

Investigating The Consistency of Stellar Evolution Models with Globular Cluster Observations via the Red Giant Branch Bump

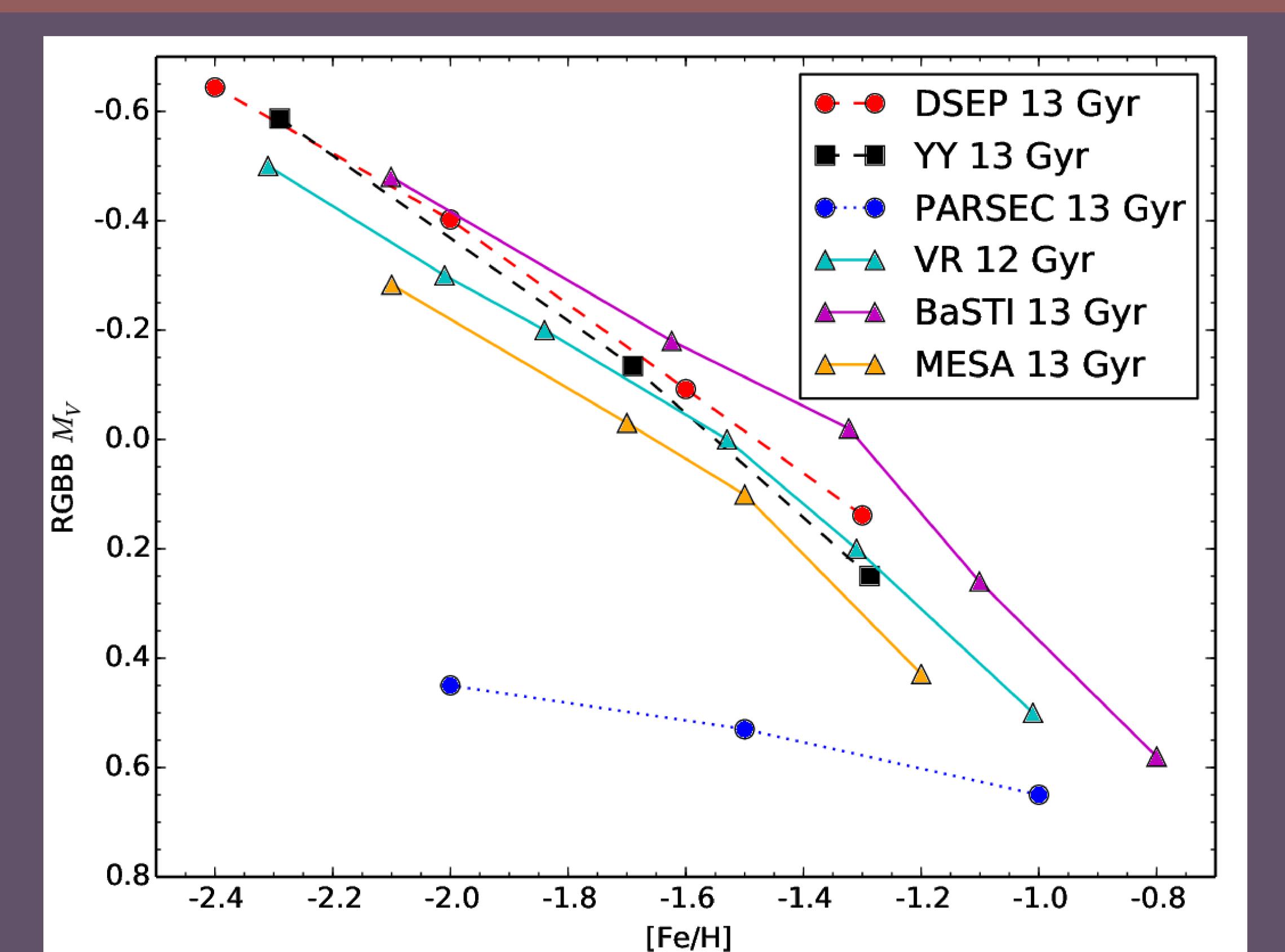
M. Joyce¹, B. Chaboyer¹

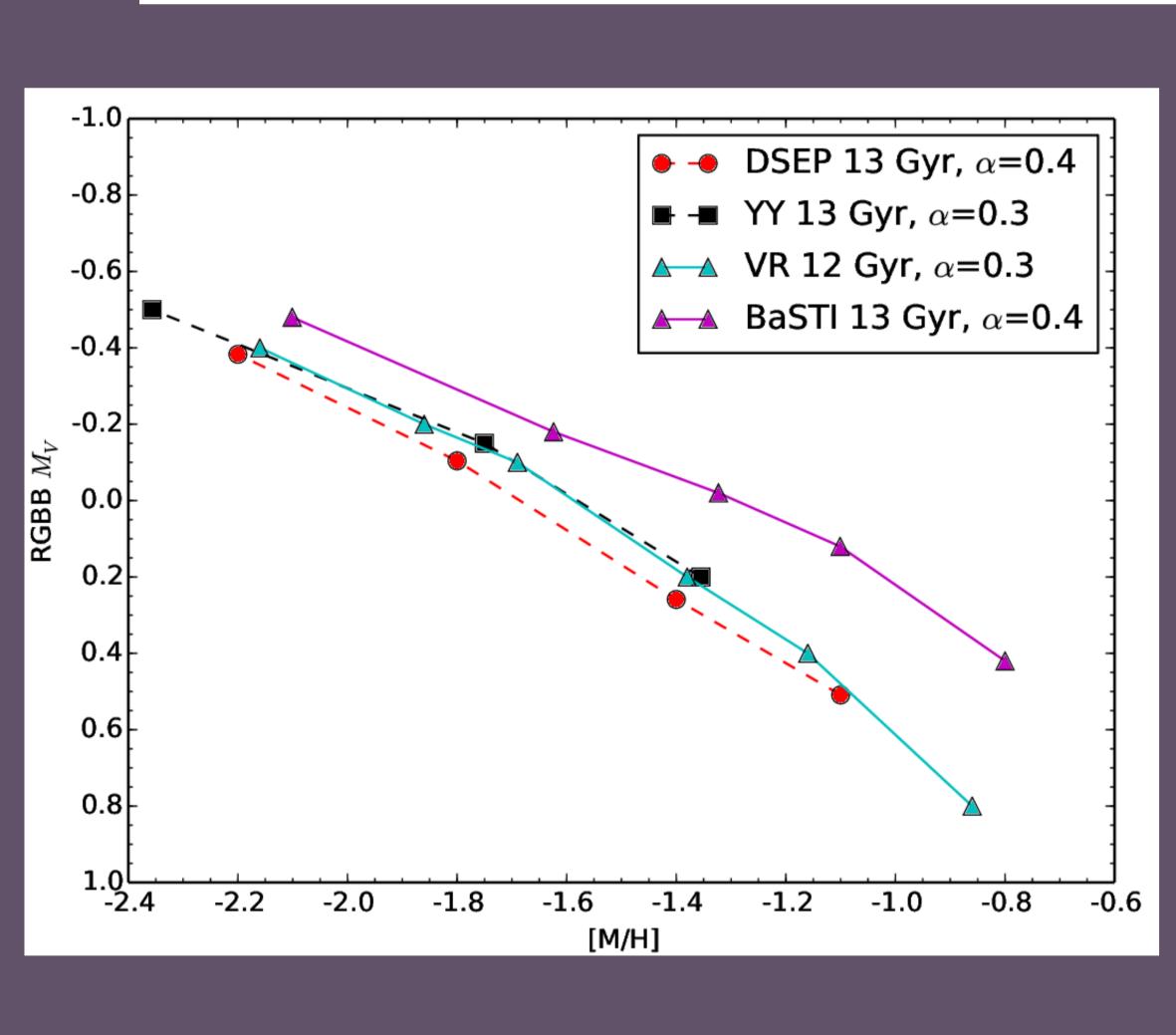
¹Dartmouth College

ABSTRACT

Synthetic Red Giant Branch Bump (RGBB) magnitudes are generated with the most recent theoretical stellar evolution models computed with the Dartmouth Stellar Evolution Program (DSEP) code. They are compared to the observational work of Nataf et al., who present RGBB magnitudes for 72 globular clusters. A DSEP model using a chemical composition with enhanced α capture $[\alpha/\text{Fe}] = +0.4$ and an age of 13 Gyr shows agreement with observations over metallicities ranging from [Fe/H] = 0 to $[\text{Fe/H}] \approx -1.5$, with discrepancy emerging at lower metallicities.

