Old Problems Require Modern Solutions:

A Data-Driven Approach to Modeling Stellar Populations

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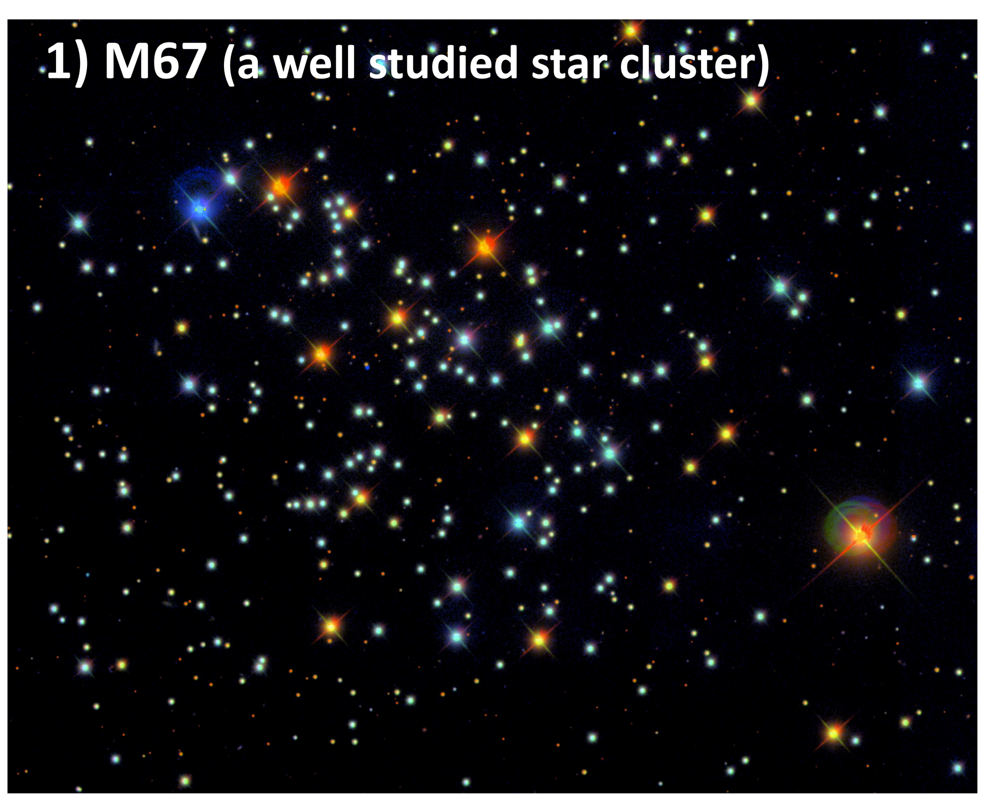
Background

