# Understanding the Formation of the Milky Way's Halo: Measuring the Star Formation History of Dwarf Galaxies and Tidal Streams

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## STELLAR AGES

Obtaining reliable stellar ages continues to be an active area of research, with age-abundance relationships (chemical clocks) becoming popular with the rise of large-scale spectroscopic surveys. Of the many calibrated chemical clocks, Spoo et al. (2022, 2025) used open and globular star clusters to calibrate the [C/N] chemical clock, which has been shown to work well within APOGEE giant populations. We apply the following relationship:

$$\log[\mathrm{Age(yr)}] = -1.78(\pm.98)[\mathrm{C/N}]^2 + 1.37(\pm.63)[\mathrm{C/N}] + 10.10(\pm.10)$$

to the Horta et al. (2023) Halo sub-structure catalog and show the distribution of ages for each structure in Figure 1 below.

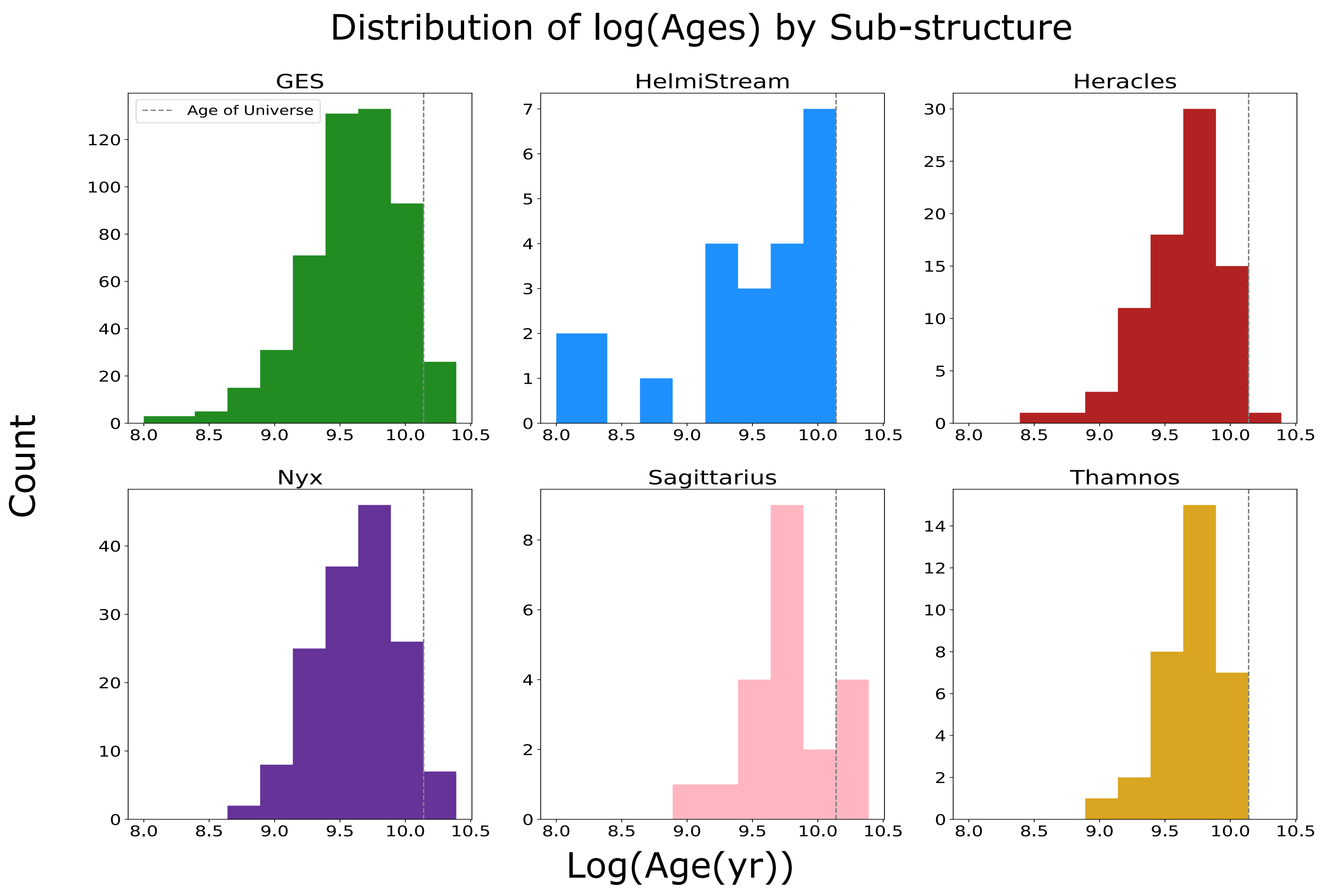

Figure 1: Histogram of the log(age) of stars in 6 selected sub-structures from Horta et al. (2023). The grey dashed line denotes the log(age) of the Universe.

## BIG PICTURE

We expect the largest burst of star formation to be early in the history of the Universe, but we are missing those stars in our observed data. We show a proof-of-concept method to recover this missing burst, using a simulated Sculptor dSph analog, to recreate star formation histories (SFHs).

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In order to gain insight into how the Milky Way formed and evolved through time, we need to further our understanding of the original stellar populations that make-up the current large-scale features of our Galaxy. Stellar streams in the outskirts of our Galaxy are believed to be remnants of small galaxies that have been broken apart and consumed by the Milky Way. We use the observed ratio of carbon to nitrogen in the surface of giant stars, to age-date these structures. Armed with these ages, we can paint a more coherent picture of how our Galaxy formed and evolved through time.

