

Evidence of a massive accretion event 1.8 billion years before the Gaia-Sausage- Enceladus merger

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Supplementary information

Historical accounting of accreted and in-situ populations in the inner Galaxy

With our findings, we unequivocally demonstrate that a population of accreted tracers exists in the inner galaxy. Such a population bears chronological properties that set it apart from the *in-situ* population even in the metal-poor regime, and is at the same time distinct from other accreted components.

In this context, we are also in the position to clarify the confusion existing in the literature about the plethora of accreted substructures in the inner Galaxy, which can be summarized as follows. Kruijssen et al. 2019¹ used a sample of GCs selected as accreted based on their location in the AMR^{2,3} to postulate the presence of three different merger events in the MW halo. These were deemed to be Sagittarius, Canis Major and a yet unknown one, named Kraken. Now that we have a better understanding of the MW assembly history, we know that while Sagittarius was obviously a correct identification, Canis Major does not exist⁴ and the majority of the GCs associated to it are actually members of GSE. The remaining clusters were used as an argument to predict the existence of the third merger, Kraken. We now know^{5,6} that the GCs tentatively associated with Kraken also include members of GSE, Sequoia,⁷ the Helmi Streams,⁸ and the MW. Therefore, the original definition of Kraken is an (implausible) ensemble gathering everything that is neither Sagittarius nor GSE. Furthermore, using the EAGLE simulations, a mass of $M_{\star} \sim 2 \times 10^9 M_{\odot}$ was estimated for the merger, significantly larger than what we have inferred here for LKH. The generous definition, coupled with the details of the comparison with the EAGLE cosmological simulations, might explain the discrepancy in the estimated masses.

Soon after Massari et al. 2019⁵ identified a group of about 20 GCs with coherent dynamical properties and which were not associated with any known merger (they also associated GCs with GSE, Sagittarius, Sequoia and the Helmi streams). They proposed that this “Low-energy” group of GCs might have been the debris of an unknown accretion event. Kruijssen et al. 2020⁹ adjusted the definition of Kraken to match that of this “Low-energy” group. Since we demonstrate here that most of the “Low-energy” group GCs are effectively tracing LKH, it is not surprising that the revised estimated properties⁹ for Kraken are similar to the ones we find here for LKH. Although the accreted origin of the “Low-energy” GCs, was supported later through other analyses,⁶ it has been challenged by other works^{10,11} using chemo-dynamical arguments. These works have argued that the enhanced [Al/Fe] of the GCs favours an in-situ origin, since one might expect for stars from accreted galaxies¹² that $[Al/Fe] < 0$. Noteworthy is that even if one removes the effect of multiple populations which induce a scatter in [Al/Fe], the first generation of stars in globular clusters associated with GSE also have $[Al/Fe] > 0$, as do the (extra-galactic) metal-poor globular clusters in the LMC.¹³ This demonstrates that

[Al/Fe] should not be used¹⁴ as an indicator of an accreted or *in-situ* origin for GCs.

Another structure that has been proposed to occupy the inner Galaxy is Heracles.¹² The Heracles system is composed of stars with dynamical properties similar to the “Low-energy” group GCs, and with chemical properties that confine them in the unevolved region of the [Mg/Mn] vs [Al/Fe] plane.¹⁵ This chemo-dynamical selection of Heracles stars, although effective for $[\text{Fe}/\text{H}] > -1.6$, is not able to distinguish the accreted from the in-situ component in the metal-poor regime, which is the one probed by GCs in this work. Based on our findings, the progenitor characterized here enters the definition of Heracles, as part of the accreted population of tracers now located in the inner halo (within ~ 6 kpc). More precisely, the one described here is the cleanest definition of this merger event. As shown in many works,^{16, 17, 18} the early life of a galaxy like the Milky Way is characterized by many merger events, the majority of which of too low mass to host GCs. In this sense, by working with GCs as tracers, we are effectively filtering the progenitors to which we are sensitive in mass. As a result, our analysis is selecting a progenitor that is massive enough to host a system of GCs. The chemo-dynamically selected Heracles, instead, includes the entire population of early mergers experienced by the Milky Way.

