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JWST Imaging of the Closest Globular Clusters—V. The White Dwarfs Cooling Sequence of M4

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ABSTRACT

We combine infrared (IR) observations collected by the *James Webb Space Telescope* with optical deep images by the *Hubble Space Telescope* taken ~20 years earlier to compute proper-motion membership for the globular cluster (GC) M4 (NGC 6121) along its entire white dwarf (WD) cooling sequence (CS). These new IR observations allow us, for only the second time in a GC, to compare WD models with observations over a wide range of wavelengths, constraining fundamental astrophysical properties of WDs. Furthermore, we investigate the presence of WDs with IR excess along the WD CS of M4, similar to the recent study conducted on the GC NGC 6397. We also determine the age difference between M4 and NGC 6397 by comparing the absolute F150W2 magnitudes of the luminosity function peak at the bottom of the observed WD CS and find that M4 is slightly younger, by 0.8 ± 0.5 Gyr.

1 | Introduction

Globular clusters (GCs), among the oldest objects in the Universe, serve as ideal laboratories for testing stellar evolution models and derive crucial information about galaxy formation and cosmology (see, e.g., the reviews by Forbes et al. 2018; Kalirai and Richer 2010), thanks to their stars' uniform age, distance, and chemical composition (at least to a first approximation; Piotto et al. 2015). In this context, the color-magnitude diagrams

(CMDs) of their stellar components are one of the most crucial tools for such investigations. To render CMDs truly informative, proper motions (PMs) are fundamental to establishing cluster membership, particularly for their faintest stars, including the white dwarf (WD) population.

Without PM measurements, these stars would be otherwise irretrievably lost and confused with the multitude of foreground and background field objects surrounding the GCs.

Abbreviations: ☉, Sun/Solar; *HST*, Hubble Space Telescope; *JWST*, James Webb Space Telescope.

Based on observations with the NASA/ESA *James Webb Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555, under GO-1979.

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By leveraging the astrometric capabilities of the *James Webb Space Telescope* (*JWST*) (Griggio, Nardiello, and Bedin 2023) alongside deep *Hubble Space Telescope* (*HST*) images collected ~ 20 years ago, we can now explore the stellar components of GCs over a wide photometric spectral range, and more importantly, obtain precise PM measurements.

Our *JWST* program GO-1979 (Bedin et al. 2021), was specifically designed to measure high-precision infrared photometry and astrometry of the faintest objects in the two nearest Galactic GCs, namely Messier 4 (M4, a.k.a. NGC 6121, at a distance $d = 1.85 \pm 0.02$ kpc) and NGC 6397 ($d = 2.48 \pm 0.02$ kpc; Baumgardt and Vasiliev 2021). Due to their proximity and different metallicities ($[\text{Fe}/\text{H}] = -1.18$ for M4 and $[\text{Fe}/\text{H}] = -1.99$ for NGC 6397; see Carretta et al. 2009) they are the first natural targets to investigate the infrared properties of the WD cooling sequences of Galactic GCs, and if/how they change with the cluster initial chemical composition.

A series of papers (presented and summarized by Bedin et al. 2024) studied different aspects of NGC 6397 based on our *JWST* GO-1979 program—Paper I (Bedin et al. 2024) has studied the white dwarfs (WDs), while the brown dwarf population was presented in Gerasimov et al. (Paper II; Gerasimov et al. 2024). The multiple population phenomenon was studied in Scalco et al. (Paper III; Scalco et al. 2024). Our fourth paper (Paper IV; Libralato et al. 2024) investigated the faint main sequence (MS) chemistry in the parallel fields of both clusters. This fifth paper of the series is focused on the WDs of M4.

The WD cooling sequence (CS) of M4 was previously studied with deep *HST* optical photometry by Hansen et al. (2002), Hansen et al. (2004), and down to its bottom by Bedin et al. (2009). These works were all centered on the age determination of the cluster from its WD cooling sequence. Such studies take advantage of the fact that WDs fade with time toward progressively fainter magnitudes. The older the WD the dimmer its magnitude, hence the CMD of the WD population in a star cluster is expected to display a cut-off at a certain magnitude. This cut-off magnitude is a function of the cluster age. Bedin et al. (2009) determined an age of 11.6 ± 0.6 Gyr (internal errors only) while Hansen et al. (2004)—improving upon the earlier analysis by Hansen et al. (2002) with the same data, taking into account various possible sources of systematic uncertainties—obtained a best estimate of 12.1 Gyr, with a 95% lower limit of 10.3 Gyr.

In this article, we investigate, for only the second time in the infrared (IR) within a GC—following NGC 6397—the effects of collision-induced absorption (CIA) of H_2 molecules in the cool atmospheres of WDs. Unlike in the optical, these effects are unambiguous in this wavelength range (see Paper I).

Furthermore, we investigate whether M4 shows evidence of a WD subpopulation with excess flux in the F322W2 filter (up to ~ 0.5 magnitudes), previously identified in NGC 6397 WDs (Paper I).

The excess observed among NGC 6397's WDs requires further confirmation, as it is limited to the F322W2 filter and becomes more pronounced at fainter magnitudes. In Paper I several potential explanations for this IR excess were explored, including a large population of WD + BD binaries, reddening from

circumstellar debris disks or post-AGB material, contributions from helium-dominated or helium-core WDs, and a possible link to the two populations in NGC 6397's stellar main sequence; however, no definitive explanation was identified. Building on our results for NGC 6397, we now aim to investigate whether a similar infrared flux excess is present in M4. This investigation could be crucial, as expanding our sample of GCs will enhance our understanding of the mechanisms behind these intriguing observations.

In addition, we revisit the cluster age derived from the cluster CS, by comparing its cut-off magnitude with that of the metal poorer cluster NGC 6397 investigated in detail in Paper I. The age difference between these two clusters has important implications for the age-metallicity relation of the Galactic GC system, which is related to the formation of the Galactic halo (see, e.g., Leaman, VandenBerg, and Mendel 2013).

Age determinations based on the main sequence turn-off brightness provided so far inconsistent results, with M4 younger by an amount ranging from less than 1 Gyr (e.g., Marín-Franch et al. 2009; Salaris and Weiss 2002) to 1.5 Gyr (VandenBerg et al. 2013). The study of NGC 6397 CS by Hansen et al. (2007) provides an age equal to 11.5 ± 0.5 Gyr (95% confidence limits), that is consistent, within the errors (that are larger for M4), with M4 age derived from its CS by Hansen et al. (2004).

Here we employ the most recent determinations of the clusters' distances (Baumgardt and Vasiliev 2021), the power of infrared photometry to minimize the effect of extinction, which is high for these two clusters ($E(B - V) \sim 0.2$ for NGC 6397 and ~ 0.4 for M4, whose extinction is also characterized by a ratio $R_V = A_V / E(B - V)$ larger than the standard value of 3.1; see, e.g., Hendricks et al. 2012), and the updated WD (Salaris et al. 2022) and progenitor models (Pietrinferni et al. 2021) from the BaSTI-IAC database.

The article is organized as follows: Section 2 presents the observations; Section 3 describes the data reduction, proper-motion analysis, and artificial star tests; Section 4 discusses the observational results on the WD CS of M4 and their interpretation. Finally, our conclusions are outlined in Section 5. As part of this publication, we also publicly release supplementary online materials, including both the astrometrized atlases of the studied field and the photometric catalogues.

2 | Observations

The original plan of the program was to maximize the overlap with the deep optical *HST* data of GO-10146 (PI: Bedin), which allowed us to study the entire WD CS of M4 (Bedin et al. 2009). This strategy would have provided both proper motions (to assess the cluster membership) and the optical counterparts of our *JWST* data. However, our GO-1979 *JWST* observations (PI: Bedin) were accepted well before the *JWST* launch and, as observations of other GCs became publicly available, our careful examination of *JWST*'s performances (Griggio, Nardiello, and Bedin 2023; Nardiello et al. 2022; Nardiello, Bedin, et al. 2023) revealed that the area covered by the GO-10146 *HST* data was too crowded for *JWST* (see end of Section 2.2). Internal reflections

and diffraction spikes make the background level too high to detect faint sources on NIRCcam images, hampering our ability to measure the faintest stellar objects in that *HST* field. Therefore, we redesigned the observations shifting the field further from the cluster's center where crowding is less severe, at the cost of a smaller overlap with the *HST* data and, in turn, a smaller sample of stars with proper motions (for the cluster membership) and optical counterparts.