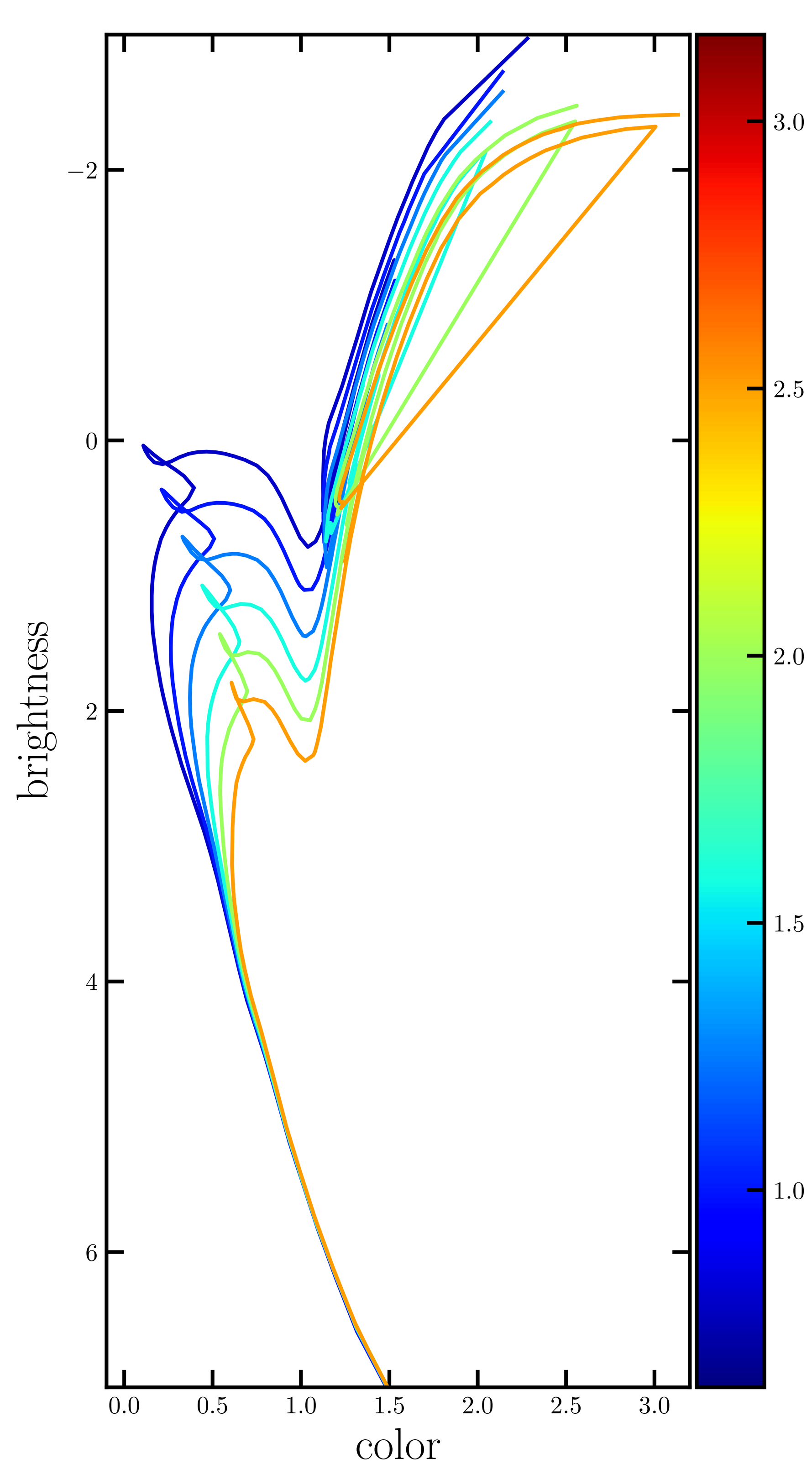
Star Clusters and Isochrones

Star clusters are groups of stars that formed together from the same cloud of gas and dust. This means that they are both the **same age** and have **the same chemical make-up**, which makes it possible to predict fairly accurately how they will evolve as a group. This leads to isochrones.

An isochrone (iso: same, chronos: time) is a model of a group of stars with the same initial chemical make-up frozen at a point in time. It is constructed by modeling the evolution of a group of stars with uniform chemical make-up but varying masses. Since more massive stars evolve more quickly, isochrone models frozen at different points in time (corresponding to star groups of different ages) are necessarily unique, so if an isochrone matches an observed star group (cluster), that group must be that age.

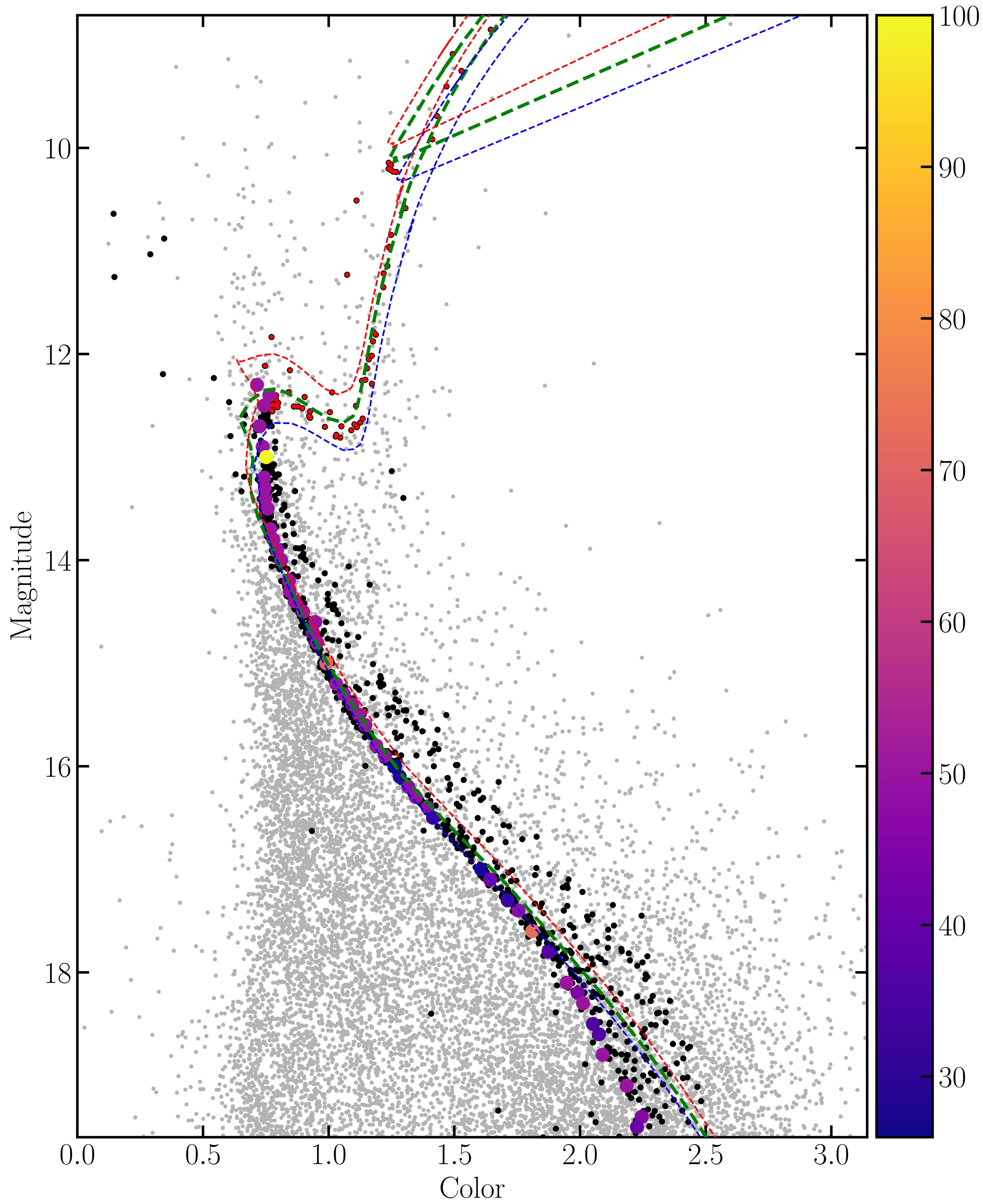


1) M67 (a well studied star cluster)