This interpretation agrees with the fact that the mass of LKH is nominally slightly lower than the mass of the Heracles “composite population”, though still consistent within the uncertainties.¹² In fact, a lower limit on its total stellar mass, estimated by only considering unevolved stars with $-1.5 < [\text{Fe}/\text{H}] < -1.0$, is $M_{\star} \simeq 7.2 \times 10^8 M_{\odot}$.¹⁹ This is larger by about a factor of 1.5 compared to our estimate for LKH, but could be off by a larger factor given that the vast majority of LKH GCs have $[\text{M}/\text{H}] < -1.4$ ($[\text{Fe}/\text{H}] \lesssim -1.7$) and are not included in the mentioned Heracles selection.

Finally we note that if some of the LKH GCs (as well as those associated with the other progenitors) have been disrupted, this implies that the currently observed AMR is less-populated than it originally was, and that its original shape might have been slightly altered by this effect. However, this is unlikely to affect the clear separation of LKH’s AMR from that of the other two massive progenitors that populate the inner Galaxy,²⁰ although it might have a small impact on the associations of individual GCs to the various sequences.

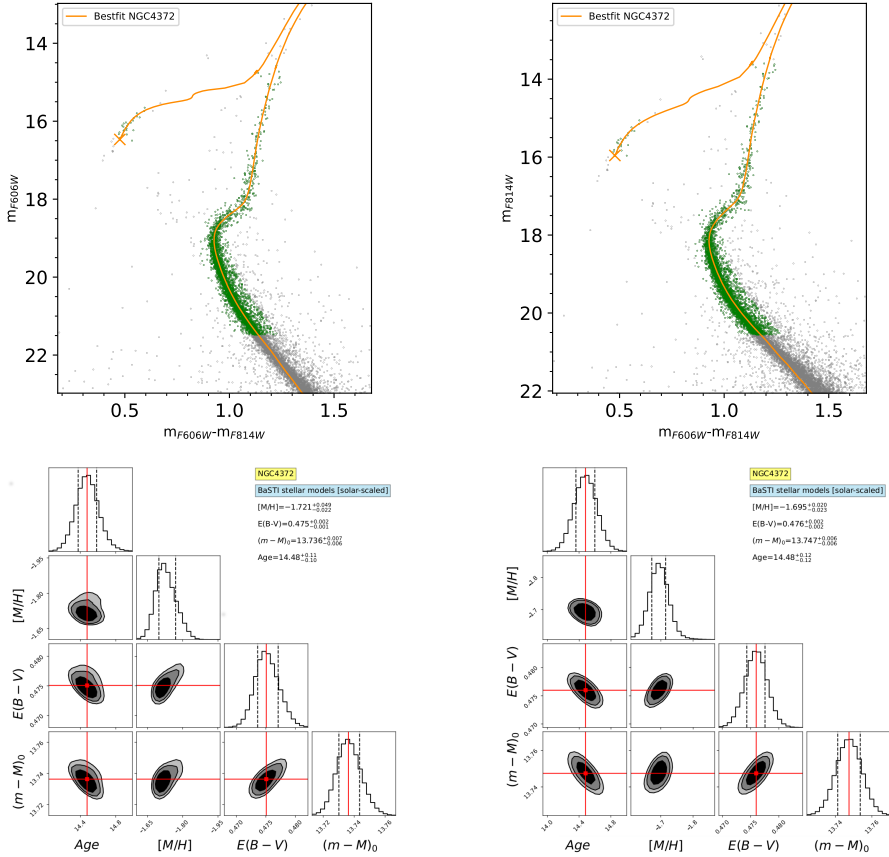
In summary, the results of this work enable identifying LKH as a clean version, extended to low metallicity, of Heracles. Since LKH’s constituents vastly match those associated with the Low-Energy group and Kraken, we can finally recognize LKH as a single massive structure accreted long ago, and that is now buried in the inner Galaxy.

Supplementary Table 1 Results of isochrone fitting. For each cluster, values of $[M/H]$, $E(B - V)$, distance modulus and age are reported along with their associated upper and lower limits.

