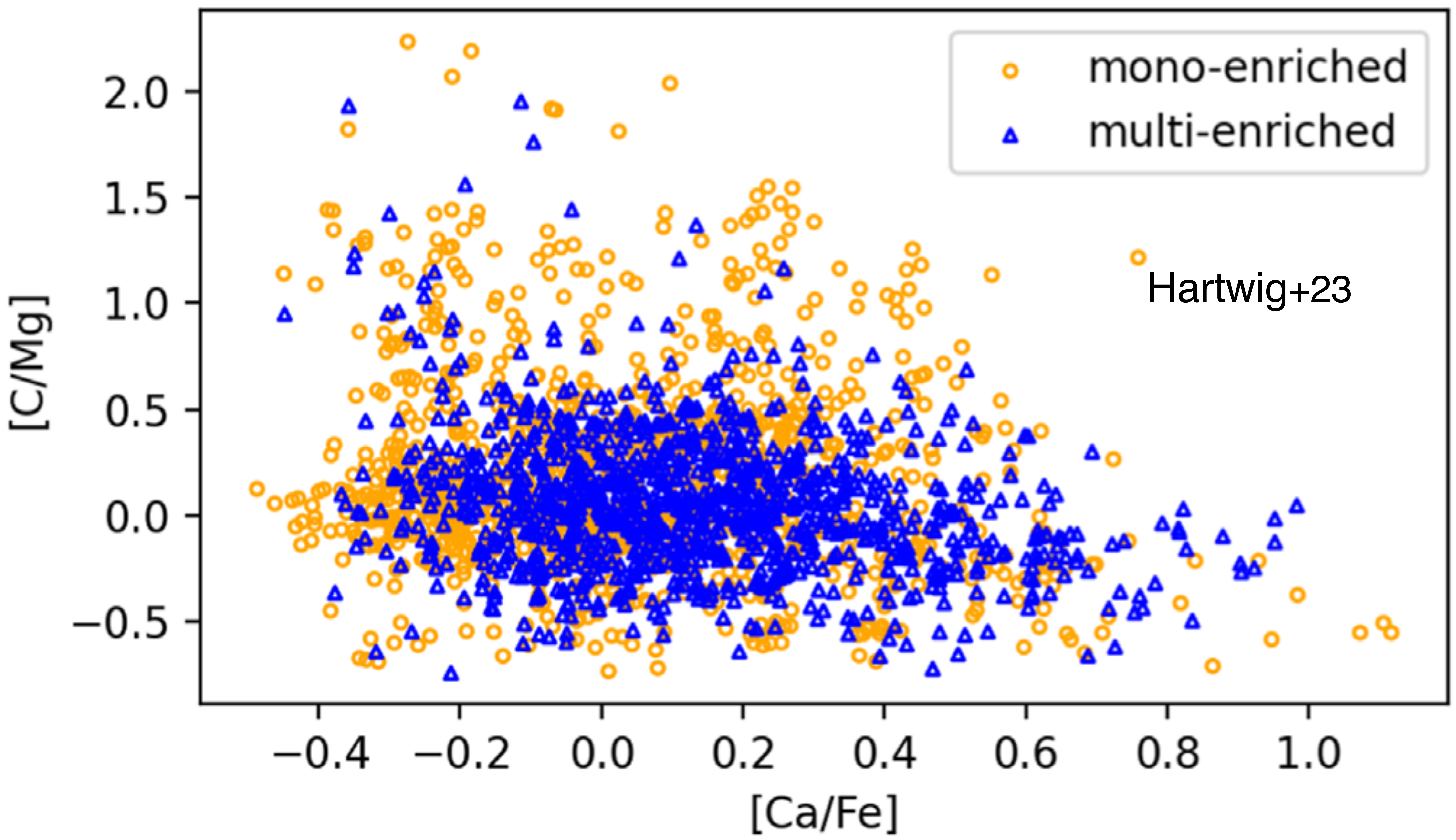
Tilman Hartwig (U. Tokyo - 2023)



- The use of multiple abundance ratios
- Training the model with theoretical supernova yields

