MNRAS **000**, 1–8 (2019) Preprint 5 March 2019 Compiled using MNRAS LaTeX style file v3.0

The Globular Cluster System of the Auriga Simulations

Timo L. R. Halbesma[1★], Robert J. J. Grand[1], Volker Springel[1], Facundo A. Gómez[2,3], Federico Marinacci[4,5], Rüdiger Pakmor[1], Wilma Trick[1], Philipp Busch[1], Simon D. M. White[1]

[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany*
[2] *Instituto de Investigación Multidisciplinar en Ciencia yTecnología, Universidad de La Serena, Raúl Bitrán 1305, La Serena, Chile*
[3] *Departamento de Física y Astronomía, Universidad de La Serena, Av. Juan Cisternas 1200 N, La Serena, Chile*
[4] *Department of Physics, Kavli Institute for Astrophysics and Space Research, MIT, Cambridge, MA 02139, USA*
[5] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Rob Grand: 'for many Auriga papers Carlos Frenk and Adrian Jenkins are offered co-authorship. Perhaps you could ask Simon about this.'

We investigate whether the galaxy formation model used for the Auriga simulations can produce a realistic globular cluster population at redshift zero. We compare properties of the simulated star particles in the Auriga haloes with catalogues of observations of the Milky Way globular cluster population available in the literature. We find that the Auriga simulations do produce sufficient mass at radii and metallicities that are typical for the MW GCS, although we observe a varying mass-excess for the different $R_{\rm GC}$-[Fe/H] bins. This implies different values for the combined product of the bound cluster formation efficiency and the globular cluster disruption rate. We investigate wether these differences could result from formation insitu vs. accreted star particles. We find ... TODO. Furthermore we test whether any of the Auriga galaxies has a metallicity and radial distribution that is consistent with the MW (M31) GCS. For all of the Auriga haloes we reject the null hypothesis that the simulated and observed metallicities are drawn from the same distribution at the 99.99% confidence level, for the GCS of the Milky Way as well as that of the Andromeda galaxy. The same holds true for the distribution of galactocentric radius.

Key words: methods: numerical – galaxies: formation – galaxies: star clusters: general.

1 INTRODUCTION

Paragraph: General introduction of GCs

Paragraph: scientific context / state of the field: briefly summarise previous work and references work of other groups

Paragraph, narrowing open questions in GC research down to formation, possibly "Bimodality suggests two formation mechanisms". In-situ formation vs. accretion in hierarchical build-up of galaxies naturally produces two populations of globular cluster.

Paragraph: narrow the scientific motivation down to the scope of this particular work

- The star formation model implemented in the Auriga simulations is capable of producing a suite/population of realistic Milky Way-like galaxies at redshift zero.
- Therefore the question naturally arises whether or not the Auriga simulations are also capable of faithfully producing a globular cluster population as observed in the Milky Way (or Andromeda).
- Globular cluster formation in cosmological zoom simulations is very interesting for two reasons. First of all, extragalactic observations typically show the integrated properties of globular clusters rather than that of the individual stars within the clusters. Moreover, the typical mass scale

★ E-mail: Halbesma@MPA-Garching.MPG.DE

of globular clusters is comparable to the numerical (mass) resolution of cosmological zoom simulations. The detailed small scale physics that is at play for real world globular clusters appears in observations as the combined effect of the 10^{3-6} M$_\odot$, compared to a mass resolution of 10^{3-5} M$_\odot$for the Auriga simulations. Globular clusters can therefore serve as an ultimate test to the star formation model that is implemented in the numerical simulations. Secondly, cosmological zoom simulations provide an accurate recording of the full and detailed merger history of the simulated galaxy. This is important because theoretical paradigms for globular cluster formation in the literature know two distinct classes of GCs that are separated by their exact formation sites: an in-situ versus an accreted population. Cosmological zoom simulations uniquely allow for an investigation into globular cluster formation with particular focus on the in-situ and accreted populations.

Paragraph: Paper outline

We summarise the relevant characteristics of the Auriga simulations in section 2, followed by a summary of the observations of the Milky Way (MW) globular cluster system (GCS) in section 3 that we use to compare our simulations to in section 4. We discuss our findings in section 5 to come to our conclusions in section 6.

2 THE AURIGA SIMULATIONS

We use the Auriga simulations (Grand et al. 2017, hereafter G17), a suite of high-resolution cosmological zoom simulations of Milky Way-mass selected initial conditions. The simulations are performed with the state-of-the art code AREPO (Springel 2010; Pakmor et al. 2016), that solves the magnetohydrodynamical equations on a moving mesh, and an elaborate galaxy formation model that produces realistic spiral galaxies at redshift $z = 0$.

The interstellar medium is modelled using a sub-grid approach which implements the physical processes most relevant to galaxy formation and evolution. This model was tailored to the AREPO code and calibrated to reproduce key observables of galaxies, such as the history of the cosmic star formation rate density, the stellar mass to halo mass relation, and galaxy luminosity functions.