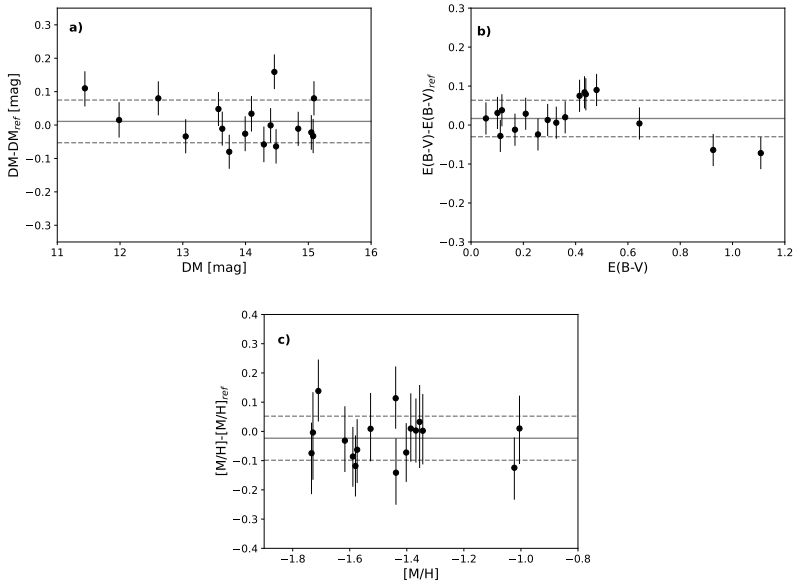
Cluster Name	$[M/H]$	$E(B-V)$	DM	Age
		[mag]	[mag]	[Gyr]
NGC4372	$-1.71^{+0.03}_{-0.04}$	$0.48^{+0.01}_{-0.01}$	$13.74^{+0.01}_{-0.01}$	$14.48^{+0.12}_{-0.12}$
NGC4833	$-1.62^{+0.04}_{-0.06}$	$0.33^{+0.01}_{-0.01}$	$14.09^{+0.02}_{-0.02}$	$13.43^{+0.26}_{-0.23}$
NGC5986	$-1.37^{+0.05}_{-0.05}$	$0.29^{+0.01}_{-0.01}$	$15.08^{+0.01}_{-0.01}$	$13.61^{+0.14}_{-0.13}$
NGC6093	$-1.59^{+0.03}_{-0.02}$	$0.21^{+0.01}_{-0.01}$	$15.05^{+0.01}_{-0.01}$	$13.72^{+0.06}_{-0.05}$
NGC6121	$-1.01^{+0.07}_{-0.05}$	$0.43^{+0.01}_{-0.01}$	$11.44^{+0.01}_{-0.02}$	$12.24^{+0.22}_{-0.30}$
NGC6144	$-1.57^{+0.05}_{-0.03}$	$0.44^{+0.01}_{-0.01}$	$14.49^{+0.01}_{-0.01}$	$14.09^{+0.14}_{-0.31}$
NGC6254	$-1.34^{+0.06}_{-0.08}$	$0.26^{+0.01}_{-0.01}$	$13.57^{+0.01}_{-0.01}$	$13.71^{+0.42}_{-0.19}$
NGC6256	$-1.36^{+0.12}_{-0.08}$	$1.11^{+0.01}_{-0.01}$	$14.46^{+0.02}_{-0.01}$	$13.31^{+0.32}_{-0.29}$
NGC6397	$-1.73^{+0.13}_{-0.10}$	$0.17^{+0.01}_{-0.01}$	$11.99^{+0.02}_{-0.02}$	$14.17^{+0.51}_{-0.35}$
NGC6401	$-1.02^{+0.04}_{-0.03}$	$0.93^{+0.01}_{-0.01}$	$14.29^{+0.02}_{-0.02}$	$13.66^{+0.39}_{-0.53}$
NGC6453	$-1.44^{+0.05}_{-0.06}$	$0.64^{+0.01}_{-0.01}$	$15.09^{+0.01}_{-0.01}$	$13.54^{+0.26}_{-0.20}$
NGC6535	$-1.53^{+0.05}_{-0.07}$	$0.42^{+0.01}_{-0.01}$	$13.99^{+0.02}_{-0.02}$	$13.55^{+0.32}_{-0.27}$
NGC6541	$-1.44^{+0.03}_{-0.04}$	$0.11^{+0.01}_{-0.01}$	$14.40^{+0.01}_{-0.01}$	$13.31^{+0.22}_{-0.35}$
NGC6656	$-1.58^{+0.03}_{-0.03}$	$0.36^{+0.01}_{-0.01}$	$12.61^{+0.01}_{-0.01}$	$14.40^{+0.25}_{-0.24}$
NGC6681	$-1.39^{+0.05}_{-0.07}$	$0.10^{+0.01}_{-0.01}$	$14.84^{+0.01}_{-0.01}$	$13.78^{+0.27}_{-0.18}$
NGC6752	$-1.40^{+0.01}_{-0.01}$	$0.06^{+0.01}_{-0.01}$	$13.05^{+0.01}_{-0.01}$	$14.30^{+0.15}_{-0.39}$
NGC6809	$-1.73^{+0.10}_{-0.03}$	$0.19^{+0.01}_{-0.01}$	$13.63^{+0.01}_{-0.01}$	$13.30^{+0.18}_{-0.17}$