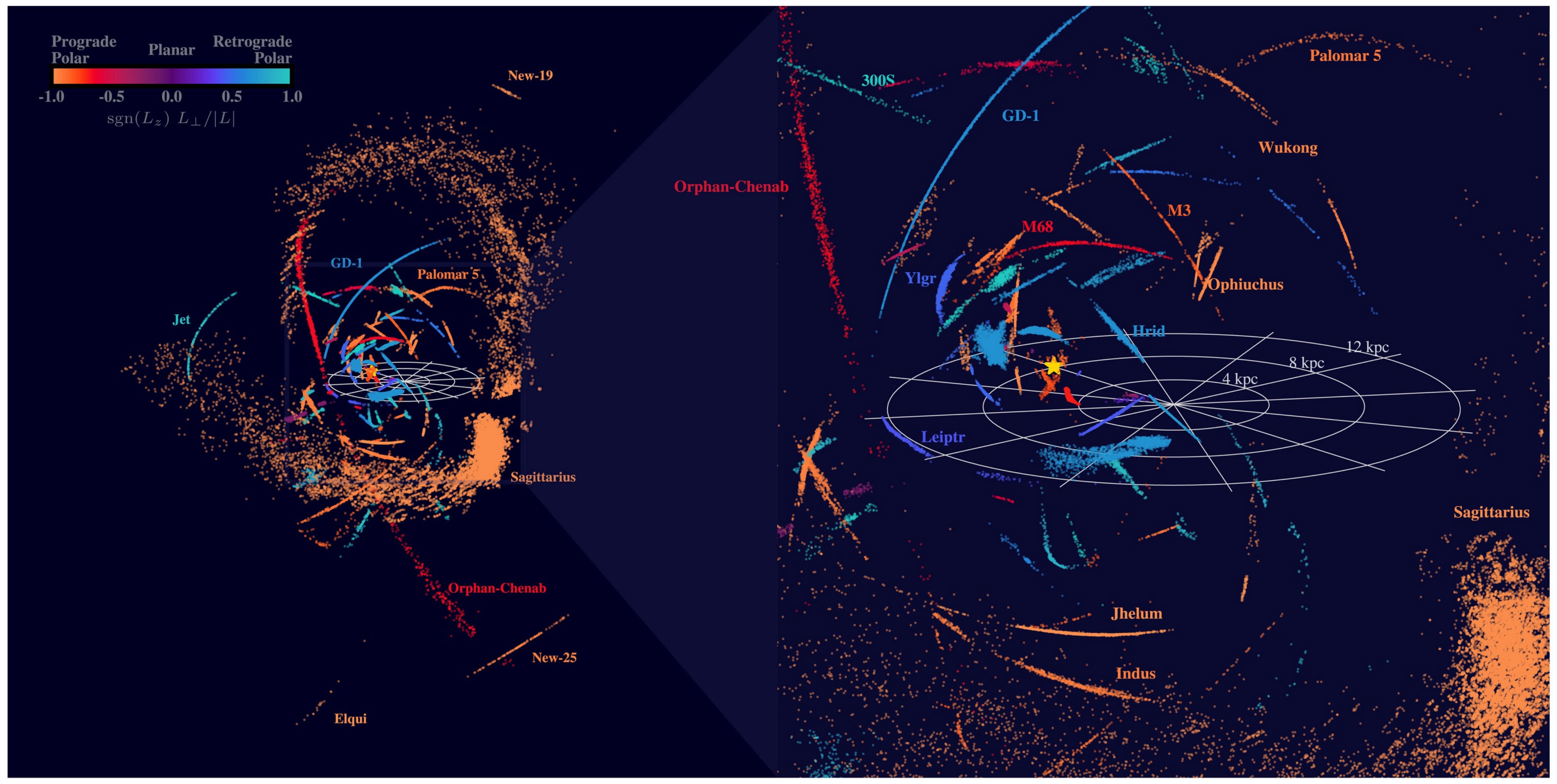

Figure 2 (left): Figure 2 from Bonaca & Price-Whelan 2025 showing all the known stellar streams in the Milky up to this point.

## MILKY WAY STREAMS

To the left in Figure 2, an atlas of all the known streams in the Milky Way is depicted. Individual points are stars that are likely members of a given stream. The left panel shows a zoomed-out view of the streams as they wrap around the Milky Way while the right panel zooms in on the many streams that have been discovered closer to the center of the Milky Way. The streams are colored by their orbital information. With streams moving with the Milky Way in redder colors while streams moving opposite of the Milky Way in bluer colors.