2.1 | *JWST* Images

The GO-1979 images were taken on April 9, 2023 (epoch ~ 2023.27) using a 6-point FULLBOX primary dither pattern with 2-POINT-LARGE-WITH-NIRISS sub-pixel positions. Each pointing comprises a single image with both short- (SW) and long-wavelength (LW) detectors using a MEDIUM8 readout pattern with 5 groups/1 integration (effective exposure time of 515.365 s). Thanks to NIRCcam's simultaneous observations, we secured images in F150W2 (SW) and F322W2 (LW) filters. The top-left panel of Figure 1 shows a Digital Sky Survey 2 InfraRed¹ image of the field around our NIRCcam pointing, which is centered at $(\alpha; \delta) = (245^{\circ}.9297; -26^{\circ}.4504)$, at an average angular distance from the cluster center of about 4.8 arcmin, ranging between 1.9 and 8 arcmin. The top-right panel of Figure 1 shows the F150W2 stacked image for the entire NIRCcam field of view (FoV), while the bottom panel shows a zoom-in of $3' \times 0.6'$ for a relatively "sparse" region, highlighting both the high density of stars and high number of background unsolved extra-Galactic sources.

The NIRCcam images were processed as described in Paper I, that is, using the official *JWST* calibration pipeline (Bushouse et al. 2023) to obtain the level-2b _cal images. We increased the dynamical range of our data by using the so-called frame zero (i.e., the first frame of each integration), which enables the ramp fit in pixels that saturate after the first group. We modified the _cal images by (i) converting the values of the pixels from MJy/sr into counts using the necessary header keywords in each FITS file, and (ii) flagging unusable pixels using the data quality (DQ) flags available in each _cal multi-extension FITS file.

2.2 | *HST* Images

The *HST* data are from GO-10146 (Bedin 2004) taken with the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS). The observations were split into two parts. The first part was obtained between 2004 July and August (~ 2004.607) in the F606W filter (20 exposures of ~ 1200 s each). The second part was secured in June 2005 and included only four exposures (of ~ 1200 s each) in the F775W filter.

A small digression here: we want to emphasize that the diffraction pattern of the PSFs in *JWST* images has profound effects on sky-background-limited detection of sources in crowding conditions, such as those of the cores of Galactic GCs. To exemplify this, in Figure 2 we show a common portion of the two *JWST* and *HST* datasets. The left-panel shows the finding chart in the NIRCcam field of this selected region (indicated by a yellow rectangle); this region is in the most crowded part of the *JWST*'s NIRCcam FoV,

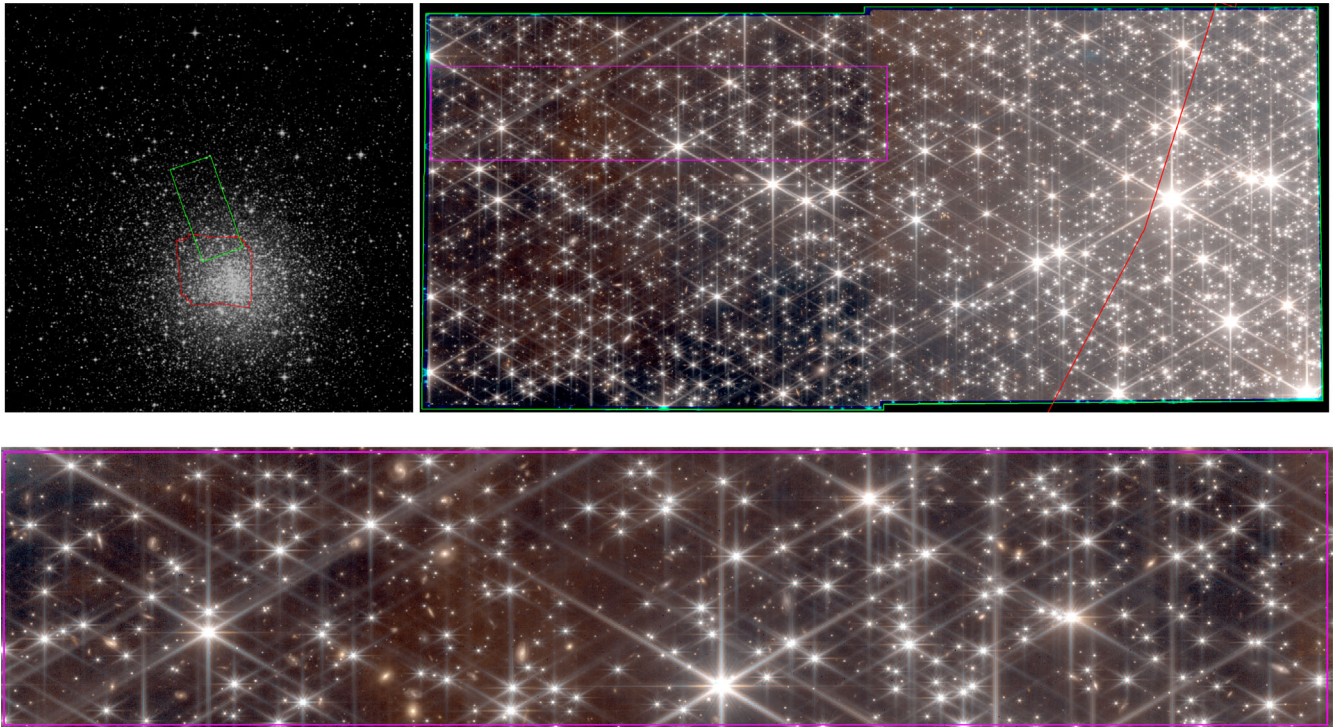


FIGURE 1 | (Top-Left:) A $25' \times 25'$ infrared image from the Digital Sky Survey 2 centered on our NIRCcam field of M4 for *JWST* program GO-1979 (green box). The image is aligned with North up and East toward the left. The region indicated in red shows the archival *HST* deep field from programs GO-10146. (Top-Right:) The entire NIRCcam primary field. (Bottom:) A zoom-in on a representative dark sub-region (of $\sim 3' \times 0.6'$) in the NIRCcam image (highlighted in magenta in the top panel).

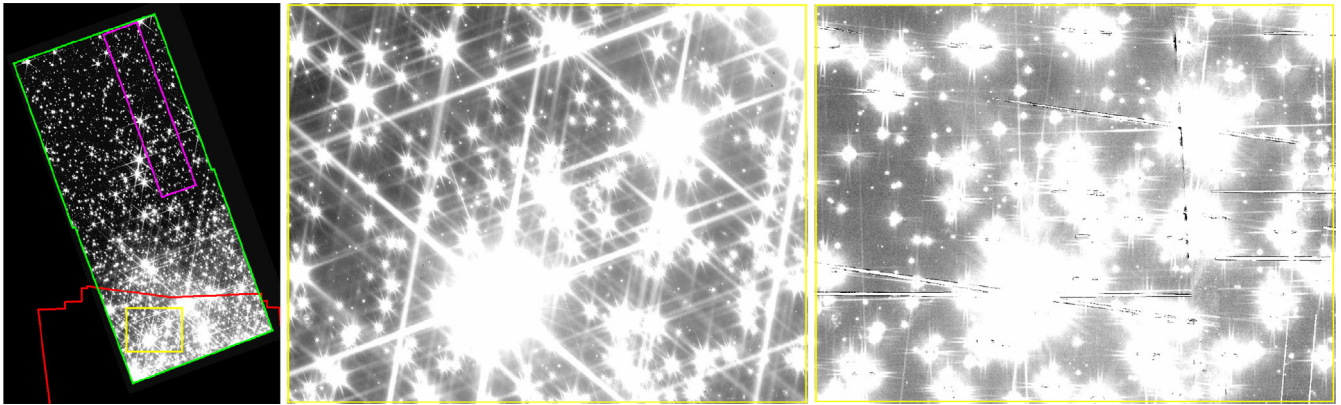


FIGURE 2 | (Left-Panel:) This figure highlights the difference in the amount of scattered light between ACS/WFC@HST and NIRCam/SW images. We define a common region between the two datasets and mark it in yellow. (Mid-Panel:) Zoom-in of the region indicated in yellow as seen with *JWST*/NIRCam/SW/F150W2. (Right-Panel:) Same region, as seen with *HST*/ACS/WFC/F775W. In these panels, the scale is stretched to reveal the fluctuations of the sky background in the darkest areas not dominated by the halos of bright stars. Clearly, *JWST* images have less regions than *HST* free from spikes and halos from the brightest stars, which makes it difficult to detect the faintest sources which should compete not only against the sky brightness but also against other features.

