MNRAS 000, 1–6 (2019) Preprint 6 January 2019 Compiled using MNRAS LaTeX style file v3.0

The Globular Cluster System of the Auriga Simulations

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

[1] Max-Planck-Institut für Astrophysik, Postfach 1317, D-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
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 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 ...

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

1 INTRODUCTION

Paragraph: General introduction of GCs

Diemand et al. (2005): "The radial profile of the stellar halo and metal-poor globular clusters of the Milky Way suggest that these components formed in rare early peaks above 2.5σ at redshift above 10. "

Renaud et al. (2017): "GCs among oldest astrophysical objects. GCs form in the early Universe in highest density peaks (e.g. Diemand et al. 2005; Boley et al. 2009)"

- "Hence, they witness most of the formation and evolution processes of galaxies, and can be used to probe them" (Brodie & Strader 2006)
- "colour bimodality, blue and red clusters (e.g. Zinn 1985; Gebhardt & Kissler-Patig 1999; Larsen et al. 2001; Peng et al. 2006)
- "blue metal-poor (with distribution peaking at [Fe/H] ≈ -1.5 for the Milky Way), no sign of rotation as a population (..) more metal-rich (peak at [Fe/H] ≈ -0.5 in the Milky Way) more spatially concentrated and rotating with the galaxy." (Harris 1996)

Paragraph: "Bimodality suggests two formation mechanisms". In-situ vs. Accreted

- "Blue clusters from in early Universe in galaxies that merge later. In (wet) merger process starbursts generate red population Ashman & Zepf (1992); Schweizer (1987)"
- "Forbes et al. (1997) propose instead that blue globulars form when the protogalaxy itself collapses, in a metal-poor and turbulence media. The red population would form later, once the galactic disc has settled. The formation of globular clusters would then be a multiphase process, with the first phase being interrupted possibly by cosmic reionization (Beasley et al. 2002)."
- "Kravtsov & Gnedin (2005); Li & Gnedin (2014) advocate that major mergers are at the origin of both sub-populations: blue clusters form during early mergers (z > 4) while the red ones appear in mergers at lower redshifts (even after z = 1). Although, this scenario, combined with star formation enhancement in mergers, seems appropriate in dense galactic environment leading to the assembly of massive elliptical galaxies, like in the Virgo Cluster as tested by Li & Gnedin (2014), it does not apply to Milky Way-like systems where no recent major merger took place (Wyse 2001; Deason et al. 2013; Ruchti et al. 2014, 2015).
- "Côté et al. (1998) argue that red clusters form in situ while the blue ones are accreted, either via merging satellite galaxies, or by tidal capture of the clusters themselves (see also Tonini 2013)."

Dark Matter - GC connection

Paragraph: scientific motivation

- The star formation model implemented in the Auriga simula-

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

tions is capable of producing a suite/population of realistic Milky Way-like galaxies at redshift zero.

- (However) State of the art simulations still face numerical restrictions that requires a subgrid approach to star formation and feedback because individual stars (and their evolution) cannot yet be accounted for. Star formation thus occurs in a heuristic/probabilistic fashion for gas cells that fulfill some star formation criterion. The star particles enrich the gas with metals and energy, both according to pre-defined/pre-calculated yields for specific feedback processes (supernova type I and II, strong stellar winds of asymptotic giant branch stars,). In addition, black holes are seeded in eligible haloes to account for feedback associated with an active galactic nucleus.
- The end-result of the star formation model is the production of simulated Milky Way-like galaxies. 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.
- 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 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 are uniquely allow for an investigation into globular cluster formation with particular focus on the in-situ and accreted populations.

Paragraph: previous work / work of other groups

This goes before the GC formation mechanism paragraph.