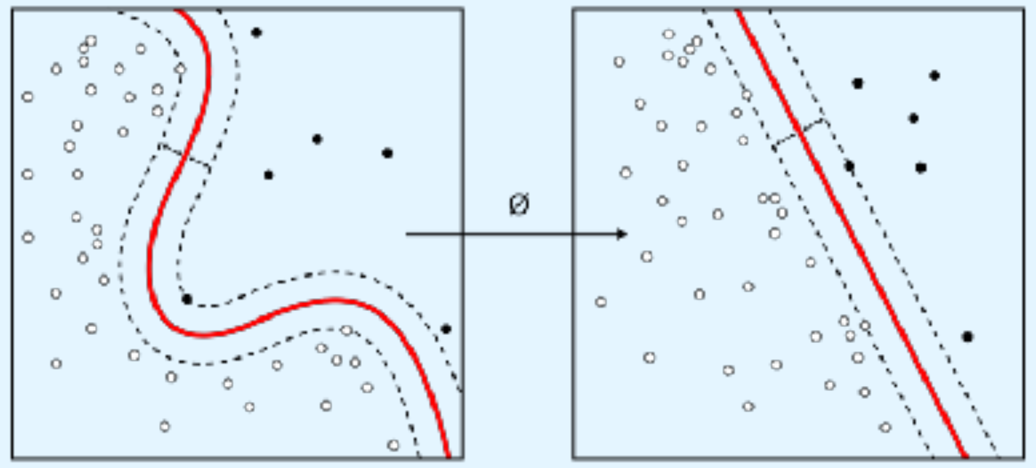
Hartwig, MI, Kobayashi, Tominaga, & Nomoto, 2023, ApJ, 946, 20

The first star's yield models of "mono-enriched" and "multi-enriched" scenarios



- Non-linear boundary
- Overlap of two classes

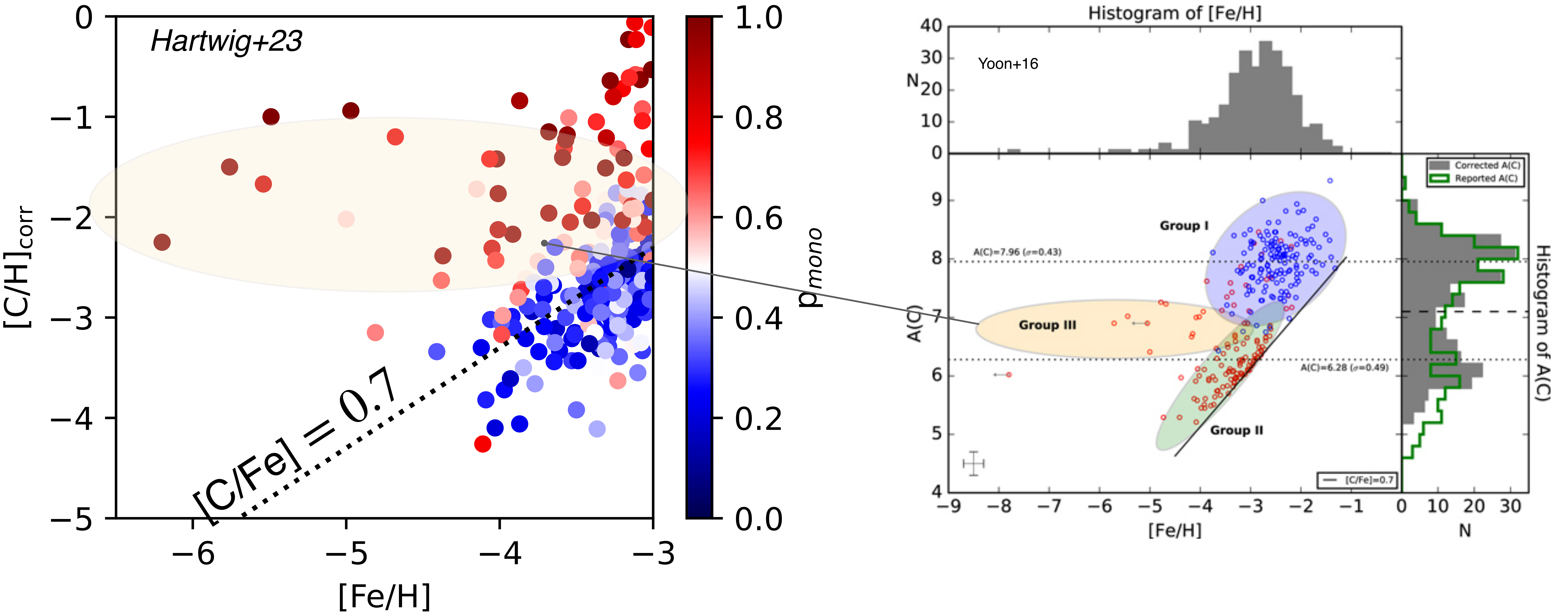
The classification by Support Vector Machine ("SVM")