The sub-grid includes primordial and metal-line cooling with self-shielding corrections. Reionization is completed at redshift six by a time-varying spatially uniform UV background (Faucher-Giguère et al. 2009; Vogelsberger et al. 2013) The interstellar medium is described by an equation of state for a two-phase medium in pressure equilibrium (Springel & Hernquist 2003) with stochastic star formation in thermally unstable gas with a density threshold of $n = 0.13\mathrm{cm}^{-3}$, and consecutive stellar evolution is accounted for. Stars provide feedback by stellar winds (Marinacci et al. 2014; Grand et al. 2017), and further enrich the ISM with metals from SNIa, SNII, and AGB stars (Vogelsberger et al. 2013). The formation of black holes is modelled which results in feedback from active galactic nuclei (Springel et al. 2005; Marinacci et al. 2014; Grand et al. 2017). Finally, the simulations follow the evolution of a magnetic field of 10^{-14} (comoving) G seeded at $z = 127$ (Pakmor & Springel 2013; Pakmor et al. 2014). See G17 for further details of the numerical setup as well as the galaxy formation model.

TODO: paraphrase "The diversity in morphological properties of these simulated galaxies reflects the stochasticity inherent to the process of galaxy formation and evolution (e.g. Bullock & Johnston 2005; Cooper et al. 2010; Tumlinson 2010)."

Paragraph about Auriga's stellar haloes. "The Auriga Stellar Haloes: Connecting stellar population properties with accretion and merging history" Monachesi et al. (2018)

3 RELEVANT OBSERVATIONAL DATA

We summarise relevant observations of the globular cluster system of the Milky Way in Sec. 3.1, and of Andromeda (M31) in Sec. 3.2.

3.1 Milky Way

Harris (1996, 2010 edition; hereafter H96e10) provides a catalogue[1] of the Milky Way globular cluster system that contains properties of 157 GCs. The authors initially estimated the size of the MW GCS to be 180 ± 10, thus, their catalogue to be ~85% complete. However, an additional 59 GCs have since been discovered by various authors. The total confirmed number of GCs in the MW adds up to 216 with new estimates now anticipating an additional thirty GCs yet to be discovered (e.g. Ryu & Lee 2018, and references therein).

Bica et al. (2019) communicate the latest efforts to aggregate the available data, presented in their CatClu catalog. Amongst 10978 star clusters and alike objects in the Milky Way, the catalog contains 200 GCs and 94 GC candidates. The CatClu catalog contains reference papers, positions, distances, and total absolute V magnitude. Therefore we rely on the H96e10 dataset for all other quantities, but we caution that the Harris catalogue is now believed to be (only) 53-72% complete.

Specifically, the relevant data fields that we use from H96e10 are the metallicity [Fe/H], the Galactic distance components X, Y, and Z (in kpc)[2], and absolute magnitude in the V-band M_V. We use the latter to calculate mass-estimates by assuming $M_{V,\odot} = 4.83$ and a mass to light ratio $M/L_V = 1.7$ M/L$_\odot$, the mean for MW clusters (McLaughlin & van der Marel 2005).

Age estimates

We supplement H96e10 with age-estimates from isochrone fits to stars near the main-sequence turnoff in 55 GCs (VandenBerg et al. 2013, hereafter V13). The mean value of the age-estimates in this data set is 11.9 ± 0.1 Gyr and the dispersion is 0.9 Gyr. Furthermore, only one of the 55 GC age-estimates is below 10 Gyr.

[1] See https://www.physics.mcmaster.ca/Fac_Harris/mwgc.dat

[2] In a Sun-centered coordinate system: X points toward Galactic center, Y in direction of Galactic rotation, and Z toward the North Galactic Pole. We calculate the galactocentric radius $R_{\mathrm{GC}} = \sqrt{(X - R_\odot)^2 + Y^2 + Z^2}$, assuming the solar radius $R_\odot = 8$ kpc.

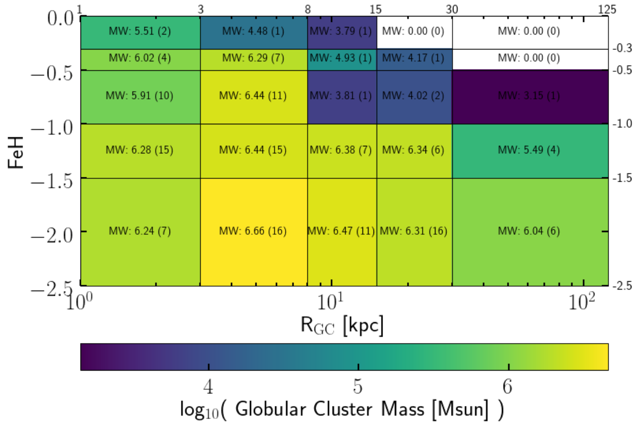

Figure 1. Mass-weighted r_{gc}-[Fe/H] distribution of 151 GCs in the MW (data from Harris 1996, 2010 ed.), which is 98.19 % of the total MW GCS mass in the Harris catalog.