RGBB MAGNITUDE PREDICTIONS FROM VARIOUS STELLAR MODELS

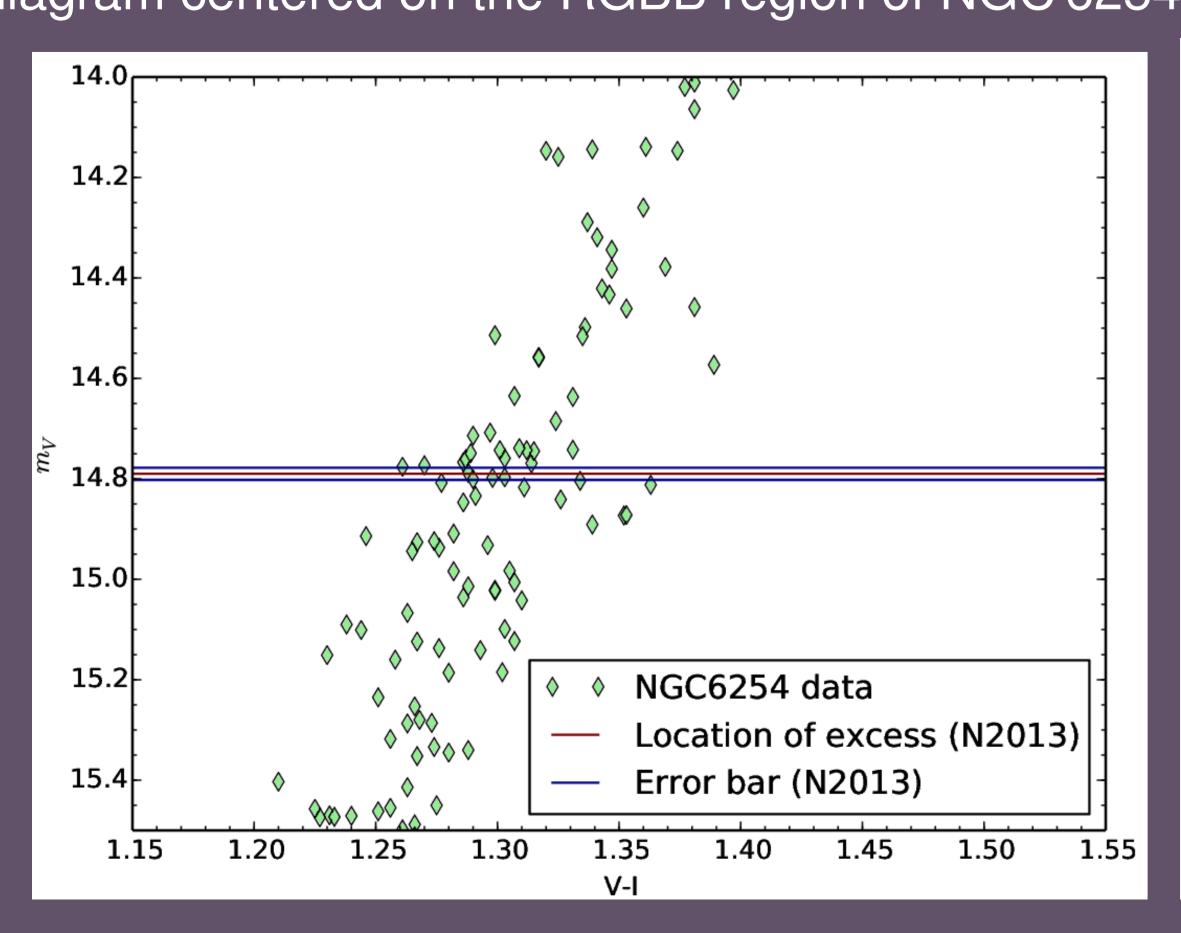


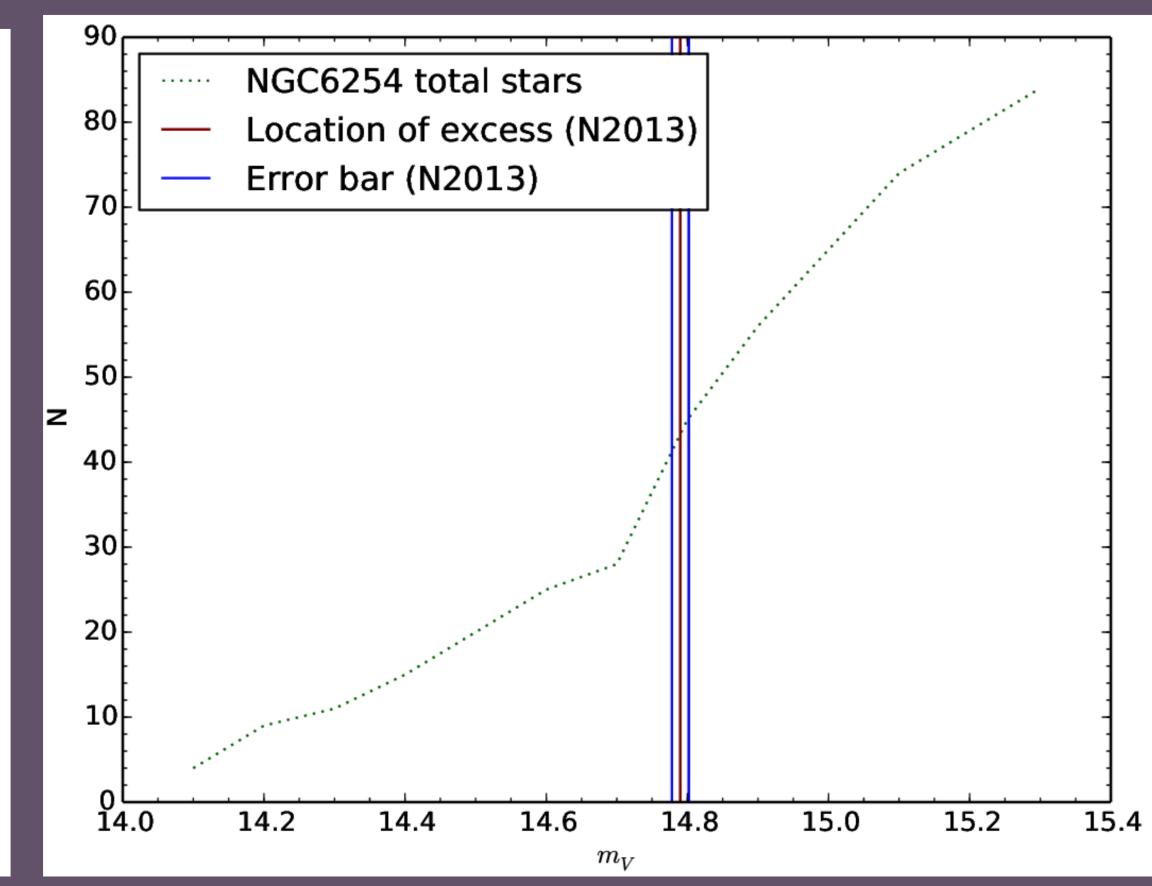


We compare DSEP's RGBB magnitude predictions to predictions given by other stellar evolution codes, including the Yonsei–Yale (YY) models, the Victoria–Regina (VR) models, the PARSEC models, the BaSTI models, and tuned MESA tracks. **TOP:** Models with scaled solar compositions. **LEFT:** Models using similar α -enhancements. The DSEP curve has $\alpha = +0.4$, the YY curve has $\alpha = +0.3$, the VR curve has $\alpha = +0.4$. All of the models excluding PARSEC agree within a span of \sim 0.2 magnitudes. Errors of this order may be due to differences in microphysical considerations.

OBSERVATIONAL SAMPLE (Nataf et al., 2013)