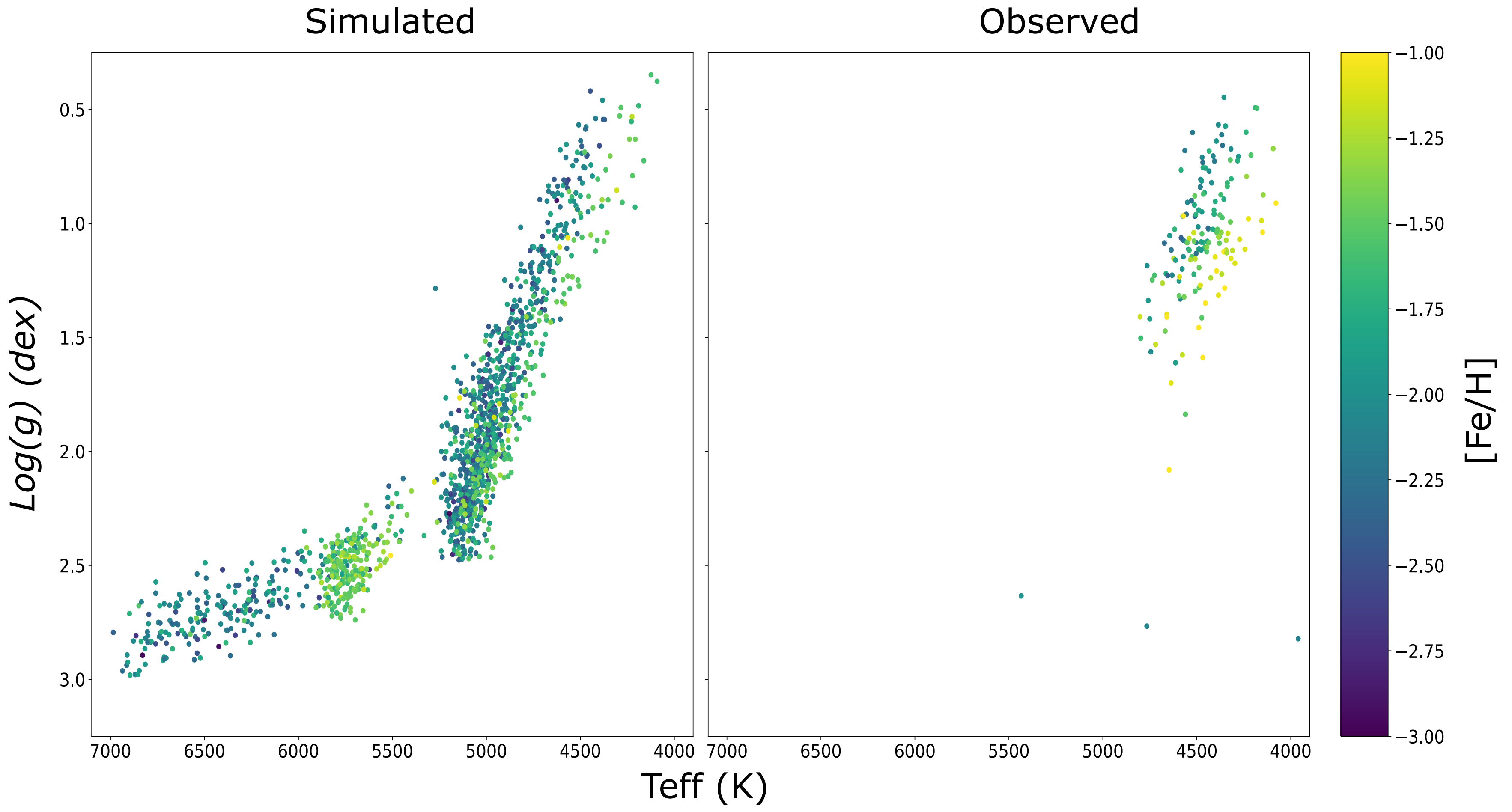

Figure 3: Kiel diagrams for the simulated Sculptor analog (left) and the Sculptor stars (right) within SDSS DR17 as determined by the internal flags. Simulated metallicities were determined by applying Gaussian noise to the "true" metallicity used to generate both stellar components.

## SIMULATING A DWARF GALAXY

There are two main reasons why we struggle to probe the oldest stars. The constraints on where the relationship works, -1.2 ≤ [Fe/H] ≤ +0.3 and 2.14 ≤ *log(g)* ≤ 3.1, and observation selection effects due to these structures being distant halo objects. To quantify the observation selections effects, we create a Sculptor dSph analog using **OCELOT**[1], a star cluster simulation package. **OCELOT** takes in positional and kinematic data, mass, age, metallicity, and distance, and produces a star cluster for the given parameters using PARSEC isochrones. We simulate our Sculptor analog by creating two clusters that correspond to the two distinct stellar components identified in Tolstoy et al. (2004), using their parameters. These two components account for ~70% of the total mass of the dwarf galaxy. We add Gaussian noise to the *log(g)*, $T_{\mathrm{eff}}$, metallicity and log(age) of each component for realism. In Figure 2 above, we plot our simulated cluster (left) next to the SDSS DR17-observed Sculptor Kiel diagram (right). We apply a random down sampling for each of the two stellar components in the simulated cluster for clarity in the plots.

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[1] Hunt & Reffert (2021) github.com/emilyhunt/ocelot

## SIMULATED VS OBSERVED

The Kiel diagrams (Figure 2) show that our simulated dwarf galaxy is a reasonable analog to Sculptor. We can also see that the horizontal branch and red clump are missing entirely from the observed data. We show the log(age) distribution of both Sculptors in Figure 3. With the simulated cluster we have replicated the findings of Shetrone et al. (*in prep*), ~70% of the mass is formed in the first 2Gyr, recovering the "missing" old starburst within the Sculptor population.