Credit:: Alisneaky, Zirguezi @Wikipedia

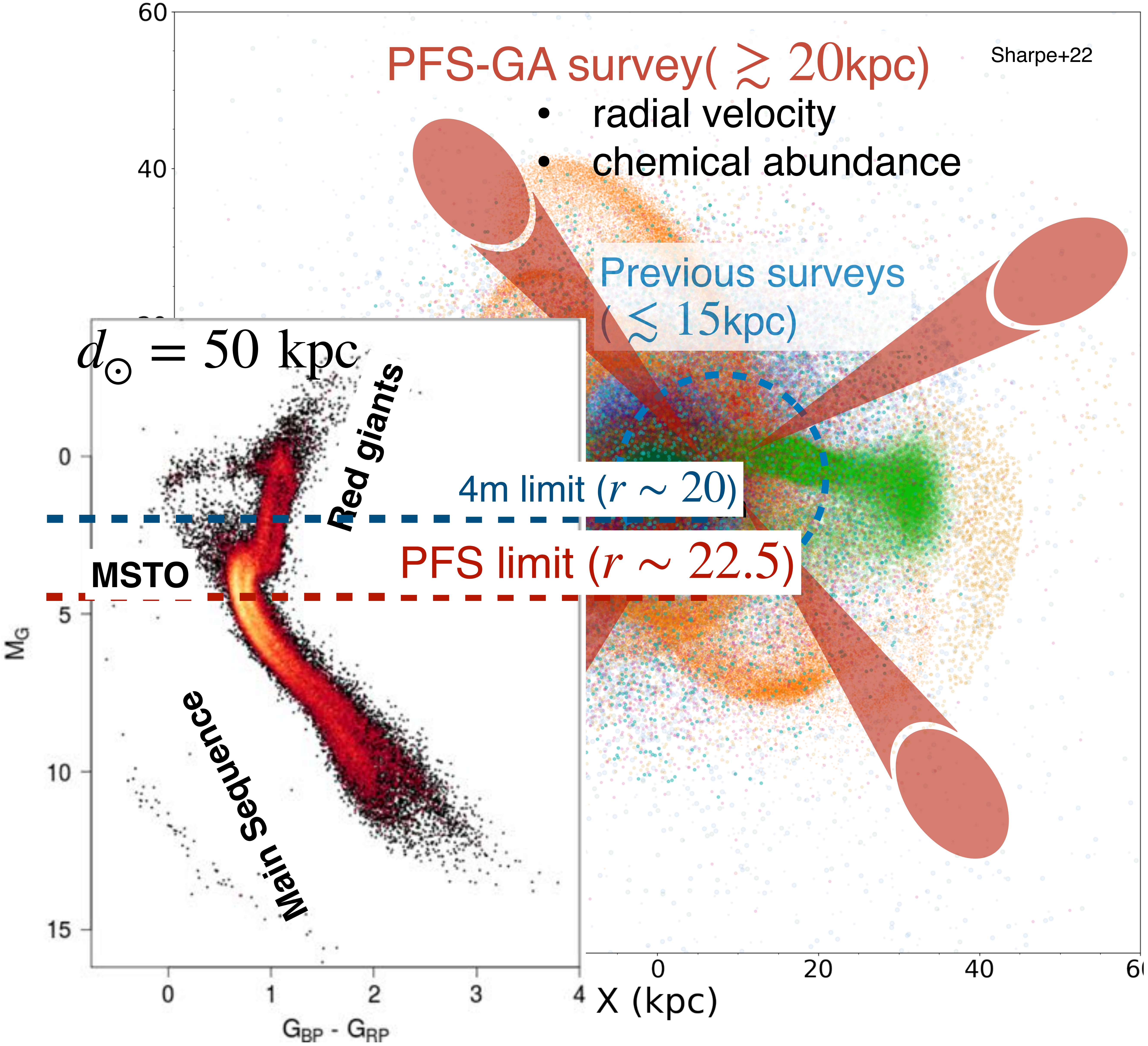
The nature of mono-enriched stars based on chemical abundances of ~400 EMP stars