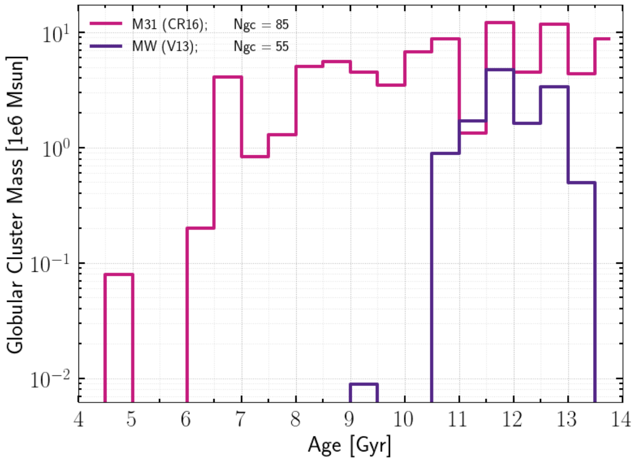

Figure 2. Mass-weighted age distribution of 55 GCs in the MW (data from VandenBerg et al. 2013) and 85 GCs in M31 (data from Caldwell & Romanowsky 2016).

Distribution of total GC mass in metallicity-radial bins

In Fig. 1 we show the two-dimensional mass-weighted metallicity-radial distribution of the MW GCS. In Sec. 4.3 we investigate whether the star formation model implemented in the Auriga simulations can produce sufficient total mass in GC candidates in the same bins.

3.2 Andromeda

The fifth revision of the revised bologna catalogue (RBC 5, last updated August, 2012) is the latest edition of three decades of systematically collecting integrated properties of the globular cluster system of the Andromeda galaxy (Galleti et al. 2004, and references therein). One contribution to RBC 5 is the work by Caldwell et al. (2011, hereafter C11), subsequently updated by Caldwell & Romanowsky (2016, hereafter CR16).

C11 and CR16 present a uniform set of spectroscopic observations calibrated on the Milky Way GCS of the inner 1.6° (~ 21) kpc that is believed to be 94% complete. GCs in the outer stellar halo, up to $R_{\rm proj}$ ~ 150 kpc, are observed in the Pan-Andromeda Archaeological Survey (PAndAS, Huxor et al. 2014, hereafter H14), but see also Veljanoski et al. (2014) and Mackey et al. (2019). H14 presents the discovery of 59 new GCs and publishes updates to RBC 5. The work of H14 is incorporated in the latest public release[3] of the C11 dataset, further revised by CR16. It seems that CR16 is the most recent aggregated dataset of M31's GCS that contains properties of interest for our study as it contains GCs in the inner region and in the outer halo. The relevant fields in the CR16 dataset that we use are the age, metallicity, and the mass-estimate[4].

[3] Last revised 23 Sep 2015, see `https://www.cfa.harvard.edu/oir/eg/m31clusters/M31_Hectospec.html`
[4] The authors assumed $M/L_V = 2$ (independent of [Fe/H])

Age estimates

For M31 we find an age distribution with a mean value of 10.8±10.8 Gyr and a dispersion of 2.3 Gyr. Furthermore, 27 GCs have age-estimates below 10 Gyr, and the minimum age is 4.8 Gyr.

We present a mass-weighted histogram of the age-estimates of the 55 MW GCs in V13 and 85 GCs in M31 for which age-estimates are available in CR16, see Fig. 2.

Calculation of galactocentric radius

The projected galacocentric radius $R_{\rm proj}$ is calculated following Wang et al. (2019, Sec. 4.1, eq. 4). Specifically,

$$X = A\sin(\mathrm{PA}) + B\cos(\mathrm{PA}) \quad \text{and}$$
$$Y = -A\cos(\mathrm{PA}) + B\sin(\mathrm{PA}), \tag{1}$$

where $A = \sin(\alpha-\alpha_0)\cos\delta$ and $B = \sin\delta\cos\delta_0 - \cos(\alpha-\alpha_0)\cos\delta\sin\delta_0$ for the right ascension α (hourangle) and declination δ (degree) of the GCs. For the central position of M31 we take the preferred position from the NASA Extragalactic Database[5] entry of M31: $(\alpha_0, \delta_0) = (0^{\rm h}42^{\rm m}44.35^{\rm s}, +41°16'08.63")$. The projected galactocentrid radius is calculated as $R_{\rm proj} = \sqrt{X^2+Y^2}$ (for X and Y in arcsec), and using the small angle approximation with a distance of $D_{\rm M31} = 778$ kpc to convert to kpc. TODO: McConnachie et al. 2005; Conn et al. 2012. Finally, we convert the projected distance ($R_{\rm proj}$) to an 'average deprojected distance' via the relationship $R_{\rm GC} = R_{\rm proj} \times (4/\pi)$.