2) Isochrones
Figure 2 shows a series of isochrones, spanning a relatively short range of ages (800 Myr to 2.5 Gyr).

Results



3) The fit!
Figure 3 shows the resulting fit. Field stars are grey, members are black. Fiducial points are colored, with the bar showing a relative density. The green line is the chosen line (corresponding to to the values in Figure 4). Blue and red lines show the worst case 1-σ uncertainty.

Fit Parameters

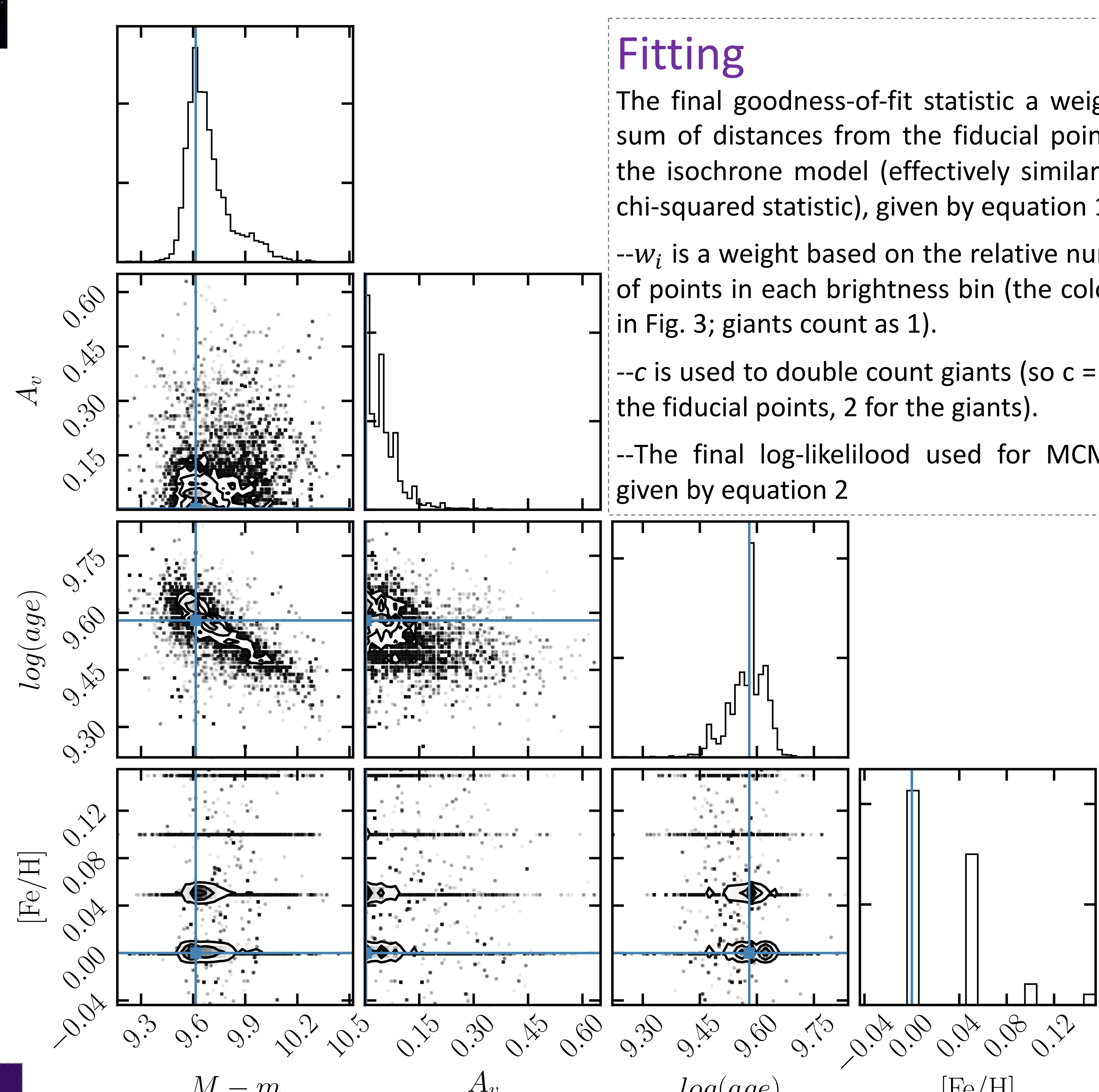
Intrinsically an isochrone is defined by chemical composition, or "metallicity" in astronomy (denoted [Fe/H]) and age. However its appearance is also affected by distance and interstellar dust. This gives 4 parameters when fitting isochrones.