and the least crowded portion of the *HST*'s ACS/WFC FoV. The middle panel shows this selected region as observed by *JWST* in NIRCam/SW filter F150W2, while the right panel shows the same region as observed in *HST* ACS/WFC filter F775W. The scales in the two rightmost panels of this figure have a stretched contrast to enable visibility of the sky-noise levels. Although not quantitative, this figure qualitatively shows that even in the darkest region in the *JWST* images, there are always diffraction spikes coming from relatively distant bright sources, effectively compromising the sky-background level. Indeed, to be detected, faint stars will have to compete not only against the local sky-level noise but also against light coming from far away sources, de facto hampering to detect easily sources just above the local sky background.

3 | Data Reduction

3.1 | *JWST*'s Astrometry and Photometry

All images obtained with NIRCam were reduced using software tools and methods described in detail in the first three papers of the series “*Photometry and Astrometry With JWST*” (Griggio, Nardiello, and Bedin 2023; Nardiello et al. 2022; Nardiello, Bedin, et al. 2023), and applied with success in the study of brown dwarfs of 47 Tucanæ by Nardiello, Griggio, and Bedin (2023), and more recently in Paper I. The method consists of a *first*- and *second*-pass photometry as defined by Anderson et al. (2008).

Briefly, the *first*-pass photometry measures the positions and fluxes of all detectable sources in each NIRCam image via effective-PSF fit (see Paper I and Nardiello, Bedin, et al. 2023 for a description of the effective-PSF models). Positions were corrected for geometric distortion using the solution provided by Griggio, Nardiello, and Bedin (2023). These astro-photometric single-image catalogues were then transformed onto a common reference frame, which was established using the *Gaia* DR3 catalogue (after the *Gaia* positions were transformed to the epoch of

our *JWST* observations). Placing all first-pass outputs onto the same system allows them to be properly compared during the next step of the data reduction.

The *second*-pass photometry takes advantage of the information stored in all images simultaneously and improves the detectability and the photometry of very faint sources that would otherwise be lost in an individual image. In our work, the second-pass photometry was performed with a modified version of the code KS2, developed by Jay Anderson and described in Bellini et al. (2017, and references therein). Along with fluxes and positions, KS2 produces several quality diagnostics, including the root mean square (RMS) error in brightness (in magnitudes), the PSF quality of fit (q), and a “stellarity index” that describes how well the shape of a given source resembles that of the PSF (the so-called RADXS; see Bedin et al. 2008).

3.2 | *HST*'s Astrometry and Photometry

The data reduction for *HST* data was performed by Bedin et al. (2009), with methodologies that are the precursor to those employed for *JWST* data and briefly described in that work, but are fully detailed in the seminal study by Anderson et al. (2008).

3.3 | Calibrations of Astrometry and Photometry

We calibrated the *JWST* and *HST* photometry to the Vega-magnitude system following the procedures outlined by Nardiello, Bedin, et al. (2023) and Bedin et al. (2005), respectively. Hereafter, we will adopt the following symbols for the calibrated magnitudes: m_{F606W} , m_{F775W} , m_{F150W2} , and m_{F322W2} . Positions were registered onto the International Celestial Reference System (ICRS) frame using the *Gaia* DR3 catalogue (after the *Gaia* positions were transformed to the epoch of the *HST* or *JWST* observations).

3.4 | Proper Motions

Proper motions were computed as the positional displacements of the sources between the *JWST* and *HST* epochs divided by the temporal baseline (~ 18.66 years). We adopted a NIRCcam SW pixel scale of ~ 31.2 mas (Griggio, Nardiello, and Bedin 2023). PMs are relative to the bulk motion of the cluster members in the field, meaning that the cluster distribution in the vector-point diagram is centered at the origin (The second [much loose] clustering of sources at ~ 20 mas/yr are mainly stars of the Galactic Bulge; Bedin et al. 2003). These PMs are oriented with the instrumental NIRCcam coordinates.

In the studied field of M4, stars have an internal dispersion of at most ~ 5 km/s (Libralato et al. 2022; Vasiliev and Baumgardt 2021; Vitral et al. 2023), which at a GC distance of ~ 1850 pc (Baumgardt and Vasiliev 2021) corresponds to a PM dispersion of < 0.5 mas/yr, that is, a displacement lower than 10 mas $\simeq 0.3$ NIRCcam SW pixel over 18.66 yr. This value is considerably smaller than the random PM uncertainties at the faint magnitudes of the bulk of the WDs in our sample; estimated to be about 1 NIRCcam/SW pixel per epoch (2.5 mas/yr ~ 1 pxl $\times \sqrt{2}$ epochs $\times 31.2$ mas/pxl/18.66 yr). Hereafter, we safely consider as cluster members all sources with a PM lower than 2.5 mas/yr from the bulk motion of the cluster in the vector-point diagram (see Figure 3).

3.5 | Artificial Stars

Artificial-star tests (ASTs) are an important step in assessing the reliability of point-source photometry and the completeness of

our sample. We generated 100,000 artificial stars homogeneously distributed within the NIRCcam FoV and with a uniform F150W2 magnitude distribution in the magnitude range of the WD CS. We then used the KS2 software to find and measure these artificial stars in the *JWST*/NIRCcam images just as we did for real stars. The comparison between the input and output parameters (positions and magnitudes) provides us with an estimate of the reliability of our photometry.

4 | The *JWST* CMD of M4

By using only 14 *HST* orbits, Bedin et al. (2009) were able to observe the entire CMD from the red-giant branch (RGB) tip to the location of the peak of the WD luminosity function (LF) at the bottom of the CS in M4, located at $m_{F606W} = 28.5 \pm 0.1$. The CMD from the MS to the horizontal branch stage was employed to determine the distance modulus, extinction, and MS TO age from isochrone fitting. A comparison of the observed white dwarf luminosity function with results from theoretical models provided an independent age determination. The age inferred from the white dwarf luminosity function was 11.6 ± 0.6 Gyr, in good (internal) agreement with the age from fitting the MS turn-off (TO) (12.0 ± 1.4 Gyr). The error bars took into account only the intrinsic errors of the methods and observations, not uncertainties in the adopted theoretical models.

Here, for the first time, thanks to *JWST*, we have been able to extend the observations of the entire WD CS to the IR; where reddening variations are less significant for a GC with a complicated foreground field extinction such as M4 (Hendricks et al. 2012).