- Origin of the Milky Way globular clusters (Renaud et al. 2017)
- GCs in FIRE (Kim et al. 2018)
- EMOSAICS project (Pfeffer et al. 2018)
- Origin of GC bimodality? (Fernandez & Bryan 2018)
- *GAIA* DR2: GC kinematics (Gaia Collaboration et al. 2018), Dating GC Tidal Disruption (Bose et al. 2018)
- GC in N-body simulation (Carlberg 2018)
- Tangentially related? role of GC mass evolution on stream properties (Balbinot & Gieles 2018)
- GC formation from dwarfs to giants (Choksi et al. 2018)
- GC contribution to EOR (Boylan-Kolchin 2018)
- Early Universe supermassive star / GC formation (Gieles et al. 2018)
- GC formation in cold filaments (Mandelker et al. 2018)
- GC formation in high-redshift dwarf galaxies (Zick et al. 2018)
- GCs in MW outer region (Peebles 2017)
- Impact of the Cutoff of the Cluster Initial Mass Function (Choksi & Gnedin 2018)
- Metallicity gradients in the globular cluster systems of early-type galaxies: in situ and accreted components (Forbes & Remus 2018)
- Globular clusters in M31, Local Group, and external galaxies (Larsen 2016)
- Globular Clusters Formed within Dark Halos I: present-day abundance, distribution and kinematics (Creasey et al. 2019)
- The mass of the Milky Way from satellite dynamics (Callingham et al. 2018)
- Globular cluster formation and evolution in the context of cosmological galaxy assembly: open questions (Forbes et al. 2018)
- The kinematics of globular clusters systems in the outer halos of the Aquarius simulations (Veljanoski & Helmi 2016)
- Star Cluster Formation in Cosmological Simulations (Li et al. 2017, 2018; Li & Gnedin 2018)
- A systematic analysis of star cluster disruption by tidal shocks – I. Controlled N-body simulations and a new theoretical model (Webb et al. 2018)
- Spatial mixing of binary stars in multiple-population globular clusters (Hong et al. 2018)
- Star Clusters Across Cosmic Time (Krumholz et al. 2018)
- Kinematics of Subclusters in Star Cluster Complexes: Imprint of their Parental Molecular Clouds (Fujii 2018)
- Investigating the population of Galactic star formation regions and star clusters within a Wide-Fast-Deep Coverage of the Galactic Plane (Prisinzano et al. 2018)

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 (Grand et al. 2017, hereafter G17) simulations, a suite of high-resolution cosmological zoom simulations ran with a galaxy formation model that produces realistic Milky Way-like galaxies at redshift $z = 0$. The simulations are performed with AREPO (Springel 2010; Pakmor et al. 2016) that solves the magneto-hydrodynamical equations on a moving mesh. See G17 for further details; here we briefly summarise the relevant properties.

Paragraph: Auriga boilerplate, paraphrased

“The simulations include a comprehensive model for galaxy formation physics which includes important baryonic processes, such as

primordial and metal-line cooling (Vogelsberger et al. 2013);

a sub-grid model for the interstellar medium that utilises an equation of state representing a two-phase medium in pressure equilibrium (Springel & Hernquist 2003) u a model for the star formation and stellar feedback that includes a phenomenological wind model (Marinacci et al. 2014; Grand et al. 2017)

and metal enrichment from SNII, SNIa and AGB stars (Vogelsberger et al. 2013)

black hole formation and active galactic nucleus feedback ((Springel et al. 2005; Marinacci et al. 2014; Grand et al. 2017)

a spatially uniform, time-varying UV background after reionization at redshift six (Faucher-Giguère et al. 2009; Vogelsberger et al. 2013)

and magnetic fields (Pakmor & Springel 2013; Pakmor et al. 2014)

The model was specifically developed for the AREPO code and was calibrated to reproduce several observational results such as the stellar mass to halo mass relation, galaxy luminosity functions and the history of the cosmic star formation rate density. "

What is the star formation density threshold?