4 RESULTS

We define GC candidates in the Auriga simulations as all star particles older than 10 Gyr based on the age distribution of the MW GCS in Fig. 2 and following Renaud et al. (2017).

Through out the analysis we use six sub sets of star

[5] `https://ned.ipac.caltech.edu/`

particles: *all stars*, and *old stars* (age > 10 Gyr, GC candidates hereafter). Both sub sets are further split up in (old) star particles that have formed *in-situ* (bound to the most-massive halo/subhalo in the first snapshot that the star particle was recorded), and (old) *accreted* star particles (i.e. those that have formed ex-situ and are bound to the most-massive halo/subhalo at $z = 0$).

In Sec. 4.1 we investigate the metallicity distribution of the GC candidates, in Sec. 4.2 we show the distribution of galactocentric radii of the globular cluster candidates within the Auriga simulations, and we combine both in Sec. 4.3.

4.1 Metallicity distribution

We investigate whether the star formation model implemented in the Auriga simulations is capable of producing sufficient mass in old star particles in each metallicity bin in comparison to the Milky Way and Andromeda globular cluster systems. In Fig. 3 we show a mass-weighted metallicity distribution where the lines show the median value of all thirty Auriga level 4 haloes for *all stars* (orange dotted), *old stars / GC candidates* (orange solid), *old in-situ* stars (blue solid), and *old accreted* stars (red solid). The shaded regions indicate the 1σ interval around the median (i.e. the scatter between runs with different initial conditions and merger histories). The MW (M31) GCS is shown in purple (magenta). We use the same bin sizes for the simulations as for the observations, explicitly shown for the observed profiles.

The peak of the distribution shifts down from [Fe/H] ~ 0.0 to ~ -0.6 for the *old stars* compared to *all stars* while the mass at the peak lowers by roughly one dex. Moreover, we find that the metallicity range $-3 <$ [Fe/H] < -1 is only populated by the GC candidates, while [Fe/H] > -1 is dominated by star particles younger than 10 Gyr. Furthermore, the *old accreted* sub set contributes most significantly to the range $-3 <$ [Fe/H] < -1, and the contribution of the *old in-situ* stars at these metallicities declines steeper with declining metallicity than the *old accreted* population. We note that the scatter between different Auriga haloes is much smaller than the difference between the MW and M31 GCSs. We conclude that old star particles in the Auriga simulation suite as a whole cannot be consistent with both the Milky Way and the Andromeda globular cluster system.

The middle (bottom) panel shows the ratio of the simulated mass to the mass in the MW (M31) GCS. We observe an increasing trend with increasing metallicity for the Milky Way over the entire range of the data, while the M31 GCS shows this increase only in the range [Fe/H]>-0.5 (although not for the *old accreted* component.

Furthermore we test the null hypothesis that the metallicity distribution of the MW (M31) GCS and the *old*, *old insitu*, and *old accreted* star particles in the Auriga simulations are drawn from the same underlying distribution. We calculate the two-sample Kolmogorov-Smirnov test statistic for all thirty Auriga level 4 haloes and reject the null hypothesis for every halo, for every sub set of star particles at least at the 99.99% confidence level. In addition, the null hypothesis that the metallicity distributions of the MW and M31 GCS are drawn from the same distribution is rejected at the 99.99997% confidence level.