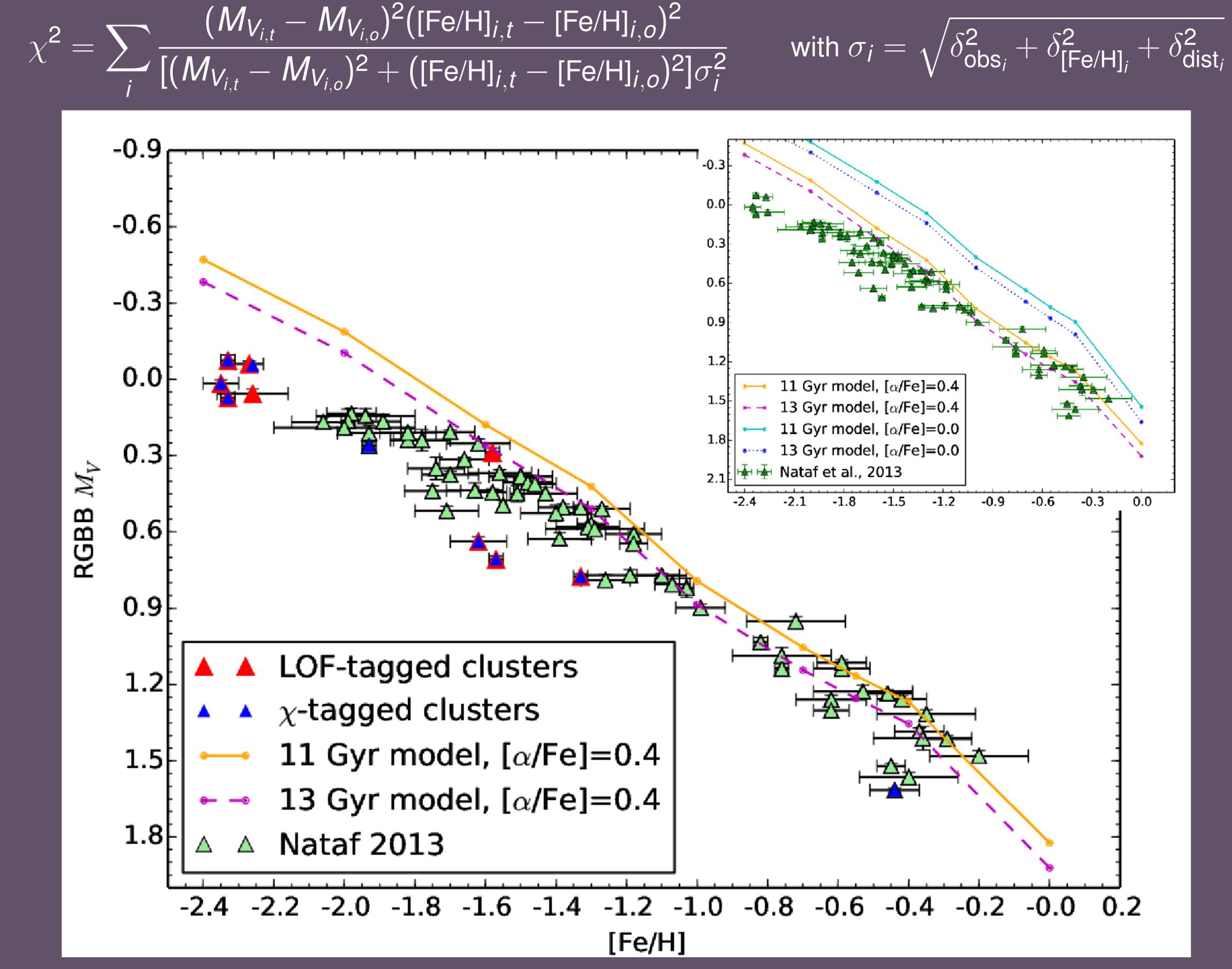
Our analysis uses the observational sample of Nataf et al. 2013 (N2013), comprising 72 GCs. The N2013 sample contained data from ACS, the current HST CCD, for 55 GCs and WFPC2 for 17 GCs. N2013 separate the data into "silver" and "gold" samples, where the gold data are regarded with higher confidence. Motivated by disagreement between N2013's magnitudes and the magnitudes reported in a previous GC survey (Zoccali et al., 1999), we examined the raw data and found that N2013 may have underestimated their magnitude uncertainties, as demonstrated here. **LEFT:** Color–magnitude diagram centered on the RGBB region of NGC 6254. **RIGHT:** Cumulative luminosity function.