Supplementary Table 2 Parameter estimates for LKH and GSE. Asymmetric 1σ errors are provided.

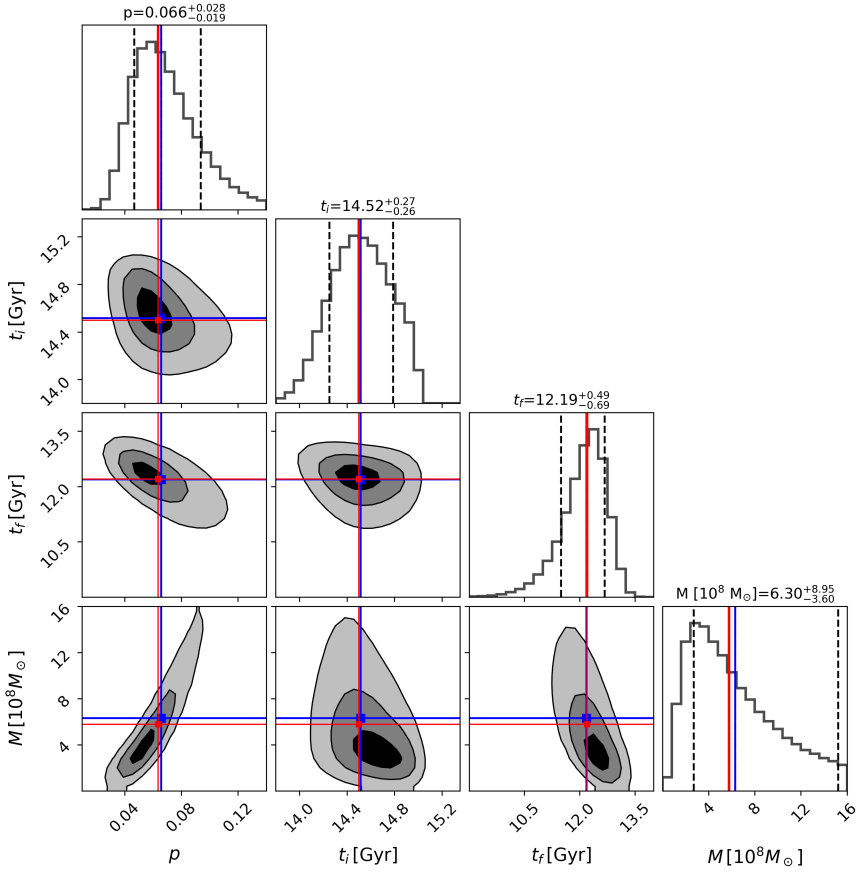
System	p	t_i	t_f	$M_\star$
		[Gyr]	[Gyr]	$[10^8 M_\odot]$
LKH	$0.066^{+0.028}_{-0.019}$	$14.52^{+0.27}_{-0.26}$	$12.19^{+0.49}_{-0.59}$	$6.30^{+8.95}_{-3.60}$
GSE	$0.058^{+0.022}_{-0.015}$	$14.32^{+0.31}_{-0.28}$	$10.43^{+0.65}_{-0.67}$	$4.49^{+5.69}_{-2.36}$