[Fe/H]: metallicity or chemical composition (-1.5 to 0.45)

Age: generally given in log(age) due to the large range (7.0 to 10.0)

m-M: "distance modulus", a numerical measurement of brightness decrease due to distance

A_V: extinction, or how much light is blocked by interstellar dust (resulting in further dimming, and slight color change)



4) Corner Plot
The corner plot after an MCMC exploration of M67, clearly showing the covariance between various parameters. Chosen values are shown with blue lines. Special thanks to the python package corner.

Fitting

The final goodness-of-fit statistic a weighted sum of distances from the fiducial points to the isochrone model (effectively similar to a chi-squared statistic), given by equation 1.

--w_i is a weight based on the relative number of points in each brightness bin (the colorbar in Fig. 3; giants count as 1).

--c is used to double count giants (so c = 1 for the fiducial points, 2 for the giants).

--The final log-likelilood used for MCMC is given by equation 2

$$X = \sum \left(\frac{\Delta_i}{\sigma_i}\right)^2 w_i \cdot c \quad (1)$$

$$\ln(\text{like}) \propto \frac{X_f + X_G}{N_f + 2N_G} \quad (2)$$

Markov-Chain Monte-Carlo (MCMC) Estimation

MCMC is a robust method for exploring a parameter space. In our parameter space there are 4 dimensions. A log-likelihood (Eq. 2) can be calculated for any position in that 4-D space. MCMC randomly walks through the parameter space, preferentially moving towards areas of higher log-likelihood.

The python package emcee uses many walkers to efficiently cover the parameter space more quickly. The result is a large sample of data-points preferentially centered around an area of higher likelihood.

The MCMC process is best visualized in a corner plot, seen in Figure 4. A corner plot shows where the over-density lies in each parameter, and quickly allows for a visualization of the covariances between all the parameters.

Galactic Chemistry

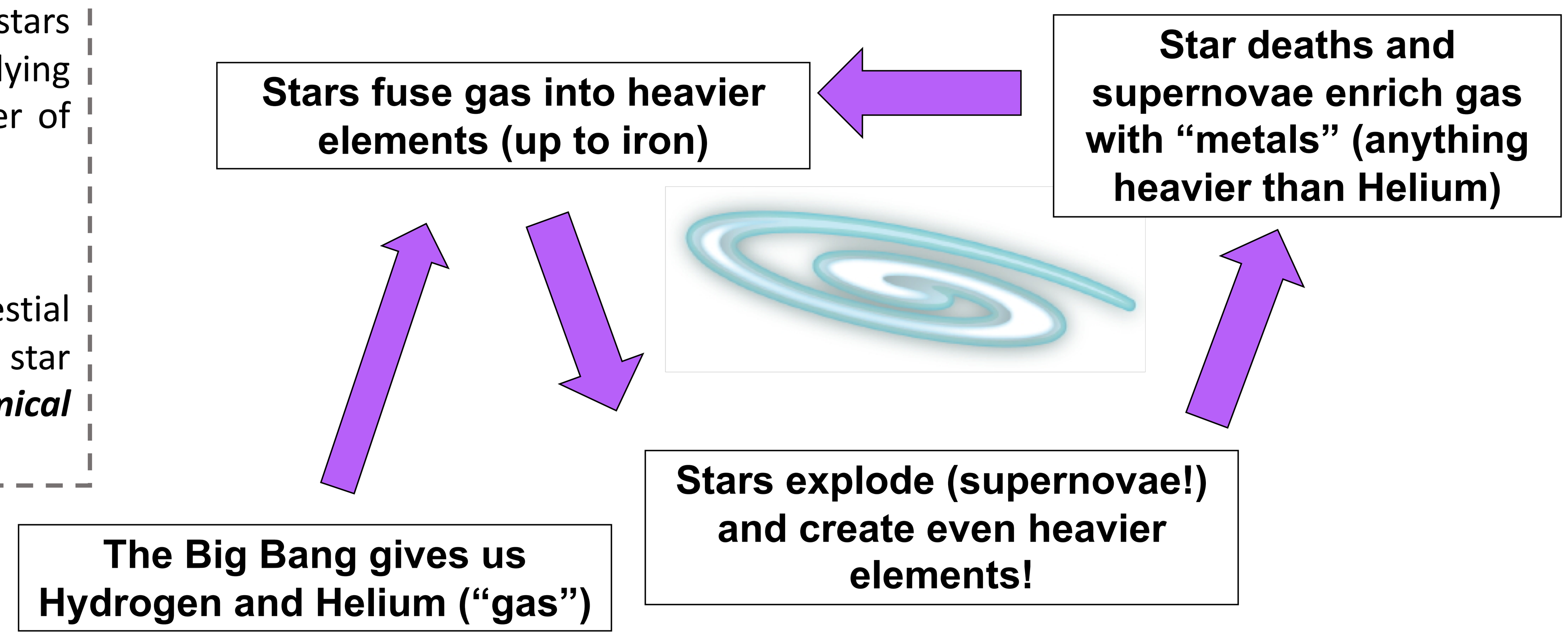
Astronomers have developed models of galaxy evolution based on stars and stellar feedback. Gravity draws gas to the center of a galaxy, and with more gas comes more star formation. More stars forming means more stars dying, which means more "metal" enrichment for the gas around the dying stars. Thus: models predict more "metals" moving towards the center of the galaxy center, as seen in Figure 5.