"The gas is assumed to be star-forming and thermally unstable for densities higher than a threshold density that we derive from the parameters of the two gas phases and the desired star formation time-scale to be $n = 0.13\mathrm{cm}^{-3}$." - (Grand et al. 2017)

‘

‘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)."

2.1 Definition of stellar halo

Possibly also relevant here. See Monachesi et al. (2018).

2.2 Definition of accreted and in-situ component

Possibly also relevant here. See Monachesi et al. (2018).

3 RELEVANT OBSERVATIONAL DATA FOR LOCAL GROUP SPIRALS

The Milky Way + M31 globular cluster system

3.1 Harris catalogue

Harris (1996, 2010 edition, H96) provides the most up-to-date and comprehensive catalog of the MW GCS that contains properties of 157 globular clusters. The catalogue is believed to be roughly 90% complete.

3.2 Age estimates

VandenBerg et al. (2013, V13) measured [Fe/H] and obtained age-estimates for 55 globular clusters in the MW GCS.

How is this particular sample selected? What biases does this introduce? Is this sample drawn from the same underlying distribution as the Harris sample (plot distributions of FeH, compare mean/std, do t-test)

3.3 M31

Get big dataset of M31 GCS

(Caldwell et al. 2011, C11) (Huxor et al. 2014; Veljanoski et al. 2014)

4 RESULTS

VandenBerg et al. (2013) presents observations of 55 GCs in the MW with age-estimates where the mean value is 11.9 ± 0.1 Gyr with a dispersion of 0.8 Gyr. Therefore we investigate the subset of star particles in the Auriga simulations that formed before a lookback time of 10 Gyr. Henceforth we will refer the this subset of star particles as ‘GC candidates’.

4.1 Metallicity distribution

Can the Auriga simulations produce star particles of > 10 Gyr (GC candidates) with a metallicity distribution that is consistent with the MW GCS?

Fig. 1

Split into insitu / accreted

Conclusion: too many metal-rich star particles.

4.2 Spatial distribution

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

Look into Pandromeda survey? Star counts, very wide angle survey

4.3 Age-metallicity distribution

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

4.4 Mass budget

Does the star formation model implemented in the Auriga simulations produce sufficient mass in star particles with properties that are consistent with the MW GCS?

What efficiencies could we afford if we would take into account the combined mass loss effect of converting from star particles to bound star clusters and globular cluster disruption?

How does the total stellar mass in R_{GC}-[Fe/H] bins compare to the MW GCS?

4.5 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

4.6 Scatter for different Auriga haloes

Are the properties of the Auriga globular cluster candidates converged for runs with different initial conditions but at the same resolution level? How much scatter do we observe in the properties of the globular cluster candidates across the full suite of Auriga haloes?

4.7 Numerical convergence (possibly in appendix)

Are the properties of the Auriga globular cluster candidates converged for runs with the same initial conditions but at different resolution levels?