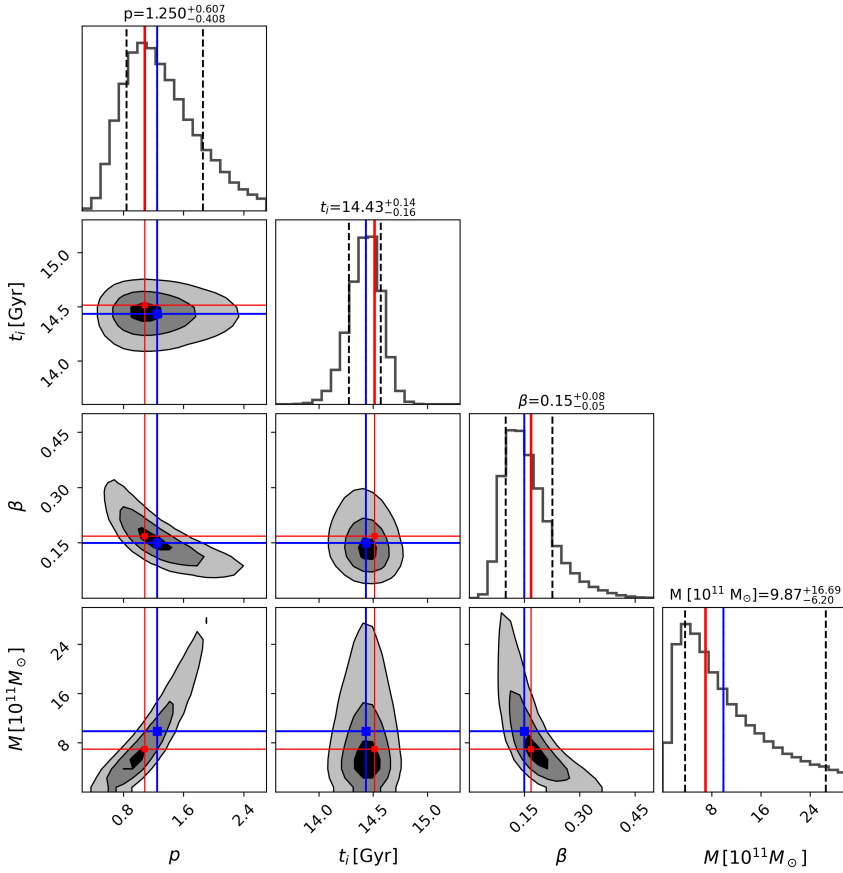
Supplementary Fig. 1 Results of the isochrone fit for NGC 4372. Top left panel: best fit model (orange line) in the $(m_{F606W}, m_{F606W} - m_{F814W})$ CMD. All likely GC members are shown as grey symbols, stars used for the fit are shown as green symbols. The red cross indicates the location of the zero-age horizontal branch. Top right panel: same in the $(m_{F814W}, m_{F606W} - m_{F814W})$ CMD. Bottom left panel: posterior distributions for the output parameters and the best-fit solution, quoted in the labels, in the $(m_{F606W}, m_{F606W} - m_{F814W})$ CMD. The red line indicates the median of each distribution, whereas the dashed black lines indicate the 16th and 84th percentiles. Bottom right panel: same for the output parameters of the fit solution in the $(m_{F814W}, m_{F606W} - m_{F814W})$ CMD.