Star Clusters

Star clusters are commonly used to study this effect. **Distances** to celestial objects are difficult to determine, and **ages** are even harder. Since star clusters can do both thy are among the best **tracers** for ***galactic chemical evolution***.

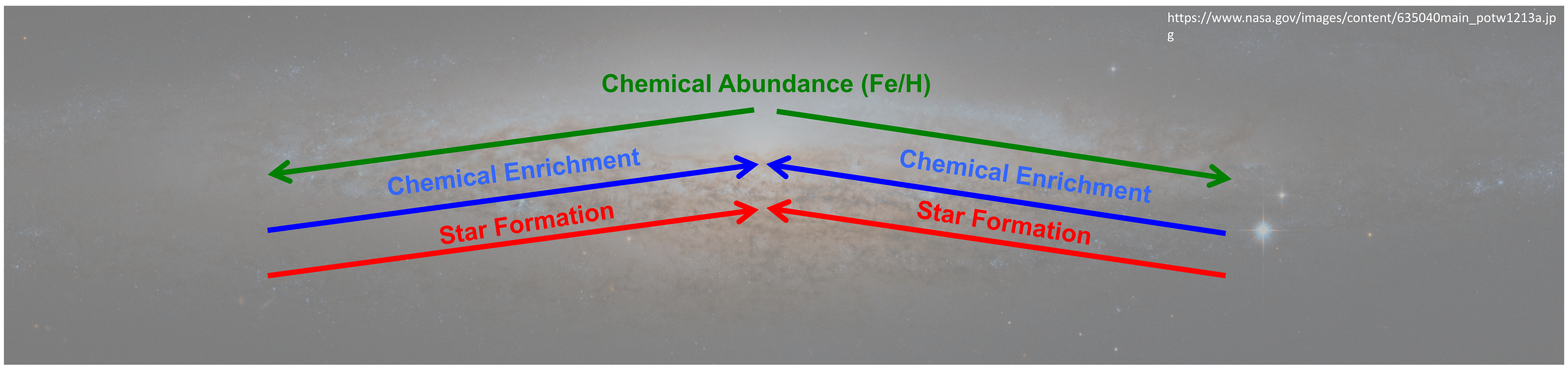
The Galactic Life Cycle:

Make a star, make heavy elements, repeat!



5) Galaxy evolution in one plot

A summary of galactic chemical evolution: more gas leads to more stars (red) which leads to more "heavy" elements in the center (blue), and consequentially a negative gradient (green) moving away from the center of a galaxy.



Comparison to Previous Work

It has not been possible until recently to fit isochrones to only member stars in a cluster (for more than a few clusters). The first research of this type was published by Bossini et al. in mid 2018, after the release of *Gaia* DR2 (which we also used). Prior to this, comparisons were made to entire clusters. One well cited catalog of such isochrone fit parameters is the Milky Way Star Cluster Catalog (MWSC) from Kharchenko et al. In Figures 6 & 7 we compare to these similar studies.

We find no systematic differences between our work and either of the previous two studies for either distance (Fig. 6) or age (Fig. 7) measurements.

In Figure 8 we compare to distance measured using traditional parallax and parallax with a geometric prior considered ("geo"). Here we see the "geo" points tend to be measured farther, which may suggest the geometric prior is overly aggressive, and we see the parallax may to be measured closer on average.