In panel (a) of Figure 4, we present the CMD ($m_{F150W2} - m_{F322W2}$) versus m_{F150W2} for all the local maxima detected across the entire NIRCcam FoV. All detected sources are shown in gray, while those that were well measured and passed all selection criteria for the KS2 quality parameters (cfr., Paper I) are marked in black. The CMD extends over ten magnitudes in brightness thanks to the NIRCcam frame zero; however, sources with magnitudes above the saturation level (marked by the horizontal dashed line at about $m_{F150W2} \simeq 20$) should be regarded with caution, as probably affected by systematic photometric errors (not yet quantified). Panel (b) displays the *total* PMs (i.e., the sum in quadrature of the PMs in the two components μ_X and μ_Y) versus m_{F150W} for a subset of the source in (a) (those detected in both *JWST* and *HST*). All sources are shown as gray dots, while those that passed the quality parameters are indicated by black symbols. Among these, we define as cluster members those sources that meet the selection criterion defined in Section 3.4 (i.e., PMs < 2.5 mas/yr, and indicated by a vertical line), and show them with filled circles, while we use open circles for likely field objects. The CMD of these sources is shown employing the same symbols in panel (c). Panel (d) shows only the member stars (filled circles) and the artificial stars (as added in magenta, and as found in gray) passing the same quality-parameter selections passed by real stars. Finally, the top panel of Figure 4 illustrates the spatial distribution of objects from panel (c) and (d), employing the same symbols. At the bottom-right of this panel, a black line marks the boundary of the region in common between *JWST* and *HST* (to the right of this line).

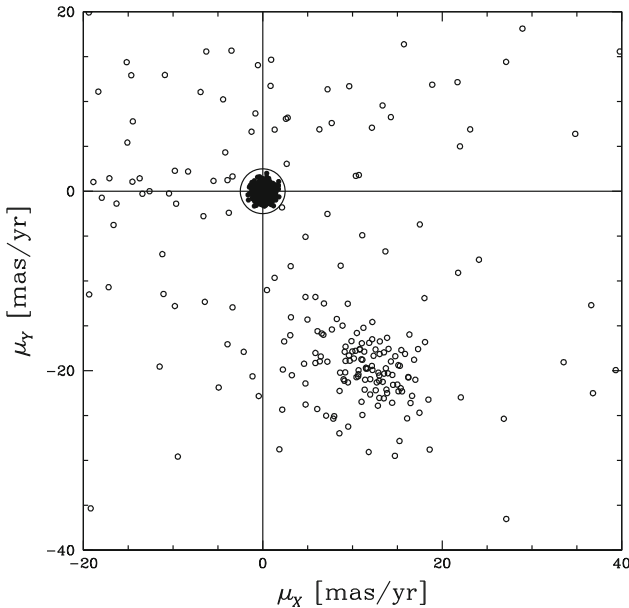


FIGURE 3 | Vector point diagram for sources that passed all selection criteria based on KS2 diagnostics. The time baseline is 18.66 years. Proper motions (oriented along NIRCcam's detectors) and are computed with respect to the cluster members, therefore the coordinates (0;0) coincide with the average motion of the stellar systems (indicated by the vertical and horizontal lines for the axes' origin). The inner circle corresponds to a proper-motion membership criterion for M4's stars (filled symbols), defined as 2.5 mas/yr (see text).

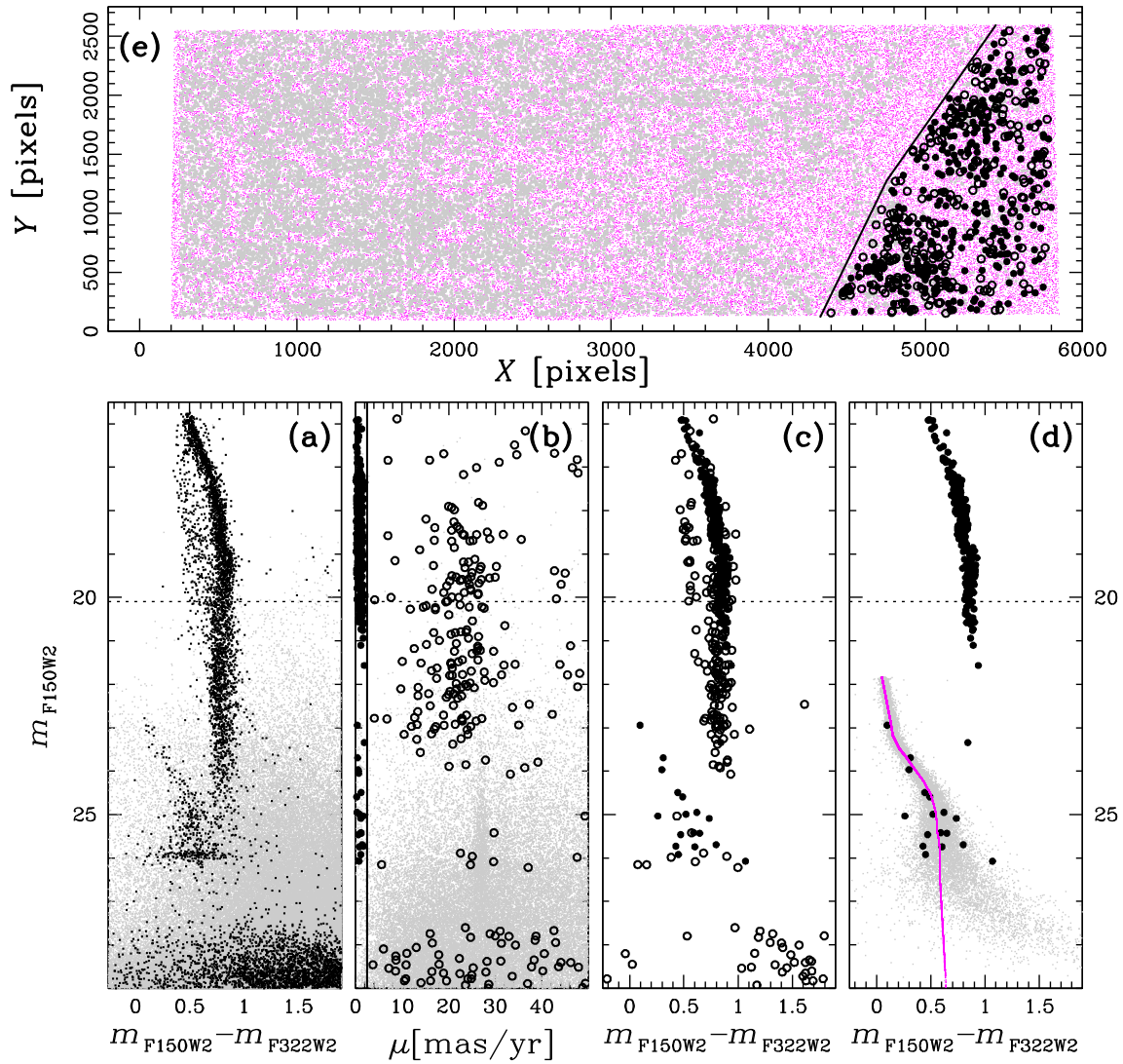


FIGURE 4 | (a) CMD of all sources detected within NIRCcam (gray dots) and of those passing the quality test (black dots). The dashed horizontal lines in all bottom panels indicate the onset of saturation for objects brighter than $m_{F150W2} \approx 20$. (b) For all sources with two epochs the total-PMs vs. m_{F150W2} (gray dots). Those passing quality selections are indicated in black symbols. A vertical line defines our membership criterion defined in Section 3.4 (2.5 mas/yr). Those with proper motions below that line are considered members (filled circles), and those with larger motions are considered field objects (open circles), and their CMD is shown in panel (c). (d) The CMD for members (filled circles) and artificial stars, these as added (in magenta) and as recovered (in gray). (e) The spatial distribution of sources in (c) and (d) across the NIRCcam FoV. The black line marks the region of overlap with ACS/WFC observations from GO-10146 overlaps, available on the right of that line (see Figure 1).