QUANTIFYING CONSISTENCY: 13 Gyr, lpha-enhanced DSEP model

We implement a χ^2 minimization routine to assess the goodness of fit of our best model to N2013's data and subsets thereof. The reduced χ^2 score for the model's fit to the entire sample is 1.38, corresponding to a p-score of 0.0175, or a \sim 2% chance of recreating this observational spread with our model. The score is computed via



IDENTIFYING OUTLIERS

A GC may be classified as an outlier in two ways: (1) if its contribution to the total reduced χ^2 score, or χ_i^2 score, is sufficiently large, and/or (2) its *o*-score computed using the 4D Local Outlying Factor (LOF) algorithm is sufficiently large. The impact on the model–observation goodness of fit as outliers are removed from the sample is shown in these tables.

χ^2 Analysis

Sample	Reduced χ^2	p score	χ_i^2	GC	[Fe/H]
all	1.38	0.0175	_	none	_
-1	1.26	0.68	10.01	NGC 6254	-1.57
-2	1.21	0.12	5.13	NGC 6681	-1.62
-3	1.15	0.18	4.75	NGC 6218	-1.33
-4	1.17	0.15	0.01	NGC 1904	-1.58

Members of the LOF-tagged anomalous cluster group are removed from the sample beginning with the most discrepant and working down. The degree of discrepancy is determined by the individual contribution a data point makes to the χ^2 score (χ_i^2) .

LOF Routine

Cluster	o-score	LOF Rank	[Fe/H]	Sample	χ^2 Rank
NGC 6254	1.522	1	-1.57	gold	1
NGC 6681	1.436	2	-1.62	gold	7
NGC 6218	1.346	3	-1.33	gold	4
NGC 7099	1.259	4	-2.33	silver	2
NGC 7078	1.259	4	-2.33	gold	6
NGC 6426	1.259	4	-2.26	silver	14
NGC 6341	1.259	4	-2.35	gold	3
NGC 4590	1.259	5	-2.27	silver	8
NGC 1904	1.227	6	-1.58	silver	64

The 4D LOF routine identifies the most anomalous clusters based on density using a given point's distance from the bulk distribution. Results are model-independent. The χ^2 rank indicates how discrepant that cluster is with respect to the χ^2 metric. The sample indicates the observational population (defined by N2013) to which the GC belongs.

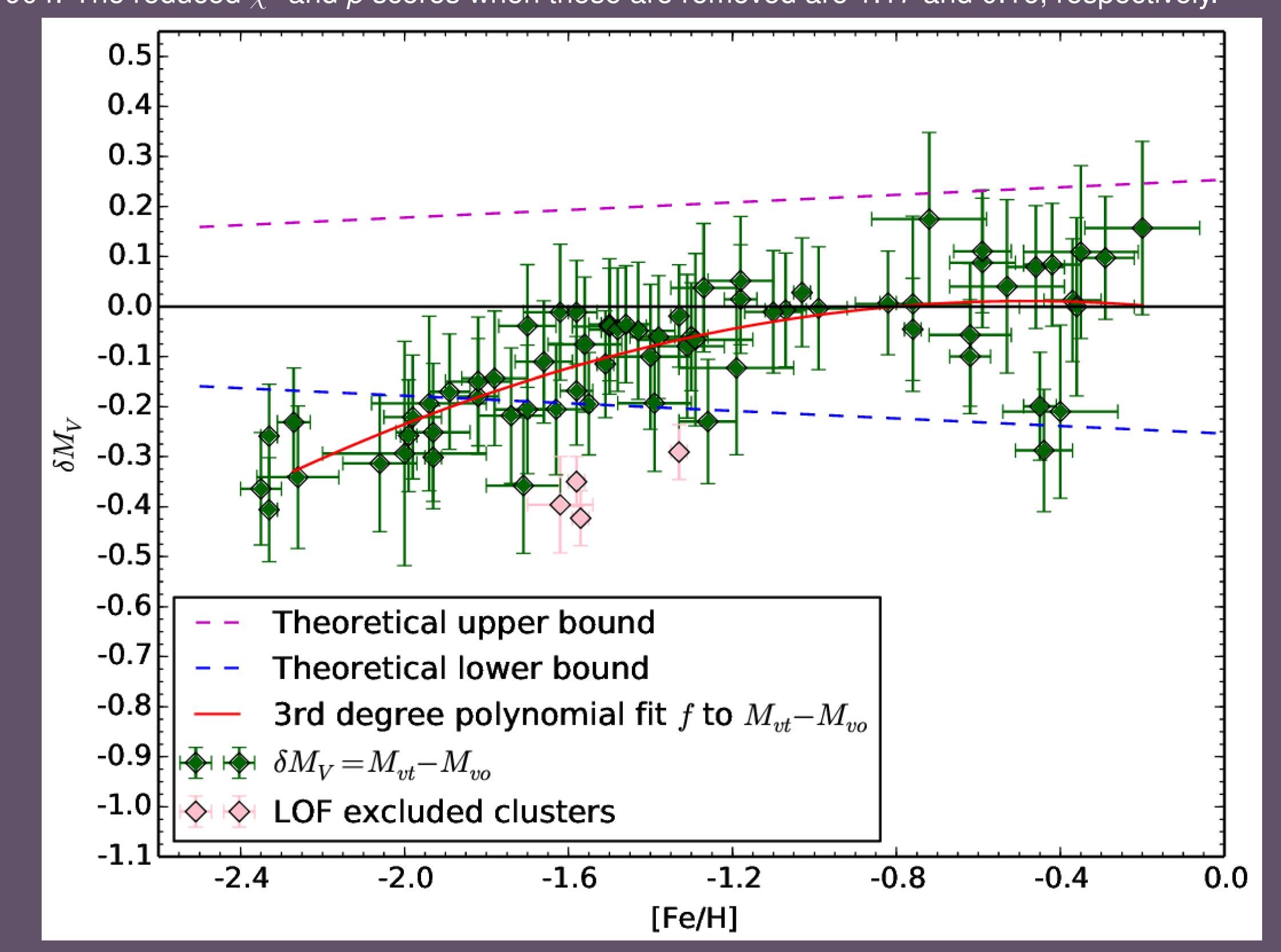
χ^2 Analysis using Kraft & Ivans Metallicity Scale