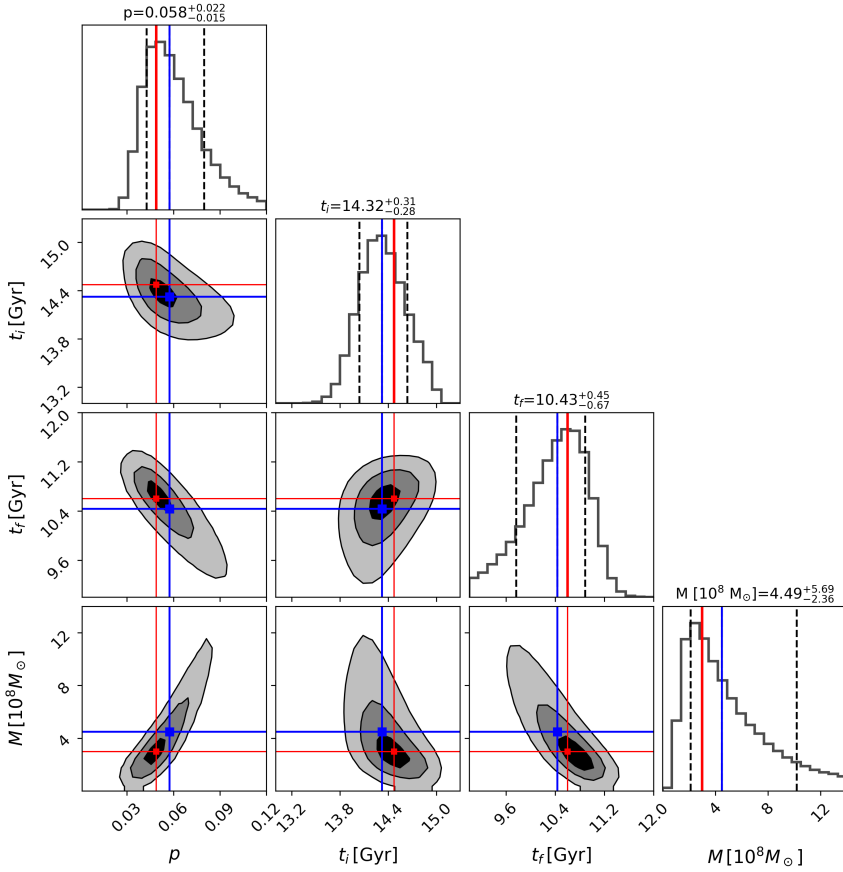
Supplementary Fig. 2 Comparison with the literature. Differences between the output of our isochrone fit and literature values for distance modulus (a), color-excess (b) and global metallicity (c). The mean difference is shown with a solid grey line, whereas the 1σ dispersion around the mean is indicated with dashed grey lines. Individual error bars correspond to the sum in quadrature between our uncertainties and those in the literature.



Supplementary Fig. 3 Corner plot of the LKH AMR model MCMC fit. Corner plot of the joint posterior for the four global parameters, yield p , star formation initial time t_i , accretion time t_f , and derived mass M (in units of $10^8 M_\odot$), for the LKH GCs. Along the diagonal are the 1D histograms with dashed lines marking the 16th and 84th percentiles. Solid blue lines indicate the median and solid red lines the MAP, with titles giving the median $\pm$ uncertainties. Off-diagonal panels show the 2D posterior contours at the 16th, 50th and 84th percentile levels, with overplotted blue and red lines denoting the medians and MAP estimates for each parameter pair.



Supplementary Fig. 4 Corner plot of the MW AMR model MCMC fit. Corner plot of the joint posterior for the four global parameters, yield p , star formation initial time t_i , coefficient of the exponential declination of the SFR β , and derived mass M (in units of $10^{11} M_\odot$), for the MW GCs. Along the diagonal are the 1D histograms with dashed lines marking the 16th and 84th percentiles. Solid blue lines indicate the median and solid red lines the MAP, with titles giving the median $\pm$ uncertainties. Off-diagonal panels show the 2D posterior contours at the 16th, 50th and 84th percentile levels, with overplotted blue and red lines denoting the medians and MAP estimates for each parameter pair.



Supplementary Fig. 5 Corner plot of the GSE AMR model MCMC fit. Corner plot of the joint posterior for the four global parameters, yield p , star formation initial time t_i , accretion time t_f , and derived mass M (in units of $10^8 M_\odot$), for the GSE GCs. Along the diagonal are the 1D histograms with dashed lines marking the 16th and 84th percentiles. Solid blue lines indicate the median and solid red lines the MAP, with titles giving the median $\pm$ uncertainties. Off-diagonal panels show the 2D posterior contours at the 16th, 50th and 84th percentile levels, with overplotted blue and red lines denoting the medians and MAP estimates for each parameter pair.

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