Although, the WD CS of M4 is partially lost in the midst of the field objects, its location can be clearly identified in the CMD presented in Panel (a) of Figure 4, a location that is confirmed by those few stars with PMs membership (filled dots in panels (d) and (e)). Even though the lack of PM memberships for all sources within the entire NIRCcam FoV, prevents a detailed quantitative study of the exact shape of the WD CS luminosity function of M4, a clear feature emerges. This is the over-density at magnitude $m_{F150W2} \sim 26$ and color $(m_{F150W2} - m_{F322W2}) \sim 0.5$, which cannot be reproduced by any other population of the Galactic field or background sources; it must correspond to the peak of the WD CS luminosity function. This feature is well above the completeness drops, and it is a feature that models can predict with great accuracy; indeed it aligns with the location predicted by the models. Also, note that essentially all background galaxies

were removed by the selection in stellarity parameters (RADXS, i.e., how well the source profiles resemble the PSFs). Therefore, a histogram distribution in magnitude (with a 0.1 mag step) for stars along the WD CS of M4, provides an accurate estimate of the luminosity of the white dwarf luminosity function peak, which is firmly located at magnitude $m_{F150W2} = 25.90 \pm 0.10$ (and comforted by visual inspection of panels (a) and (d) of Figure 4).

A major difference between optical and IR CMDs of a GC CS is that in the optical the CS displays a characteristic “blue turn” (e.g., Bono, Salaris, and Gilmozzi 2013), which corresponds to the appearance of increasingly more massive and thus smaller radius WDs originating from shorter-lived progenitors. This blue turn, depending on the cluster age—hence of the T_{eff} of the coolest WDs—may be further enhanced by the onset

of CIA of H_2 in the atmospheres of the coolest WDs (Hansen and Phinney 1998). In the optical-IR CMD, obtained with the *JWST*/NIRCam filters F150W2 and F322W2, combined with the optical *HST*/ACS/WFC/F775W filter, the effect of CIA is evident and unambiguous. It begins at higher T_{eff} compared with optical CMDs when the isochrone still aligns with the cooling track of single low-mass ($\sim 0.55 M$) WDs.

This transpires clearly from Figure 5, which shows an IR and a mixed optical-IR CMD of the cluster CS, together with a representative theoretical 12 Gyr WD (with hydrogen atmospheres) isochrone from progenitors with $[\text{Fe}/\text{H}] = -1.0$ (from Salaris et al. 2022). The isochrone has been shifted by the labeled distance (from Baumgardt and Vasiliev 2021) and means reddening (from Hendricks et al. 2012), employing A_λ/A_V ratios calculated as in Bedin et al. (2005)² using $R_V = 3.6$ (from Hendricks et al. 2012).

Whilst the IR CMD (and the isochrone) shows a sequence that at the faint magnitudes is almost vertical, the optical/IR CMD displays a turn to the blue corresponding to the portion of the isochrone populated by constant mass ($\sim 0.55 M$) objects, hence caused by the onset of CIA, as we have seen in NGC 6397.

4.1 | Possible Red Excess WDs in M4?

Given the relatively straightforward modeling of cool WD photospheres in the infrared bands, we use these NIRCam observations to search for infrared excess that could be caused by circumstellar debris disks (Chu et al. 2011). Disk-induced infrared excess is well documented among young WDs in the Milky Way (Su et al. 2007), and finding debris disks around WDs in globular clusters would suggest favorable conditions for planet formation in these ancient systems, thus making such a discovery especially significant. Recently, an infrared excess was hinted at for the first time in a GC in *JWST* observations of WDs in NGC 6397 (Paper I). While this feature requires further confirmation—being significant only in the F322W2 filter and more pronounced at fainter magnitudes—it would be valuable to investigate whether similar features are also present in a second cluster: M4.

However, the *JWST* data for M4 are of substantially lower quality than those used for NGC 6397 in this investigation for two main reasons. First, membership could only be established in a much smaller region, and second, this region lies too close to the cluster core, where crowding significantly increases photometric errors.

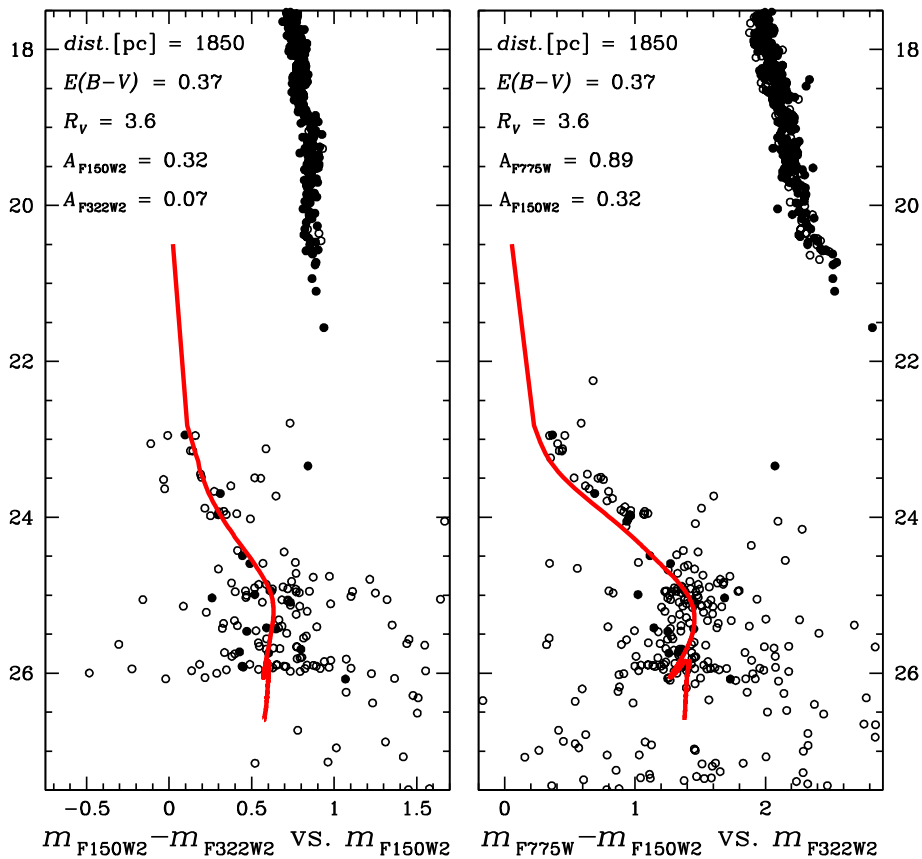


FIGURE 5 | The two most informative CMDs, for the WD CS in M4, F150W2–F322W2 vs. F150W2 (left), and F775W–F150W2 vs. F322W2 (right). In these CMDs we display sources with a PM estimate, and in particular only those with PMs within 1.7 mas/yr the cluster’s bulk motion (open-circles). Those that also passed the quality-check parameters are indicated by filled circles. The red lines show the 12-Gyr DA WD isochrone from Salaris et al. (2022).

In Figure 6 we intend to demonstrate first that the dispersion along the observed WD CS of M4 is significantly larger than what is inferred by our estimated uncertainties. The top panels refer to real sources, while the bottom ones to artificial stars. In the left panel we show the CMDs, in the middle ones the rectified CMD along the reference WD CS, and on the right ones the histogram distributions in magnitude for stars in a very specific magnitude interval, that is, between $m_{F150W2} = 24$ and 26 (area shaded in cyan). In these histograms we show the Gaussians obtained taking as dispersion the 68.27th percentile of the distributions. In red the Gaussian for the observed sources (labeled in the same color the corresponding values of $\sigma_O = 0.173$ mag), while in magenta the Gaussian for the artificial stars. Not having reliable PM estimates for the ASTs, we estimated the dispersion for the entire sample ($\sigma_A^* = 0.098$ mag) and for those ASTs passing all the quality selections ($\sigma_A = 0.047$ mag). The observed dispersion is significantly larger than the estimated one even in the worst case ($\sigma_O > \sigma_A$). Therefore, assuming that errors are well understood, we note that the observed dispersion of the final portion of the WD CS of M4 has a significantly broader color than expected on the basis of photometric errors (by more than 50%).