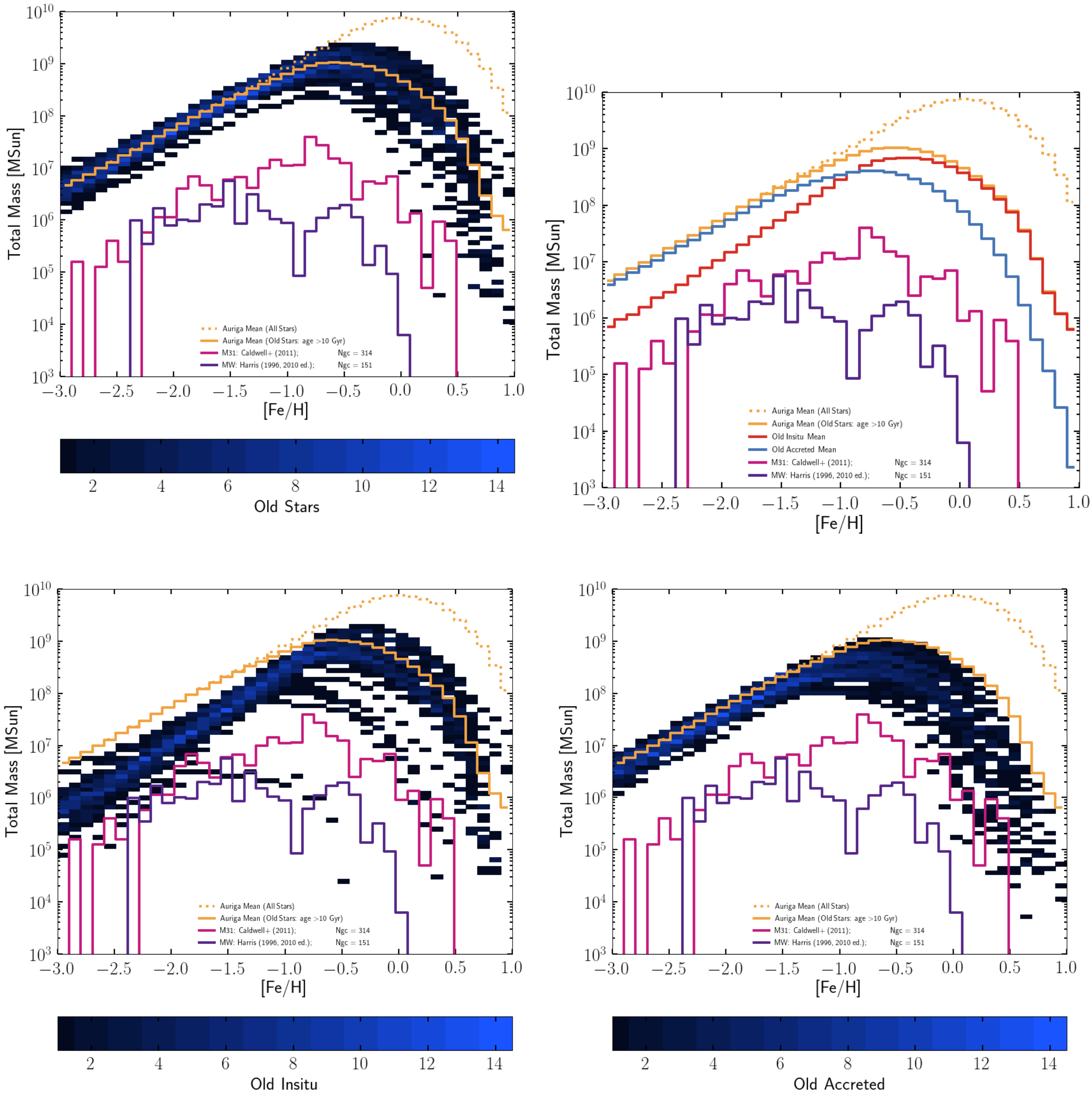

Figure 1. Caption

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 $r_{\rm gc}$, and [Fe/H]-$r_{\rm gal}$ bins to the total mass in the MW GCS (using the H96 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.