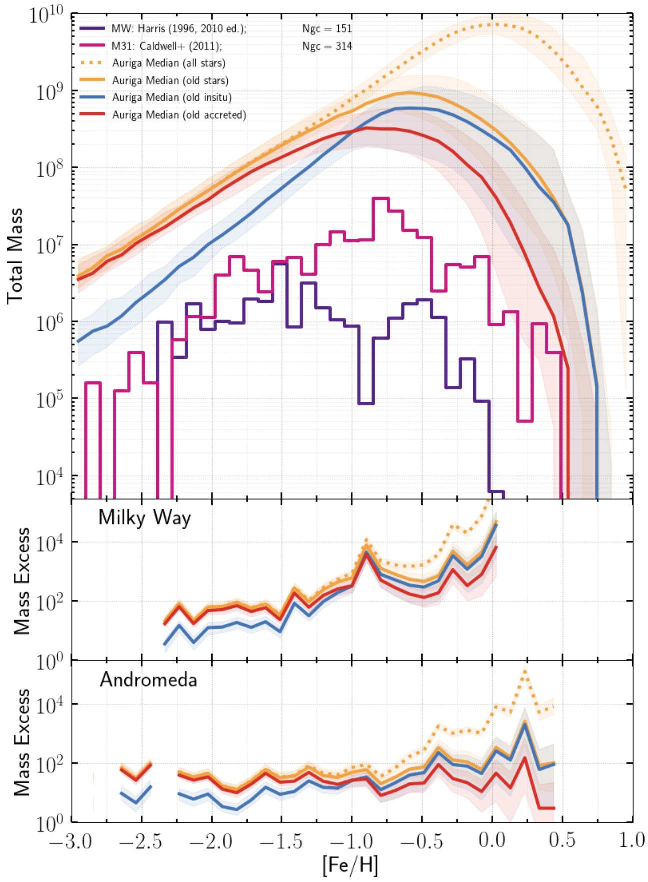

Figure 3. Mass-weighted metallicity distribution of star particles in the Auriga simulations. We show the median value of all Auriga haloes for all stars (orange dotted) and globular cluster candidates (i.e. stars with age > 10 Gyr; orange solid). The latter sub set is further split up between stars that formed in-situ (blue solid), and those that were accreted (red solid). Shaded regions indicate the 1σ interval. The MW (M31) GCS is shown in purple (magenta). The middle (bottom) panel shows the ratio of the simulated mass to the mass in the MW (M31) GCS.

4.2 Radial distribution

Somewhat arbitrarily, I will take the region $r_p > 3$ kpc (containing 75 clusters) as the fiducial Mikly Way sample. If we were to view the Mikly Way at the same inclination angle to the disk as we see M31, this cutoff in projected distance would correspond roughly to the inner distance limits in the M31 halo sample.

Is the spatial distribution of the GC candidates in the Auriga simulations consistent with the MW GCS?

4.3 Metallicity-radial distribution

What age-metallicity distribution is produced by star formation events in the Auriga simulations? ?

4.4 Metallicity-radial distribution: higher resolution

Do we even want this?

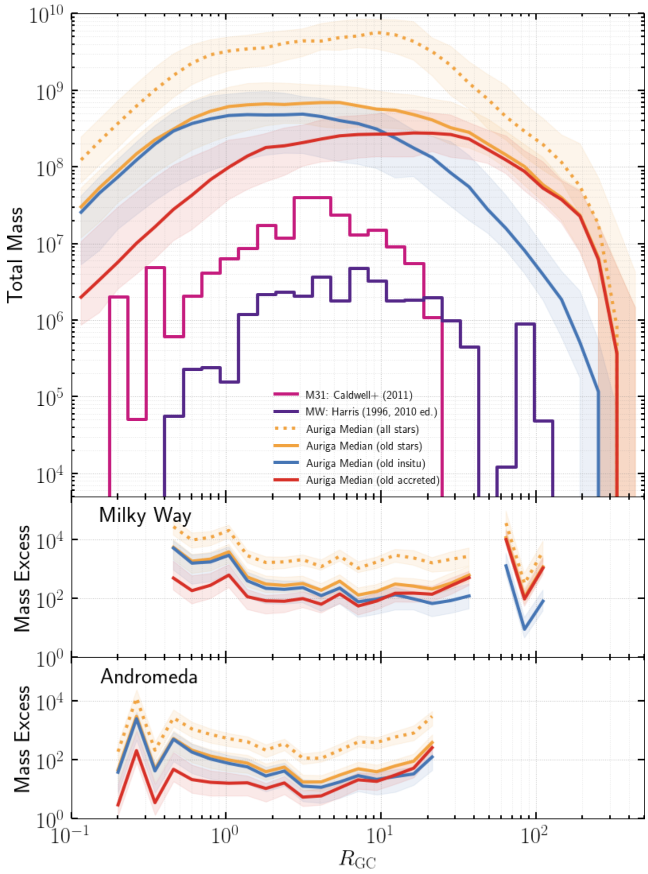

Figure 4. Mass-weighted distribution of (two-dimensional) galactocentric radii at which star particles in the Auriga simulations are found. For Andromeda we show the projected galactocentric radius, assuming its center is located at ($0^{\rm h}42^{\rm m}44.3^{\rm s}$, $+41°16'9''$) at a distance of 778 kpc.

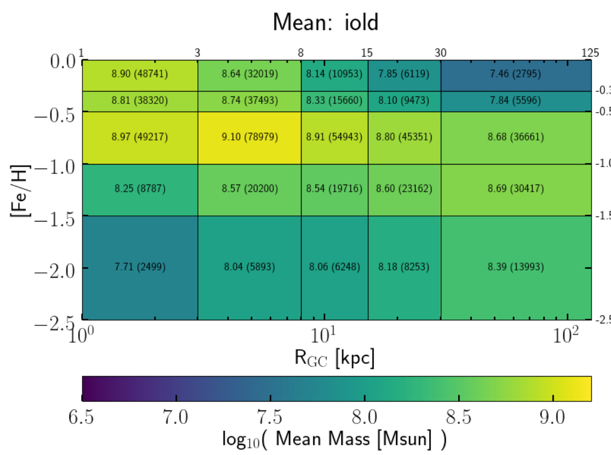

Figure 5. Mass-weighted [Fe/H]-$R_{\rm GC}$ distribution of all Auriga haloes (level 3, 4 and 5). Here we consider the old (> 10 Gyr) stars in all simulations and color-code the **mean value** (of 40 Auriga haloes)