- The fraction of mono-enriched stars $(p_{\mathrm{mono}} > 0.5)$: $31.8\% \pm 2.3\,\%$
- Carbon-enriched ([C/Fe] > 0.7) stars : more likely classified as mono-enriched stars



More realistic yield models + statistical sample of extremely metal-poor stars ➡
Improve the classification accuracy

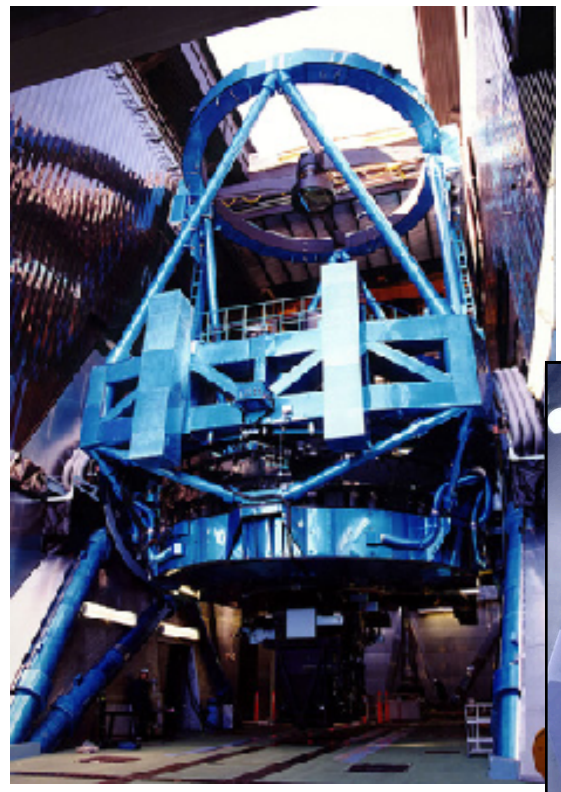
The Milky Way's outer halo with Subaru/PFS



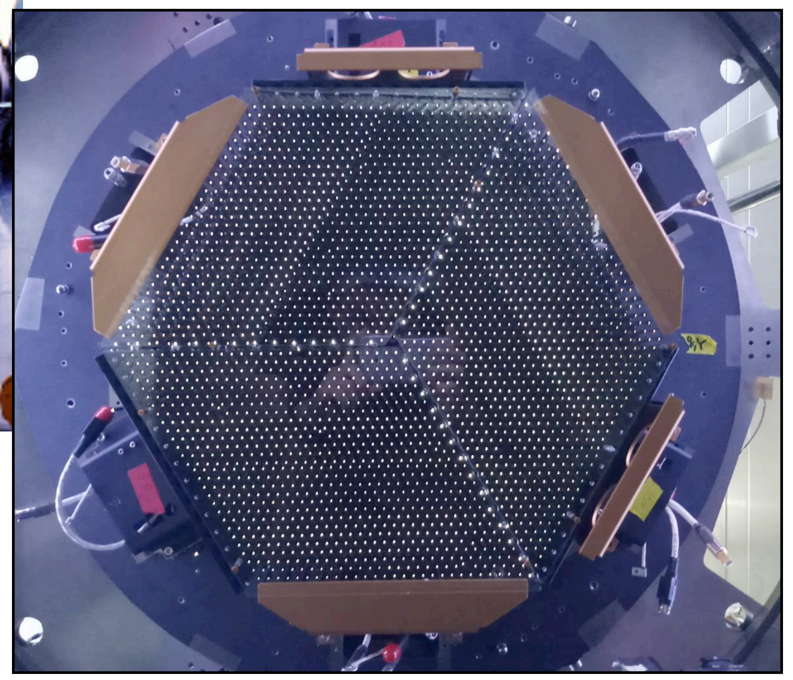
What has been overlooked in previous surveys?