Furthermore, assuming that the isochrone is “the truth,” we can quantify the number of WDs on the red side and the blue side of this isochrone within $3\sigma_O$. For stars with proper motions within 2.5 mas/yr from the cluster members, we count 63 red WDs and 38 blue WDs, providing a $\sim 2.5\sigma$ significance for the excess

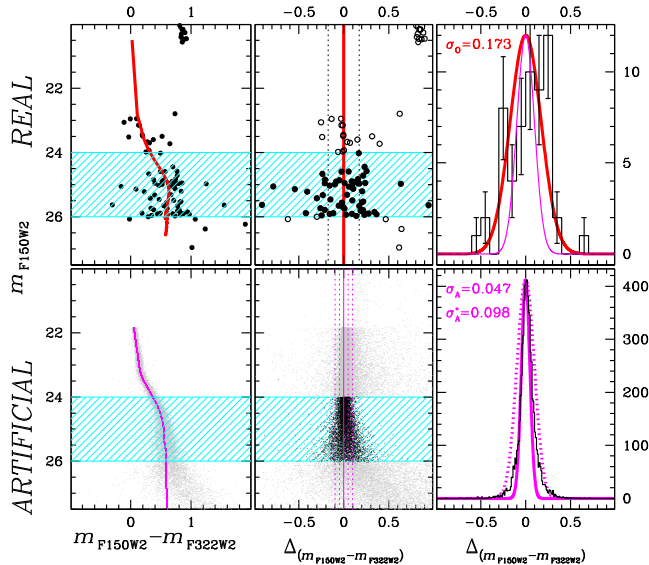


FIGURE 6 | (Top): Real stars. (Bottom): Artificial stars. (Top-Left): CMD for all sources with PM within 1 mas/yr of the cluster. The red line is the same isochrone used in Figure 5. (Top-Middle): The rectified CMD along the isochrone. The histogram for the sources within the magnitude interval indicated by the shaded area in cyan (filled dots), is shown on the (Top-Right) panel. The dispersion value of these observed data points (σ_O) was fitted with a Gaussian, whose σ is indicated in red. The bottom panels show the same for artificial stars. The magenta line is the line along which the ASTs were added. We do not have PMs for ASTs, therefore we show the two dispersions values (indicated in magenta) obtained for all ASTs (σ_A^*) and for those ASTs that have passed all the photometric quality tests (σ_A).

number of red WDs. Limiting the sample to stars with proper motions within 1 mas/yr, the significance becomes $\sim 2\sigma$.

Next, analogous to the approach in Paper I, we *arbitrarily* define two regions on the CMD ($m_{F150W2} - m_{F322W2}$) versus m_{F150W2} : one on the red side and one on the blue side of the isochrone, around the nearly vertical section between $m_{F150W2} = 24$ and 26.5. We then investigate whether the two samples of blue and red WDs, defined by the two regions indicated in the mid panel on the left in Figure 7, would correspond to distinct locations in other CMDs generated by combining all available filters in the overlapping *HST* and *JWST* FoVs. The results of these tests are shown in Figure 7, displaying eleven CMDs and one two-color diagram (TCD). As observed for NGC 6397, the two samples can be disentangled only when the F322W2 filter is involved. This suggests that any potential IR excess—as large as ~ 0.5 magnitudes—among WDs appears solely in the F322W2 filter.

In summary, the ($m_{F150W2} - m_{F322W2}$) color dispersion of the faint end of the WD CS of M4 appears considerably larger than what was expected on the basis of the photometric errors (by as much as 50%; likely more). However, this excess seems to be present only in filter F322W2. Furthermore, while in the case of NGC 6397 (Paper I) there was an indication of a split of the faint part of the WD CS, in the case of M4, there is not even a hint of such a feature. The lack of a similar indication could be due to the considerably lower quality of the M4 data set (membership is available only for sources in a small field of high crowding).

Finally, although we consider it unlikely, we cannot confidently exclude the presence of yet unidentified large errors in filter F322W2 that our artificial star tests cannot track. Such error could potentially inflate the observed dispersion of the faintest part of the WD CS.

Follow-up observations are needed to confirm this broader color distribution than expected for the faint end of the WD CS of M4, for members across the whole NIRCcam field of view (particularly in less crowded regions), and at even redder wavelengths to better understand the nature of these IR excesses. At a minimum, a second epoch with observations in the F444W filter of NIRCcam is required to verify this feature, ideally complemented by MIRI low-resolution spectra.

4.2 | Comparison Between M4 and NGC 6397

As already mentioned, we found that in NGC 6397 the peak of the luminosity function at the bottom end of the CS is located at $m_{F150W2} = 26.55 \pm 0.10$, while in the case of M4 we have estimated $m_{F150W2} = 25.90 \pm 0.10$, corresponding to a difference $\Delta m_{F150W2} = 0.65 \pm 0.14$ mag.

If we take into account the different distances (that have a negligible formal error compared with the error on the observed difference of the peak magnitudes) and extinctions ($E(B - V)$ variations up to $\pm 0.05 - 0.06$ mag around the adopted mean values for the two clusters provide a negligible contribution to the error budget on the luminosity function peak magnitudes), the peak of M4 WD luminosity function is 0.24 ± 0.14 mag brighter than the