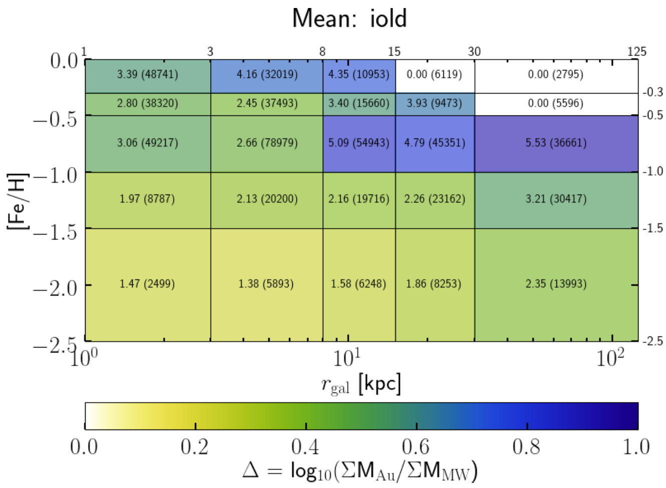

Figure 6. Ratio

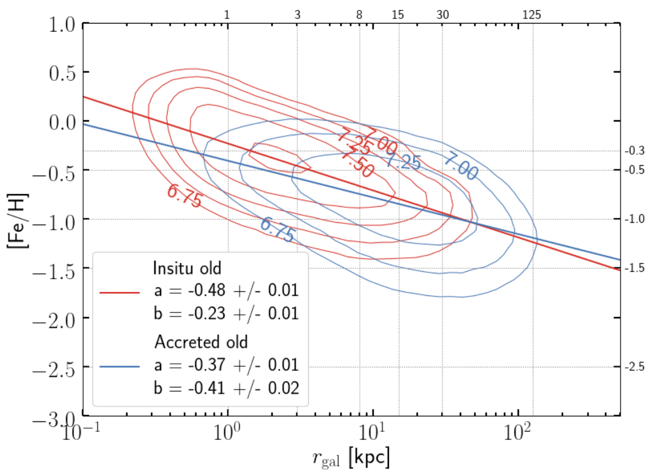

Figure 7. TODO: add 1σ interval around both relations, and flip x and y.

4.5 From star particles to globular clusters

Star particles are not globular clusters. Many stars do form in clusters, but not all clusters end up gravitationally bound. Star particles in the Auriga simulations represent single-age stellar populations that have formed at the same location within the galaxy. Therefore one could assume a model for the star cluster formation efficiency Γ, which could be used to 'convert' star particles to bound star clusters e.g. Kruijssen (2012). This model relies on the local birth properties of the star particles. However, in our analysis we can retrieve the properties of the star particle in the first snapshot it was recorded, but not the gas properties at times of birth. Therefore we are unable to model the formation of star clusters in more detail.

Furthermore, we compare star particles to present-day globular clusters, thereby ignoring the effects of (dynamical) disruption of globular clusters over nearly a Hubble time. As shown by Pfeffer et al. (2018), a detailed model of the tidal history of star clusters requires a temporal resolution of order mega year. For the Auriga level 4 simulations we have 128 snapshots for the age of the Universe, thus, a far too coarse temporal resolution for meaningful calculations.

Therefore we investigate the over-production of simulated mass in the metallicity and radial bins and use the term 'efficiency' to refer to the combined product of bound cluster formation and globular cluster disruption. In Fig. **??** we show the efficiencies that we find when we compare the simulations to the globular cluster systems of the Milky Way as well as that of Andromeda (M31).

4.6 Properties of birth haloes of the accreted population

Auriga galaxy /w 5 Myr snapshots.

4.7 Age-metallicity distribution

What age-metallicity distribution is produced by star formation events in the Auriga simulations?

4.8 Formation history

Can we identify particular star formation events that generate GC candidates with the correct age, metallicity, and radial properties as expected or the MW GCS?

Can we distinguish between particles that have formed in-situ and those that have been accreted? Can we identify specific features in the age-metallicity plane, or in the R_{GC}-[Fe/H] plane, that result from one of both populations? How does this connect to proposed mechanisms for globular cluster formation in the literature?