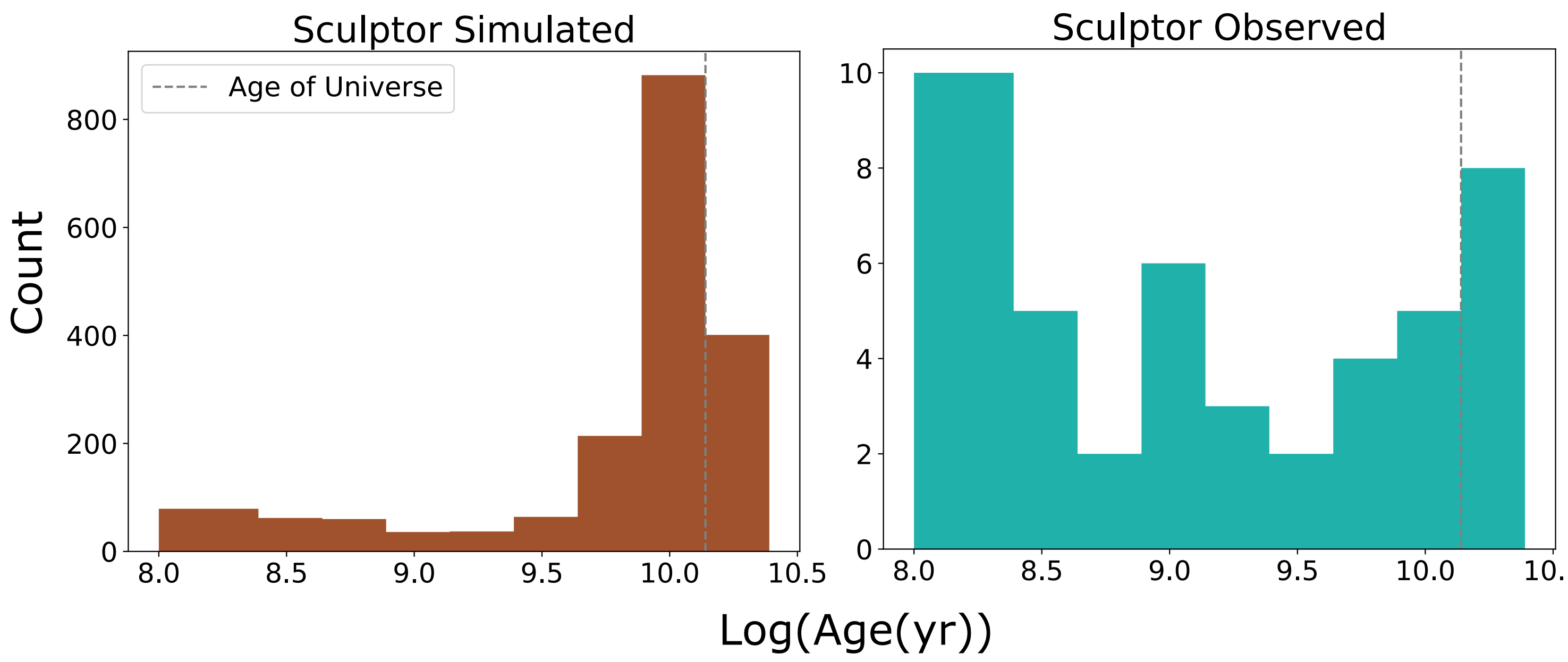

Figure 4: Log(age) histograms for the simulated (left) and observed (right) dwarf galaxy.

## NEXT STEPS

We've shown that we can create a reasonable analog to a dwarf galaxy with a simple SFH Our next steps include:

1. Applying the methodology to the other Galactic sub-structures with more complex SFHs
2. Adding the [Fe/H] and *log(g)* constraints.
3. Reconstructing the SFHs of each of the sub-structures based on these corrections.

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