Sample	χ^2_R	p score	χ_i^2	GC removed	N2013	K8
0	1.59	0.01	-	_	-	
-1	1.37	0.06	10.01	NGC 6254	-1.57	-1.4
-2	1.27	0.12	5.13	NGC 6681	-1.62	-1.6
-3	1.18	0.21	4.75	NGC 6218	-1.33	-1.3
-4	1.12	0.28	3.26	NGC 6093	-1.75	-1.7

To test our results' dependence on uncertainty in metallicity, the reduced χ^2 scores are computed adopting the cluster metallicities reported in Kraft & Ivans. Clusters for which Kraft & Ivans metallicities were not available are removed from the N2013 sample, leaving 40 clusters total.

QUANTIFYING THE TREND

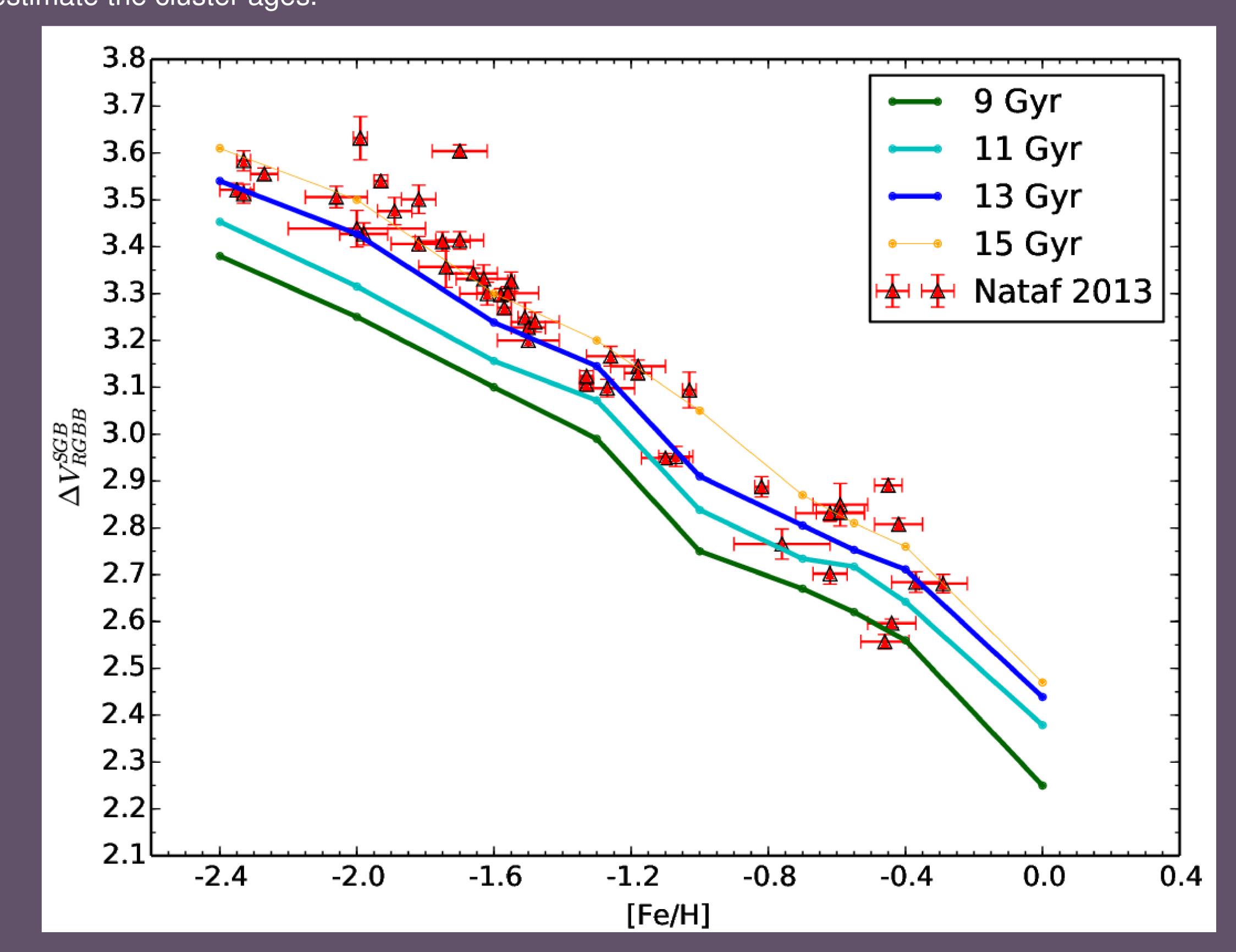
Anomalous vs Outlying We reserve the special designation of "anomalous cluster" for GCs that (1) do not not belong to the isolated cluster of 5 GCs in the lowest metallicity regime, but (2) still rank in the highest 10% for discrepancy as defined by either method. This leaves us with the clusters that are not impacted by the LOF routine's sampling issue and which are not subject to the model–dependent inflation of their χ_i^2 scores when DSEP's model is used as the baseline. What remains is a physically meaningful set of statistically aberrant clusters: NGCs 6254, 6681, 6218, and 1904. The reduced χ^2 and p scores when these are removed are 1.17 and 0.16, respectively.