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

“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

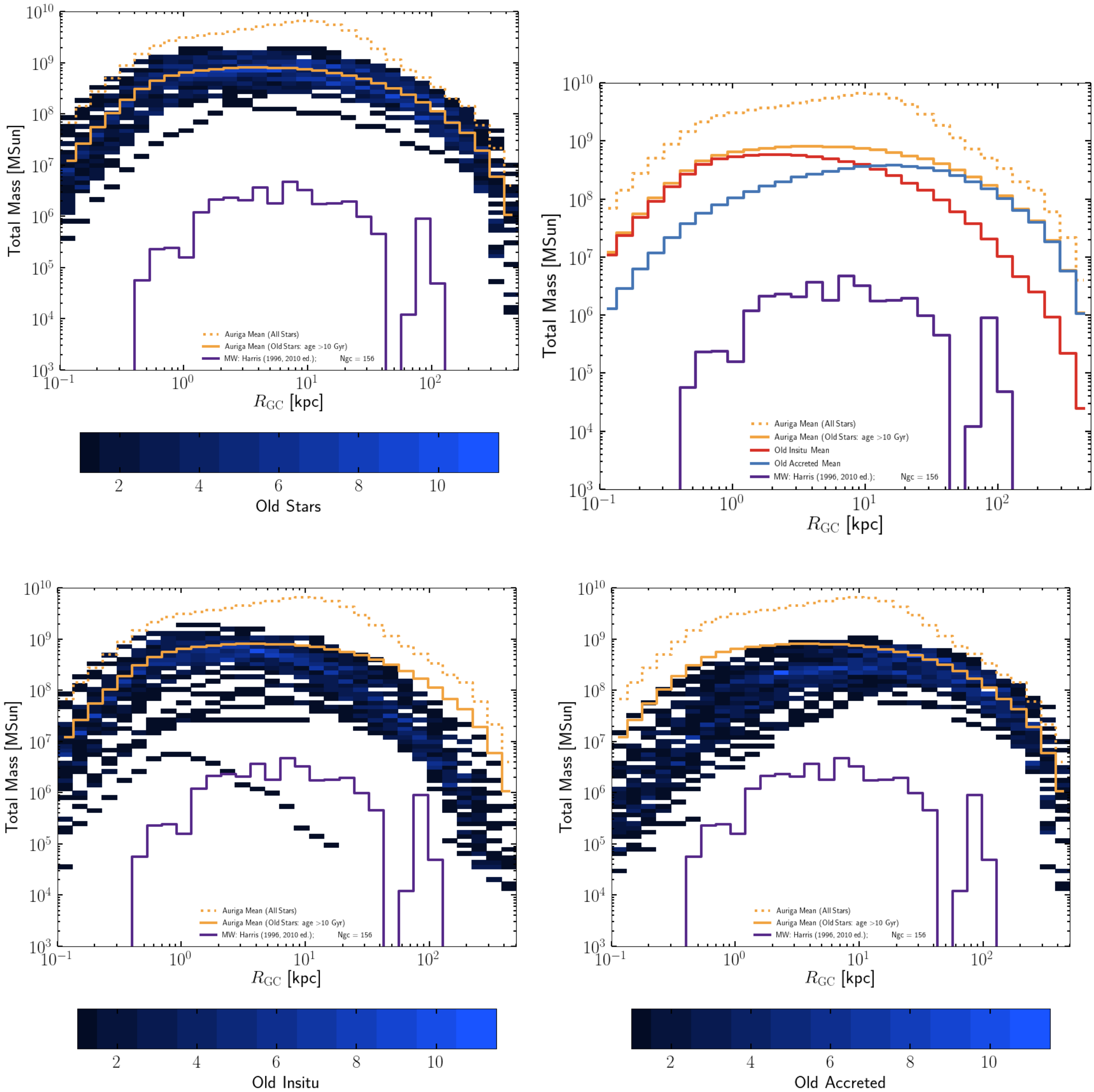

Figure 2. Caption

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

Ashman K. M., Zepf S. E., 1992, ApJ, 384, 50
Balbinot E., Gieles M., 2018, MNRAS, 474, 2479
Beasley M. A., Baugh C. M., Forbes D. A., Sharples R. M., Frenk C. S., 2002, MNRAS, 333, 383
Boley A. C., Lake G., Read J., Teyssier R., 2009, ApJ, 706, L192
Bose S., Ginsburg I., Loeb A., 2018, ApJ, 859, L13
Boylan-Kolchin M., 2018, MNRAS, 479, 332
Brodie J. P., Strader J., 2006, ARA&A, 44, 193
Bullock J. S., Johnston K. V., 2005, ApJ, 635, 931
Caldwell N., Schiavon R., Morrison H., Rose J. A., Harding P., 2011, AJ, 141, 61
Callingham T., et al., 2018, arXiv e-prints,
Carlberg R. G., 2018, ApJ, 861, 69