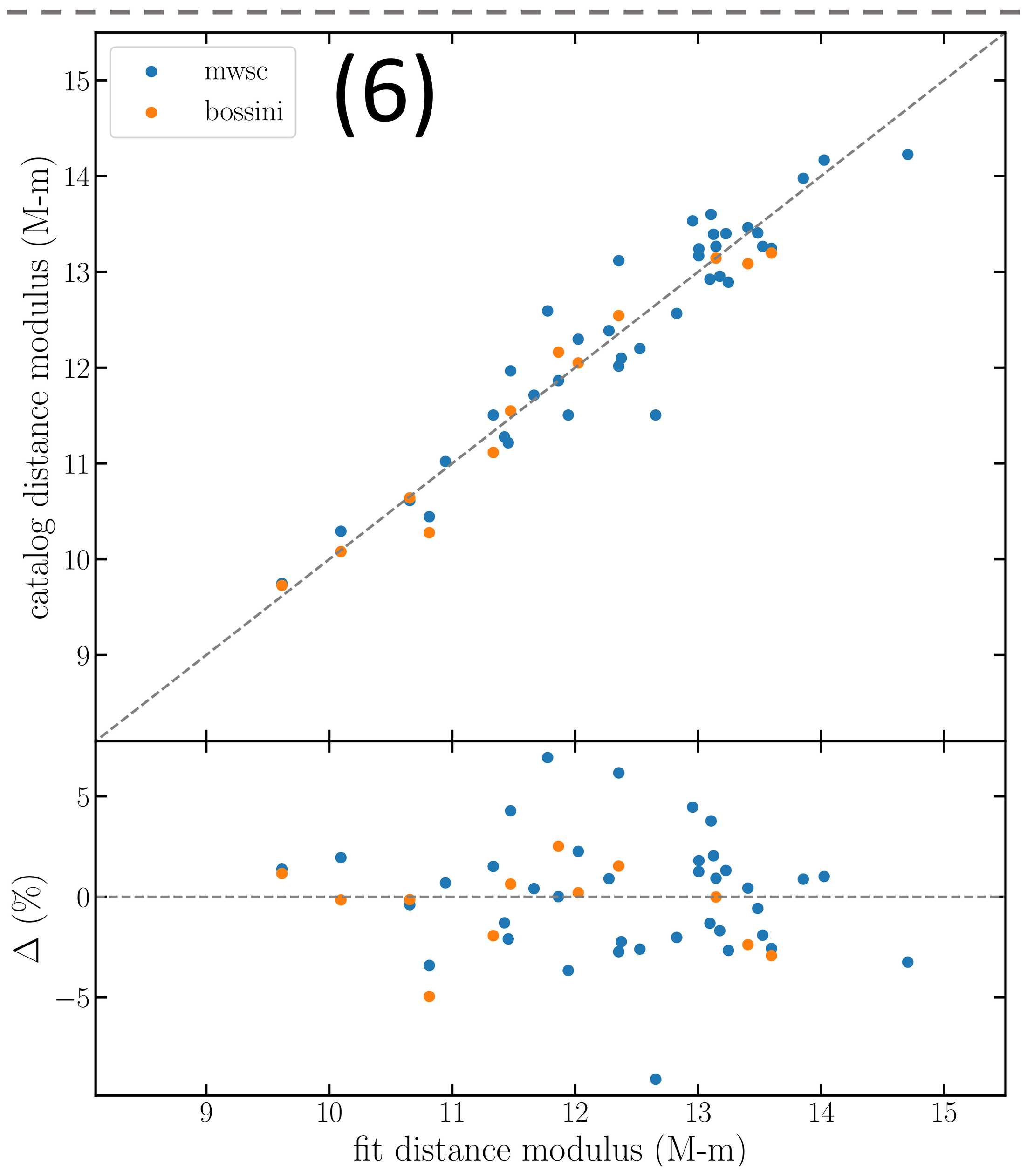
Measuring Galactic Abundance Gradients

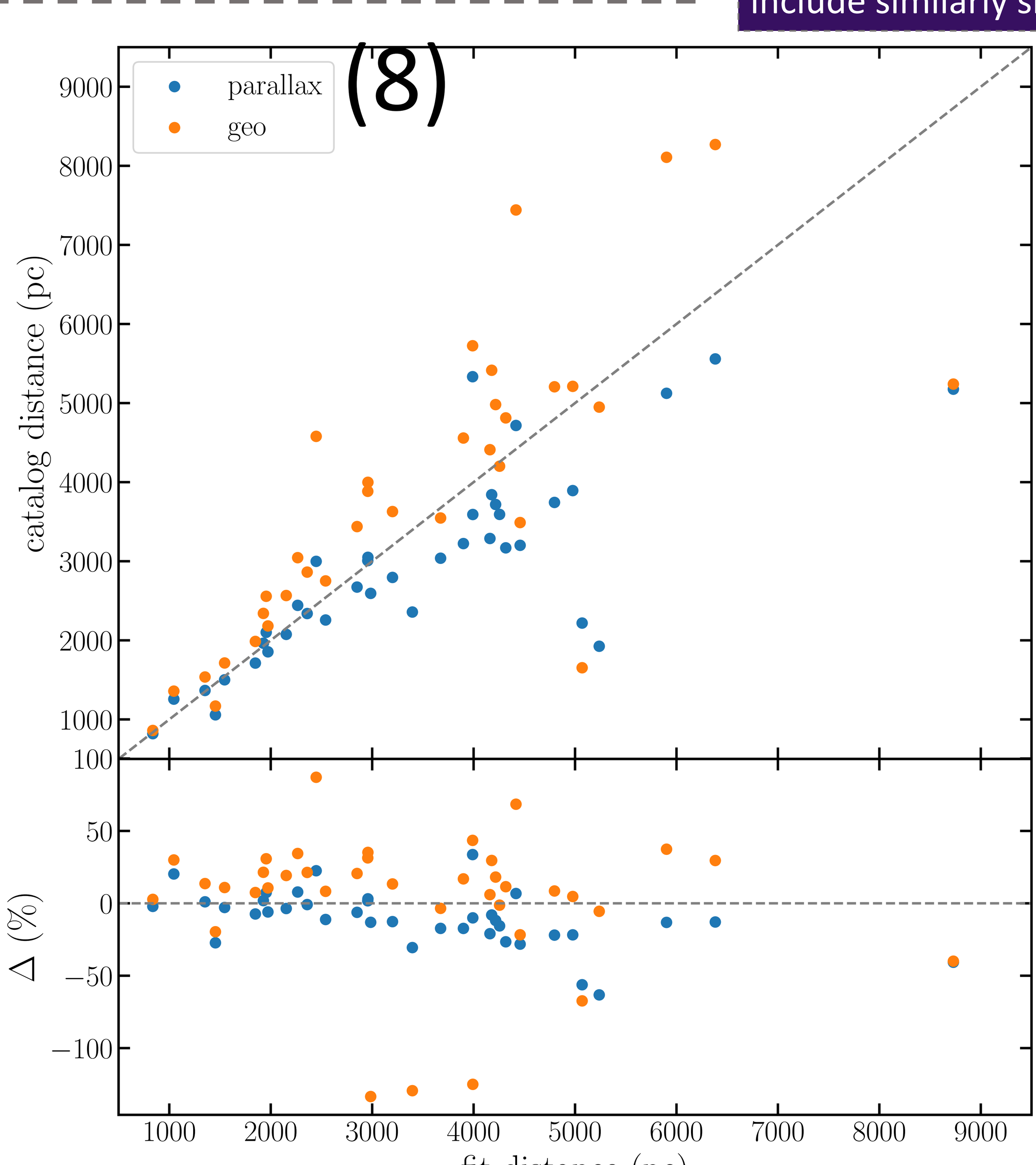
Our final goal is to apply our measurements of **distance** and **age** to determine galactic abundance gradients for cluster groups of different ages. If we continue our simple galaxy evolution model, we might predict that eventually star formation in the rest of the galaxy would lead to an abundance gradient becoming less steep.