- Tidal streams from recent accretion events
- Debris of a dwarf galaxy that has large orbital angular momentum
- Faintest satellite galaxies (the candidates of the first galaxy)

Prime Focus Spectrograph (PFS)



8m Subaru Telescope

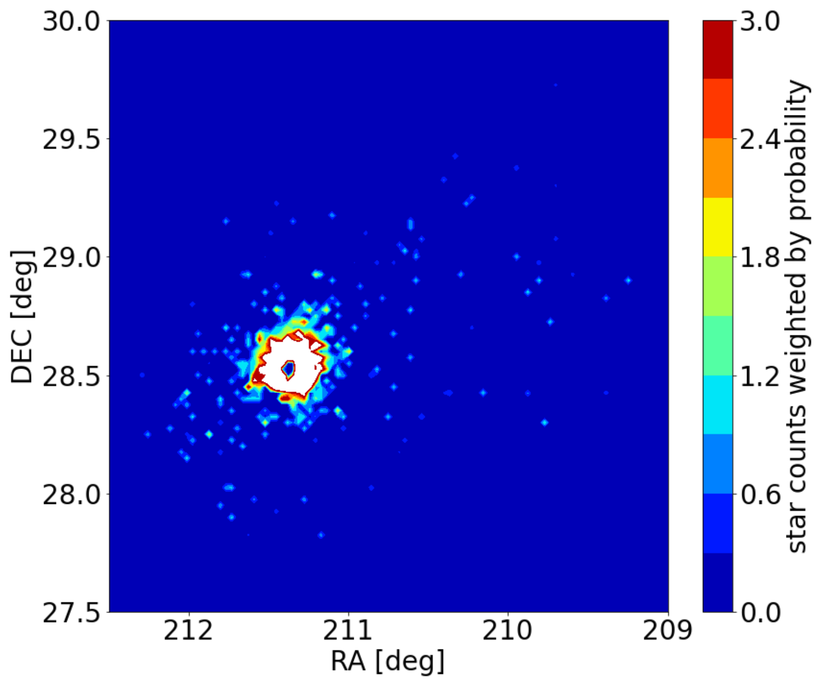


2400 fibers over 1.3 deg2

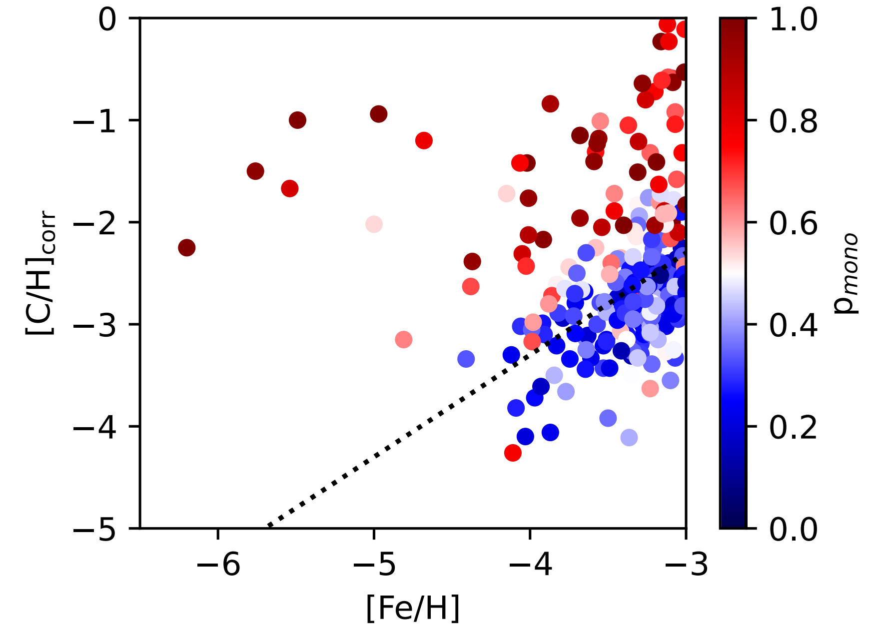
Summary

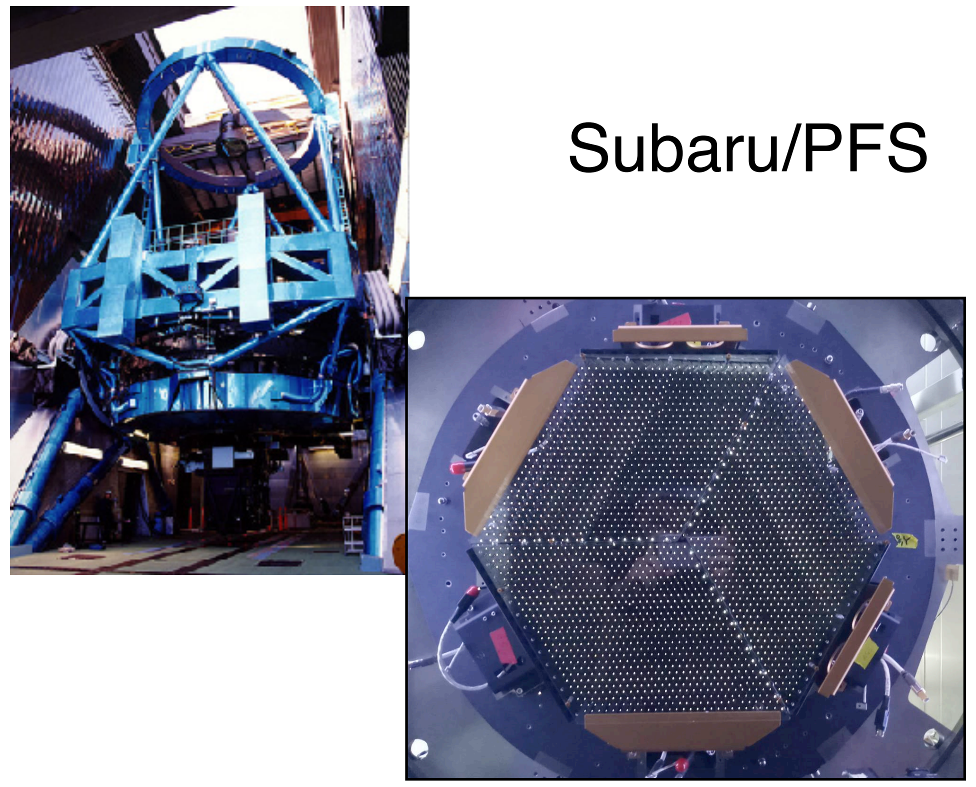
- The Milky Way's outer halo: a laboratory of dark matter
- The importance of stellar chemical abundances:
  - The timing and characteristics of past merger events:
    - Subaru/HSC search for extra-tidal structures of the outer halo globular clusters ➡ associate each cluster with a past dwarf-galaxy accretion event
  - Understanding the very first step of the structure formation in the universe
    - The machine learning algorithm can classify EMP stars into mono- or multi-enriched stars by the Pop III star's supernovae
- Subaru/PFS survey (~2025) provides new insights into the formation of the Milky Way to test the nature of dark matter

Ogami, MI+24 in prep



Hartwig, MI+23





Subaru/PFS