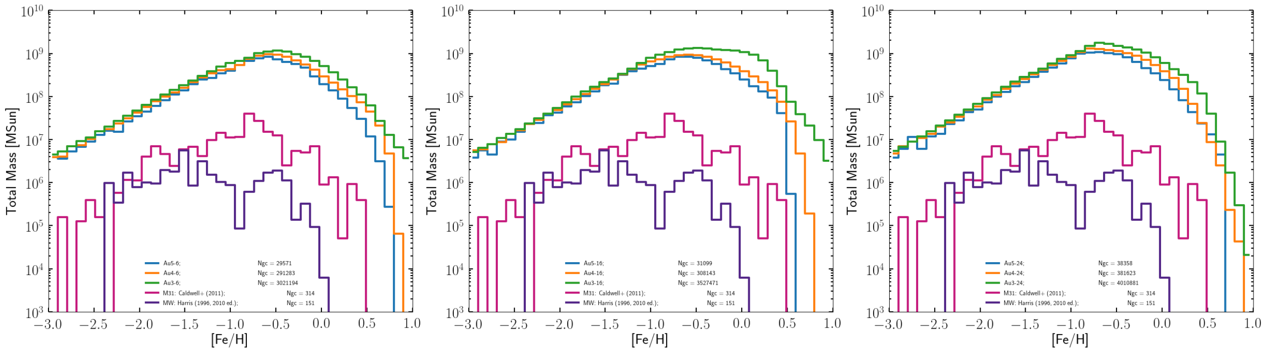

Figure 3. Caption

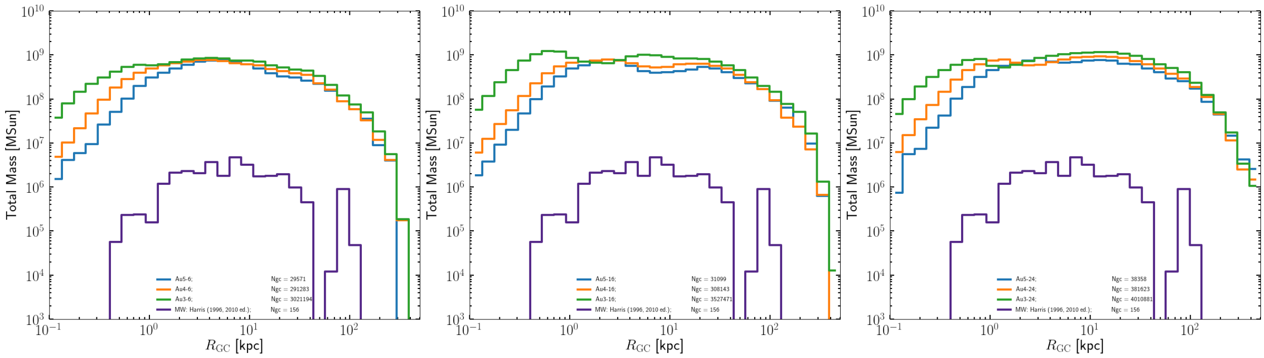

Figure 4. Caption

Choksi N., Gnedin O. Y., 2018, arXiv e-prints,

Choksi N., Gnedin O. Y., Li H., 2018, MNRAS, 480, 2343

Cooper A. P., et al., 2010, MNRAS, 406, 744

Côté P., Marzke R. O., West M. J., 1998, ApJ, 501, 554

Creasey P., Sales L. V., Peng E. W., Sameie O., 2019, MNRAS, 482, 219

Diemand J., Madau P., Moore B., 2005, MNRAS, 364, 367

Faucher-Giguère C.-A., Lidz A., Zaldarriaga M., Hernquist L., 2009, ApJ, 703, 1416