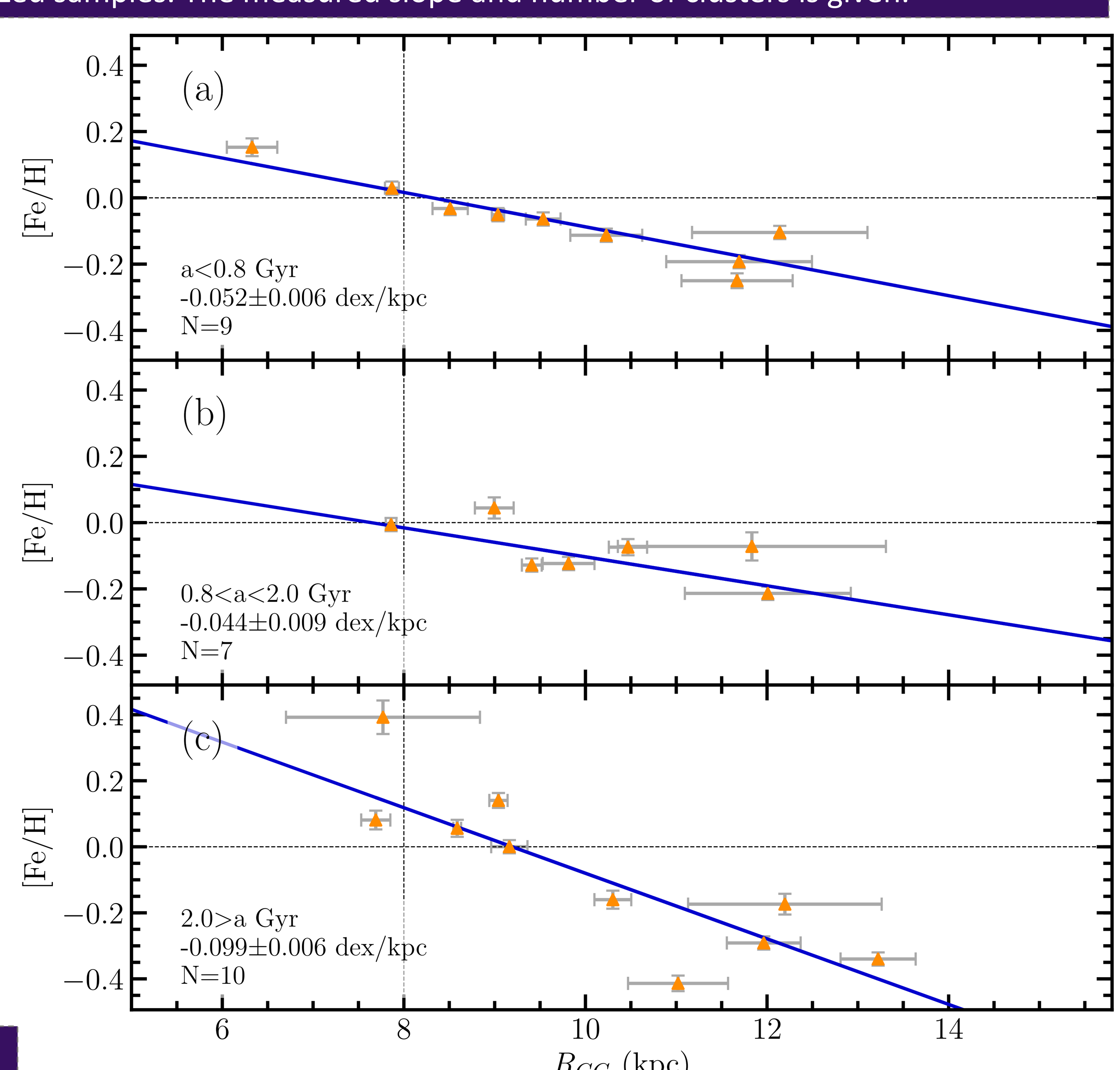
In Figure 9, if we consider only the oldest clusters, we do indeed find the steepest slope. The slope in the younger two bins is shallower, as expected, but exactly which of these two bins has the shallowest slope is not well established by these measurements.