We quantify the trend by fitting a cubic polynomial (red) to the magnitude differences. We exclude the four anomalous clusters (pink) from the calculation. Theoretical uncertainties from Bjork and Chaboyer 2006 (BC2006) are shown. Our model agrees with N2013's data over the metallicity range [Fe/H]=(0,-1.5) dex, but disagreement amplifies in the most metal—poor regime.

AGE ANALYSIS

We can remove the uncertainty imparted by using N2013's distance moduli by examining instead the difference in magnitude between the RGBB and subgiant branch (SGB). We use the MSTO colors reported by N2013 (available for 48 of 72 GCs) to estimate SGB magnitudes. We may then superimpose these 48 predicted ΔV s on a grid of DSEP isochrones ranging from 9 to 15 Gyr to estimate the cluster ages.



ACKNOWLEDGEMENTS

- This work is supported by grant AST-1211384 from the National Science Foundation.
- D. M. Nataf, A. P. Gould, M. H. Pinsonneault, and A. Udalski. *ApJ*, 766:77, April 2013.
- M. Joyce and B. Chaboyer. *ApJ*, 814:142, December 2015.
- Markus M. Breunig, Hans-Peter Kriegel, Raymond T. Ng, and Jörg Sander. *SIGMOD Rec.*, 29(2):93–104, May 2000. R. P. Kraft and I. I. Ivans. *PASP*, 115:143–169, February 2003.
- S. R. Bjork and B. Chaboyer. *ApJ*, 641:1102–1112, April 2006.
- Zoccali, M., Cassisi, S., Piotto, G., Bono, G., & Salaris, M. 1999, *ApJ Letters*, 518, L49