Fernandez R., Bryan G. L., 2018, MNRAS, 479, 200

Forbes D. A., Remus R.-S., 2018, MNRAS, 479, 4760

Forbes D. A., Brodie J. P., Grillmair C. J., 1997, AJ, 113, 1652

Forbes D. A., et al., 2018, Proceedings of the Royal Society of London Series A, 474, 20170616

Fujii M. S., 2018, arXiv e-prints, p. arXiv:1812.01858

Gaia Collaboration et al., 2018, A&A, 616, A12

Gebhardt K., Kissler-Patig M., 1999, AJ, 118, 1526

Gieles M., et al., 2018, MNRAS, 478, 2461

Grand R. J. J., et al., 2017, MNRAS, 467, 179

Harris W. E., 1996, AJ, 112, 1487

Hong J., Patel S., Vesperini E., Webb J. J., Dalessandro E., 2018, MNRAS, p. 3147

Huxor A. P., et al., 2014, MNRAS, 442, 2165

Kim J.-h., et al., 2018, MNRAS, 474, 4232

Kravtsov A. V., Gnedin O. Y., 2005, ApJ, 623, 650

Kruijssen J. M. D., 2012, MNRAS, 426, 3008

Krumholz M. R., McKee C. F., Bland-Hawthorn J., 2018, arXiv e-prints, p. arXiv:1812.01615

Larsen S. S., 2016, in Bragaglia A., Arnaboldi M., Rejkuba M., Romano D., eds, IAU Symposium Vol. 317, The General Assembly of Galaxy Halos: Structure, Origin and Evolution. pp 120–127, doi:10.1017/S1743921315006821

Larsen S. S., Brodie J. P., Huchra J. P., Forbes D. A., Grillmair C. J., 2001, AJ, 121, 2974

Li H., Gnedin O. Y., 2014, ApJ, 796, 10

Li H., Gnedin O. Y., 2018, preprint, (arXiv:1810.11036)

Li H., Gnedin O. Y., Gnedin N. Y., Meng X., Semenov V. A., Kravtsov A. V., 2017, ApJ, 834, 69

Li H., Gnedin O. Y., Gnedin N. Y., 2018, ApJ, 861, 107

Mandelker N., van Dokkum P. G., Brodie J. P., van den Bosch F. C., Ceverino D., 2018, ApJ, 861, 148

Marinacci F., Pakmor R., Springel V., 2014, MNRAS, 437, 1750

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

Peebles P. J. E., 2017, preprint, (arXiv:1708.04542)

Peng E. W., et al., 2006, ApJ, 639, 95

Pfeffer J., Kruijssen J. M. D., Crain R. A., Bastian N., 2018, MNRAS, 475, 4309

Prisinzano L., et al., 2018, arXiv e-prints, p. arXiv:1812.03025

Renaud F., Agertz O., Gieles M., 2017, MNRAS, 465, 3622

Schweizer F., 1987, in Faber S. M., ed., Nearly Normal Galaxies. From the Planck Time to the Present. pp 18–25

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

Tonini C., 2013, ApJ, 762, 39

Tumlinson J., 2010, ApJ, 708, 1398

VandenBerg D. A., Brogaard K., Leaman R., Casagrande L., 2013, ApJ, 775, 134

Veljanoski J., Helmi A., 2016, A&A, 592, A55

Veljanoski J., et al., 2014, MNRAS, 442, 2929

Vogelsberger M., Genel S., Sijacki D., Torrey P., Springel V., Hernquist L., 2013, MNRAS, 436, 3031

Webb J. J., Reina-Campos M., Kruijssen J. M. D., 2018, arXiv e-prints, p. arXiv:1812.00014

Zick T. O., Weisz D. R., Boylan-Kolchin M., 2018, MNRAS, 477, 480

Zinn R., 1985, ApJ, 293, 424

APPENDIX A: SOME EXTRA MATERIAL

If you want to present additional material which would interrupt the flow of the main paper, it can be placed in an Appendix which appears after the list of references.

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