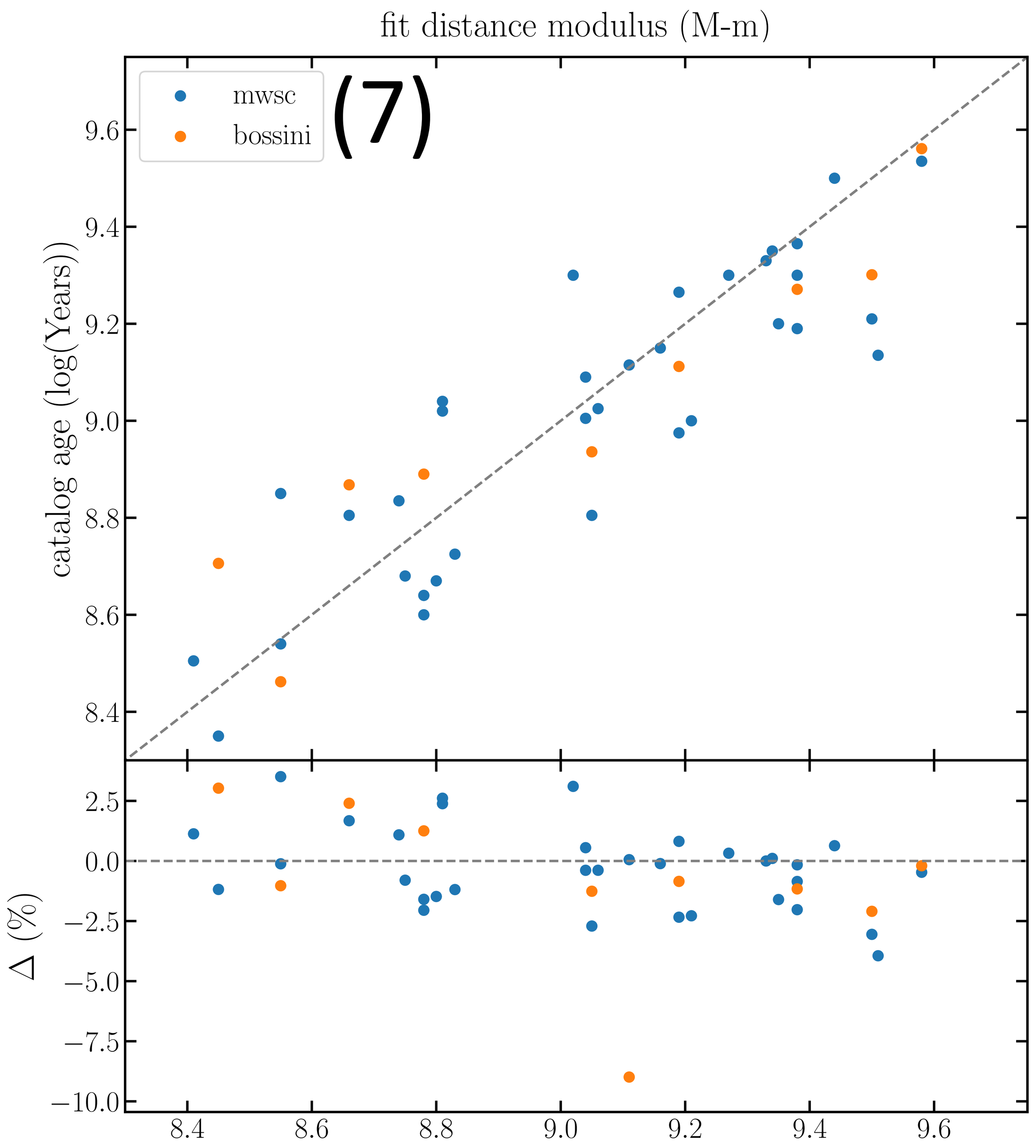
9) Galactic abundance gradients

We measure the gradient, or slope, of [Fe/H] against distance from the center of the galaxy (R_{GC}) for groups of stars spit into 3 age bins. The bins are chosen to be similar to the literature and to include similarly sized samples. The measured slope and number of clusters is given.









6-8) Literature Comparison

Figures 6-8 show comparisons of our work with previous studies. The diagonal line is 1:1 (perfect agreement), our work is always plotted on the x-axis. The bottom of each figure shows the % difference.

Figure 6 shows distance modulus (m-M) , compared to the MWSC catalog and recent work from Bossini et al. Bossini et al. have so far only published a handful of clusters that overlap our sample.

Figure 7 shows a comparison of age (in log(age)) for the same two studies.

Figure 8 shows a comparison to studies which measured the distance more "physically", utilizing parallax (also from the space based *Gaia* mission). The "geo" points are a modified version of the parallax, after a geometric prior is considered. The obvious trends are discussed above.

We describe a robust and efficient method for fitting models of star clusters to those clusters. This fitting allows us to determine the distance to these star clusters, as well as their ages. Star clusters are important tools in studying galactic chemical evolution because they span a wide range in ages (from tens of millions of years to nearly 10 billion years), allowing us to study the chemical make-up of the galaxy over that entire time period.

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Acknowledgements

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