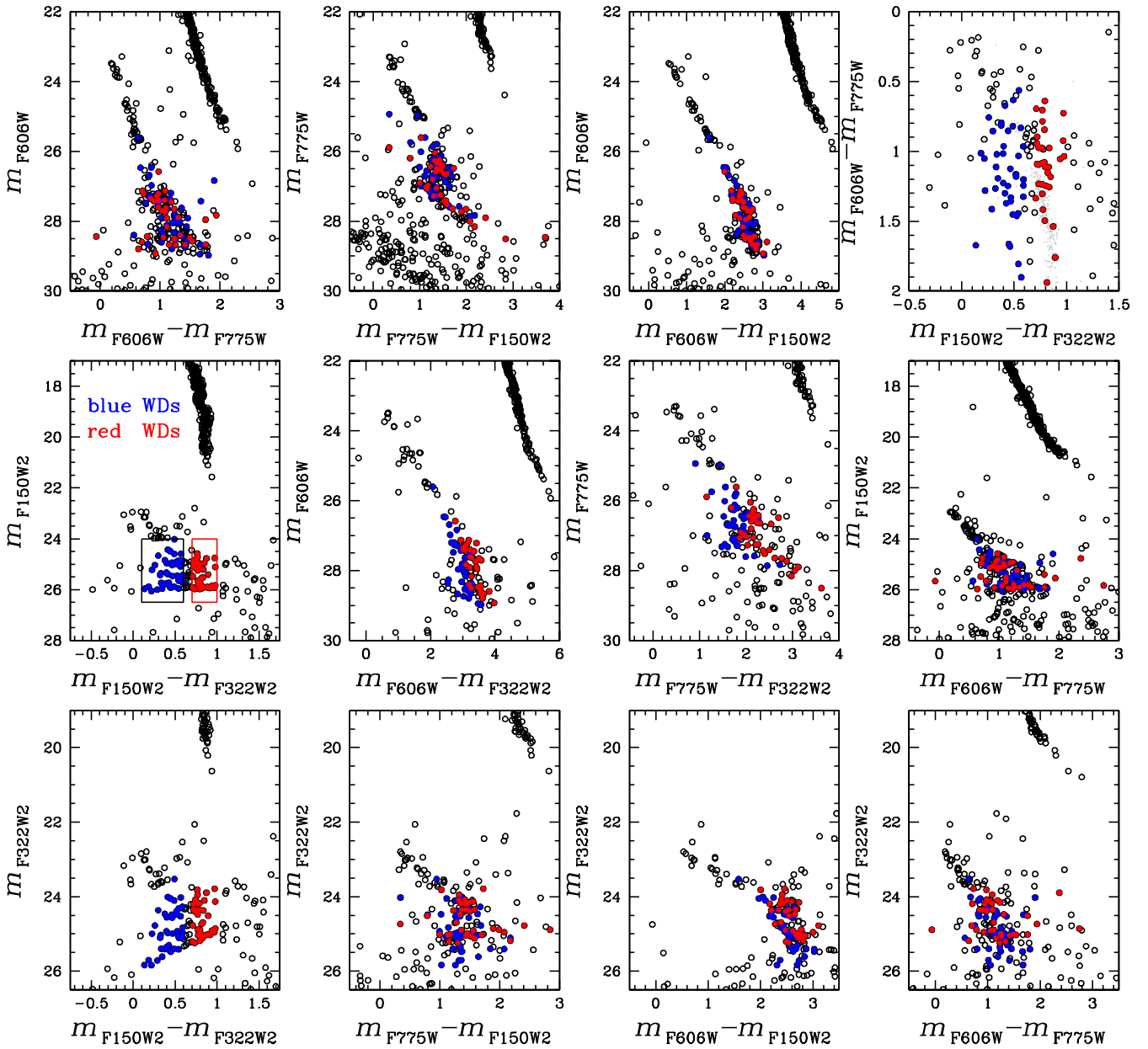


FIGURE 7 | Eleven CMD combinations and one TCD from the four *HST* and the *JWST* filters employed in this study. These figures highlight the red and blue WD samples defined in the F150W2 – F322W2 vs. F322W2 CMD (leftmost panel in the middle row). In the TCD we have marked as gray-small dots the main sequence stars (top-right panel). In summary, the color dispersion of the faint end of the WD CS of M4 appears considerably larger than what was expected on the basis of the photometric errors, but this excess seems to be present only in filter F322W2. Those sources, defined as red WDs, appear to show an excess only in filter F322W2 (by as much as ~ 0.5 mag).

NGC 6397 counterpart. This corresponds to an age difference Δt equal to 0.8 ± 0.5 Gyr, using Salaris et al. (2022) WD models. Considering the error on Δt we find that M4 is only very marginally younger than NGC 6397, if at all.

Such a small value of Δt is broadly consistent with the differences between the clusters' main sequence turn-off ages obtained by Salaris and Weiss (2002) and Marin-Franch et al. (2009), who found the two clusters virtually coeval within the errors (errors equal to 1.1 Gyr for Salaris and Weiss 2002, and 0.7 Gyr for Marin-Franch et al. 2009), whilst the turn-off ages determined by

VandenBerg et al. (2013) give a more significant age difference $\Delta t = 1.5 \pm 0.5$, M4 being younger.

In terms of absolute age our derived value of Δt translates to 12.2 ± 0.5 Gyr for M4, consistent with the best estimate of 12.1 Gyr derived by Hansen et al. (2004) from their analysis of M4 white dwarf cooling sequence.

The absolute turn-off based ages of M4 derived by Salaris and Weiss (2002) and Marin-Franch et al. (2009) are in the range 11.7–11.9 Gyr and 12.7–13.3 Gyr (with the previously quoted

errors), respectively, the exact values depending on adopted [Fe/H] scale and set of theoretical isochrones, while VandenBerg et al. (2013) obtain 11.5 ± 0.4 Gyr.

5 | Conclusions

This study offers our first in-depth view of the M4 system at infrared wavelengths. Future studies will build on these data to explore the main sequence (MS) population into the substellar regime, analyze field populations surrounding the cluster, and examine cluster kinematics. In this work, we focused on the IR counterpart of the complete white dwarf cooling sequence in M4, previously observed in the optical through deep *HST* observations (Bedin et al. 2009). The results of this work can be summarized as follows:

- To verify the current predictions of CIA effects along the WD CS for only the second time in a globular cluster (after NGC 6397, Paper I), we focus on M4, a cluster with significantly different chemical composition, age, and kinematic status compared with NGC 6397. Our observations show that the model predictions are consistent with the data within the uncertainties, also for M4.
- Searching for WDs with possible IR excess, we found that the WDs with magnitudes between $m_{F322W2} = 24$ and 26 exhibit a color distribution significantly broader (~ 0.17 mag) than the expected errors (~ 0.10 mag), and somehow compatible with the recent findings in Paper I for NGC 6397, where $\sim 25\%$ displayed IR excess. In the case of M4, however, while the breadth of the bottom part of the WD CS is also a notable and significant feature—as 50% larger than the expected errors—there is no indication for a separation between two populations. This could be due to the limited sample of members and to the degraded photometry in the dense cluster core region probed, the only area for which proper motion memberships were available.
- By comparing the absolute $F150W2$ magnitudes of the luminosity function peak at the bottom of the observed WD CSs in M4 and NGC 6397, we find only marginal evidence suggesting that M4 is slightly younger, by 0.8 ± 0.5 Gyr. This age difference translates to an absolute age 12.2 ± 0.5 Gyr for M4.
- Finally, one of our goals is to make publicly available our reduced data, high-accuracy photometric catalogue for members, and atlases in multiple filters as part of this article's supplementary online material.³ Further theoretical investigations by other independent groups might find these data useful.

We plan to extend these observations to additional long-wavelength NIRCcam filters (e.g., F444W) and possibly to MIRI at $10 \mu\text{m}$ (F1000W). This will enable us to confirm and eventually spectroscopically characterize the infrared excess detected around a significant fraction of M4 WDs. This approach could help disentangle the possible contributions from sub-stellar companions and/or dust emission (Reach et al. 2005; Swan et al. 2023). A future *JWST* epoch also will allow us to extend proper-motion membership to a larger sample of WD members and to fainter objects, well into the BD sequence.

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Conflicts of Interest

The authors declare no conflicts of interest.

Endnotes

¹ Plate ID: A376 collected 1982/07/28.

² We used the extinction law by Gordon et al. (2023) that covers the wavelength range of our chosen IR filters.

³ https://web.oapd.inaf.it/bedin/files/PAPERS_eMATERIALs/JWST/GO-1979/P05/.

References

- Anderson, J., A. Sarajedini, L. R. Bedin, et al. 2008. “The ACS Survey of Globular Clusters. V. Generating a Comprehensive Star Catalog for Each Cluster.” *Astronomical Journal* 135, no. 6: 2055–2073.
- Baumgardt, H., and E. Vasiliev. 2021. “Accurate Distances to Galactic Globular Clusters Through a Combination of Gaia EDR3, HST, and Literature Data.” *Monthly Notices of the Royal Astronomical Society* 505, no. 4: 5957–5977.
- Bedin, L. 2004. “Solving the Problem of the White Dwarf Cooling Sequence End in M4: An Efficient Approach. HST Proposal.” Cycle 13, ID. #10146.
- Bedin, L. R., J. Anderson, D. Apai, et al. 2021. “The Faintest and Coolest Stars in the Two Closest Globulars. JWST Proposal.” Cycle 1, ID. #1979.
- Bedin, L. R., S. Cassisi, F. Castelli, et al. 2005. “Transforming Observational Data and Theoretical Isochrones Into the ACS/WFC Vega-Mag System.” *Monthly Notices of the Royal Astronomical Society* 357, no. 3: 1038–1048.
- Bedin, L. R., I. R. King, J. Anderson, et al. 2008. “Reaching the End of the White Dwarf Cooling Sequence in NGC 6791.” *Astrophysical Journal* 678, no. 2: 1279–1291.
- Bedin, L. R., D. Nardiello, M. Salaris, et al. 2024. “JWST Imaging of the Closest Globular Clusters—I. Possible Infrared Excess Among White Dwarfs in NGC 6397.” *Astronomische Nachrichten* 345: e20240039.
- Bedin, L. R., G. Piotto, I. R. King, and J. Anderson. 2003. “Hubble Space Telescope Astrometry of m4 and the Galactic Constant V_0/R_0 .” *Astronomical Journal* 126, no. 1: 247–254.
- Bedin, L. R., M. Salaris, G. Piotto, J. Anderson, I. R. King, and S. Cassisi. 2009. “The End of the White Dwarf Cooling Sequence in M4: An Efficient Approach.” *Astrophysical Journal* 697, no. 2: 965–979.
- Bellini, A., J. Anderson, L. R. Bedin, et al. 2017. “The State-of-the-Art HST Astro-Photometric Analysis of the Core of ω Centauri. I. The Catalog.” *Astronomical Journal* 842, no. 1: 6.
- Bono, G., M. Salaris, and R. Gilmozzi. 2013. “On the White Dwarf Cooling Sequence With Extremely Large Telescopes.” *Astronomy & Astrophysics* 549: A102.