Orbits: are the pericentres different? Look at velocity + specific angular momentum distribution in the different FeH/Rgc bins as proxy for the pericenter

5 DISCUSSION

We investigate all star particles in the Auriga simulations that are older than 10 Gyr, an approach equal to the method of (Renaud et al. 2017). This approach does not take the bound cluster fraction (e.g. Kruijssen 2012) into account. This means that our sub set, which is based on selection by age, comprises both stars in the field as well as globular clusters. We compare the total mass in the simulations in metallicity ([Fe/H]), galactocentric radius R_{GC}, and [Fe/H]-R_{GC} bins to the total mass in the MW GCS (using the H96e10 data set). The mass excess in the simulations gives a maximum mass loss 'budget' for the product of cluster formation efficiency and dynamical evolution. We find fractions that vary with metallicity, radius and metallicity-and-radius.

"The fraction of all star formation that occurs in bound stellar clusters (the cluster formation efficiency, hereafter CFE) follows by integration of these local clustering and survival properties over the full density spectrum of the ISM, and hence is set by galaxy-scale physics. We derive the CFE as a function of observable galaxy properties, and find that it increases with the gas surface density" (Kruijssen 2012)

5.1 Age cut

Although the age distribution of M31 Perhaps an age cut of 6 Gyr would would be more appropriate for M31, see Fig. 2.

Caldwell & Romanowsky (2016) writes: "there are two broad, well-established differences: (1) the M31 GC system is more populous than the MW system, by a factor of ~2-3, and (2) it does not exhibit the same obvious bimodality in metallicity (Barmby et al. 2000; Galleti et al. 2009; Caldwell et al. 2011; Cezario et al. 2013). Both of these aspects may be reflections of dramatic differences discovered in these galaxies stellar halos, where the M31 halo appears much more metal-enriched, with massive substructures suggesting a more active satellite accretion history (e.g. McConnachie et al. 2009)"

6 SUMMARY AND CONCLUSIONS

ACKNOWLEDGEMENTS

TLRH acknowledges support from the International Max-Planck Research School (IMPRS) on Astrophysics.

Check Auriga boilerplate that we need to acknowledge

RG and VS acknowledge support by the DFG Research Centre SFB-881 'The Milky Way System' through project A1. This work has also been supported by the European Research Council under ERC-StG grant EXAGAL- 308037. Part of the simulations of this paper used the SuperMUC system at the Leibniz Computing Centre, Garching, under the project PR85JE of the Gauss Centre for Supercomputing. This work used the DiRAC Data Centric system at Durham University, operated by the Institute for Computational Cosmology on behalf of the STFC DiRAC HPC Facility 'www.dirac.ac.uk'. This equipment was funded by BIS National E-infrastructure capital grant ST/K00042X/1, STFC capital grant ST/H008519/1 and STFC DiRAC Operations grant ST/K003267/1 and Durham University. DiRAC is part of the UK National E-Infrastructure.

REFERENCES

Barmby P., Huchra J. P., Brodie J. P., Forbes D. A., Schroder L. L., Grillmair C. J., 2000, AJ, 119, 727
Bica E., Pavani D. B., Bonatto C. J., Lima E. F., 2019, AJ, 157, 12
Bullock J. S., Johnston K. V., 2005, ApJ, 635, 931
Caldwell N., Romanowsky A. J., 2016, ApJ, 824, 42
Caldwell N., Schiavon R., Morrison H., Rose J. A., Harding P., 2011, AJ, 141, 61
Cezario E., Coelho P. R. T., Alves-Brito A., Forbes D. A., Brodie J. P., 2013, A&A, 549, A60
Cooper A. P., et al., 2010, MNRAS, 406, 744
Faucher-Giguère C.-A., Lidz A., Zaldarriaga M., Hernquist L., 2009, ApJ, 703, 1416
Galleti S., Federici L., Bellazzini M., Fusi Pecci F., Macrina S., 2004, A&A, 416, 917
Galleti S., Bellazzini M., Buzzoni A., Federici L., Fusi Pecci F., 2009, A&A, 508, 1285
Grand R. J. J., et al., 2017, MNRAS, 467, 179
Harris W. E., 1996, AJ, 112, 1487
Huxor A. P., et al., 2014, MNRAS, 442, 2165
Kruijssen J. M. D., 2012, MNRAS, 426, 3008

Mackey A. D., et al., 2019, MNRAS, 484, 1756
Marinacci F., Pakmor R., Springel V., 2014, MNRAS, 437, 1750
McConnachie A. W., et al., 2009, Nature, 461, 66
McLaughlin D. E., van der Marel R. P., 2005, ApJS, 161, 304
Monachesi A., et al., 2018, preprint, (arXiv:1804.07798)
Pakmor R., Springel V., 2013, MNRAS, 432, 176
Pakmor R., Marinacci F., Springel V., 2014, ApJ, 783, L20
Pakmor R., Springel V., Bauer A., Mocz P., Munoz D. J., Ohlmann S. T., Schaal K., Zhu C., 2016, MNRAS, 455, 1134
Renaud F., Agertz O., Gieles M., 2017, MNRAS, 465, 3622
Ryu J., Lee M. G., 2018, ApJ, 863, L38
Springel V., 2010, MNRAS, 401, 791
Springel V., Hernquist L., 2003, MNRAS, 339, 289
Springel V., Di Matteo T., Hernquist L., 2005, MNRAS, 361, 776
Tumlinson J., 2010, ApJ, 708, 1398
VandenBerg D. A., Brogaard K., Leaman R., Casagrande L., 2013, ApJ, 775, 134
Veljanoski J., et al., 2014, MNRAS, 442, 2929
Vogelsberger M., Genel S., Sijacki D., Torrey P., Springel V., Hernquist L., 2013, MNRAS, 436, 3031
Wang S., Ma J., Liu J., 2019, arXiv e-prints

APPENDIX A: SCATTER BETWEEN INDIVIDUAL AURIGA HALOES, AND NUMERICAL CONVERGENCE

We check whether the properties of the Auriga globular cluster candidates are well converged between the three different resolution levels used for the Auriga simulations. Here we consider all three Auriga haloes for which simulation runs were performed at all three resolution levels: Au6, Au16, and Au24. Here we can investigate differences between individual haloes.

Fig. A1 shows the mass-weighted metallicity distribution, Fig. A2 shows the mass-weighted radial distribution, and Fig. **??**

This paper has been typeset from a TEX/LATEX file prepared by the author.

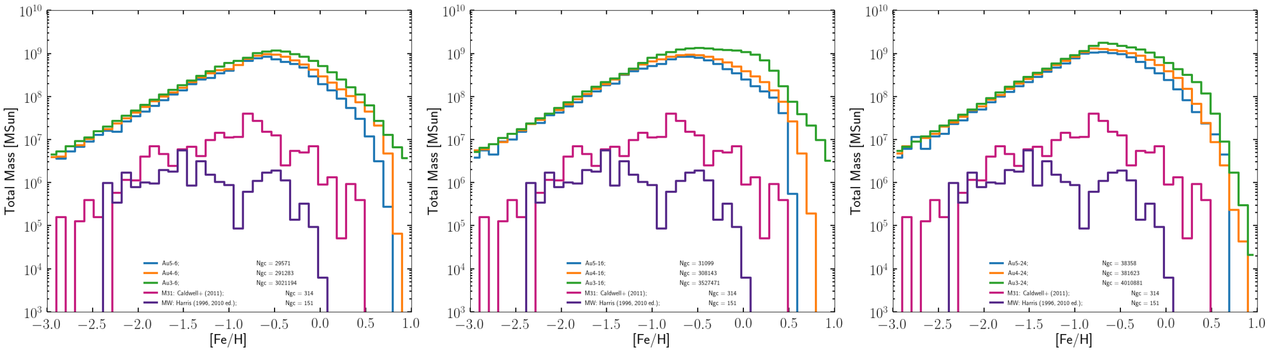

Figure A1. Same as Fig. 3, but here the colours indicate resolution level: L3 green, L4 orange, and L5 blue. *Left:* Auriga halo 6. *Mid:* Auriga halo 16. *Right:* Auriga halo 24. For all three haloes we find marginal increases in the mass normalization with increasing resolution level.

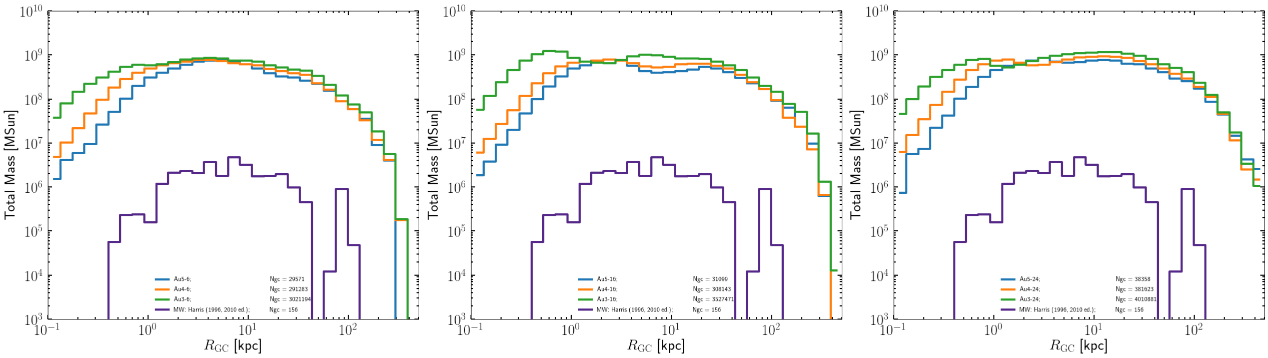

Figure A2. Same as Fig. 4, but here the colours indicate resolution level: L3 green, L4 orange, and L5 blue. *Left:* Auriga halo 6. *Mid:* Auriga halo 16. *Right:* Auriga halo 24. For all three haloes we find marginal increases in the mass normalization with increasing resolution level.