- Bushouse, H., J. Eisenhamer, N. Dencheva, et al. 2023. "JWST Calibration Pipeline."
- Carretta, E., A. Bragaglia, R. Gratton, V. D'Orazi, and S. Lucatello. 2009. "Intrinsic Iron Spread and a New Metallicity Scale for Globular Clusters." *Astronomy & Astrophysics* 508, no. 2: 695–706.
- Chu, Y.-H., K. Y. L. Su, J. Bilikova, et al. 2011. "Spitzer 24 μ m Survey for Dust Disks Around Hot White Dwarfs." *Astronomical Journal* 142, no. 3: 75.
- Forbes, D. A., N. Bastian, M. Gieles, et al. 2018. "Globular Cluster Formation and Evolution in the Context of Cosmological Galaxy Assembly: Open Questions." *Proceedings of the Royal Society of London Series A* 474, no. 2210: 20170616.
- Gerasimov, R., L. R. Bedin, A. J. Burgasser, et al. 2024. "JWST Imaging of the Closest Globular Clusters. II. Discovery of Brown Dwarfs in NGC 6397 and Measurement of Age From the Brown Dwarf Cooling Sequence, Using SANDee—A New Grid of Model Isochrones Across the Hydrogen-Burning Limit." *Astrophysical Journal* 971, no. 1: 65.
- Gordon, K. D., G. C. Clayton, M. Declair, et al. 2023. "One Relation for All Wavelengths: The Far-Ultraviolet to Mid-Infrared Milky Way Spectroscopic R(V)-Dependent Dust Extinction Relationship." *Astrophysical Journal* 950, no. 2: 86.
- Griggio, M., D. Nardiello, and L. R. Bedin. 2023. "Photometry and Astrometry With JWST-II: NIRCам Distortion Correction." *Astronomische Nachrichten* 344, no. 3: e20230006.
- Hansen, B. M. S., J. Anderson, J. Brewer, et al. 2007. "The White Dwarf Cooling Sequence of NGC 6397." *Astrophysical Journal* 671, no. 1: 380–401.
- Hansen, B. M. S., J. Brewer, G. G. Fahlman, et al. 2002. "The White Dwarf Cooling Sequence of the Globular Cluster Messier 4." *Astrophysical Journal* 574, no. 2: L155–L158.
- Hansen, B. M. S., and E. S. Phinney. 1998. "Stellar Forensics. I. Cooling Curves." *Monthly Notices of the Royal Astronomical Society* 294: 557–568.
- Hansen, B. M. S., H. B. Richer, G. G. Fahlman, et al. 2004. "Hubble Space Telescope Observations of the White Dwarf Cooling Sequence of M4." *Astrophysical Journal Supplement* 155, no. 2: 551–576.
- Hendricks, B., P. B. Stetson, D. A. Vandenberg, and M. Dall'Ora. 2012. "A New Reddening Law for M4." *Astronomical Journal* 144, no. 1: 25.
- Kalirai, J. S., and H. B. Richer. 2010. "Star Clusters as Laboratories for Stellar and Dynamical Evolution." *Philosophical Transactions of the Royal Society of London. Series A* 368, no. 1913: 755–782.
- Leaman, R., D. A. Vandenberg, and J. T. Mendel. 2013. "The Bifurcated Age-Metallicity Relation of Milky Way Globular Clusters and Its Implications for the Accretion History of the Galaxy." *Monthly Notices of the Royal Astronomical Society* 436, no. 1: 122–135.
- Libralato, M., A. Bellini, E. Vesperini, et al. 2022. "The Hubble Space Telescope UV Legacy Survey of Galactic Globular Clusters. XXIII. Proper-Motion Catalogs and Internal Kinematics." *Astrophysical Journal* 934, no. 2: 150.
- Libralato, M., R. Gerasimov, L. Bedin, et al. 2024. "JWST Imaging of the Closest Globular Clusters – IV. Chemistry, Luminosity, and Mass Functions of the Lowest-Mass Members in the NIRISS Parallel Fields." *Astronomy & Astrophysics* 690: A371.
- Marín-Franch, A., A. Aparicio, G. Piotto, et al. 2009. "The ACS Survey of Galactic Globular Clusters. VII. Relative Ages." *Astrophysical Journal* 694, no. 2: 1498–1516.
- Nardiello, D., L. R. Bedin, A. Burgasser, et al. 2022. "Photometry and Astrometry With JWST – I. NIRCам Point Spread Functions and the First JWST Colour-Magnitude Diagrams of a Globular Cluster." *Monthly Notices of the Royal Astronomical Society* 517, no. 1: 484–497.
- Nardiello, D., L. R. Bedin, M. Griggio, M. Salaris, M. Scalco, and S. Cassisi. 2023. "Photometry and Astrometry With JWST – III. A NIRCам-Gaia DR3 Analysis of the Open Cluster NGC 2506." *Monthly Notices of the Royal Astronomical Society* 525, no. 2: 2585–2604.
- Nardiello, D., M. Griggio, and L. R. Bedin. 2023. "JWST Unveils the Brown Dwarf Sequence of 47 Tucanae." *Monthly Notices of the Royal Astronomical Society* 521, no. 1: L39–L43.
- Pietrinferni, A., S. Hidalgo, S. Cassisi, et al. 2021. "Updated BaSTI Stellar Evolution Models and Isochrones. II. α -Enhanced Calculations." *Astrophysical Journal* 908, no. 1: 102.
- Piotto, G., A. P. Milone, L. R. Bedin, et al. 2015. "The Hubble Space Telescope UV Legacy Survey of Galactic Globular Clusters. I. Overview of the Project and Detection of Multiple Stellar Populations." *Astronomical Journal* 149, no. 3: 91.
- Reach, W. T., M. J. Kuchner, T. von Hippel, et al. 2005. "The Dust Cloud Around the White Dwarf G29-38." *Astrophysical Journal* 635, no. 2: L161–L164.
- Salaris, M., S. Cassisi, A. Pietrinferni, and S. Hidalgo. 2022. "The Updated BaSTI Stellar Evolution Models and Isochrones – III. White Dwarfs." *Monthly Notices of the Royal Astronomical Society* 509, no. 4: 5197–5208.
- Salaris, M., and A. Weiss. 2002. "Homogeneous Age Dating of 55 Galactic Globular Clusters. Clues to the Galaxy Formation Mechanisms." *Astronomy & Astrophysics* 388: 492–503.
- Scalco, M., M. Libralato, R. Gerasimov, et al. 2024. "JWST Imaging of the Closest Globular Clusters: III. Multiple Populations Along the Low-Mass Main-Sequence Stars of NGC 6397." *Astronomy & Astrophysics* 689: A59.
- Su, K. Y. L., Y. H. Chu, G. H. Rieke, et al. 2007. "A Debris Disk Around the Central Star of the Helix Nebula?" *Astrophysical Journal* 657, no. 1: L41–L45.
- Swan, A., J. Farihi, C. Melis, et al. 2023. "Planetesimals at DZ Stars – I. Chondritic Compositions and a Massive Accretion Event." *Monthly Notices of the Royal Astronomical Society* 526, no. 3: 3815–3831.
- Vandenberg, D. A., K. Brogaard, R. Leaman, and L. Casagrande. 2013. "The Ages of 55 Globular Clusters as Determined Using an Improved Delta VHB_TO Method Along With Color-Magnitude Diagram Constraints, and Their Implications for Broader Issues." *Astrophysical Journal* 775, no. 2: 134.
- Vasiliev, E., and H. Baumgardt. 2021. "Gaia EDR3 View on Galactic Globular Clusters." *Monthly Notices of the Royal Astronomical Society* 505, no. 4: 5978–6002.
- Vitral, E., M. Libralato, K. Kremer, et al. 2023. "An Elusive Dark Central Mass in the Globular Cluster M4." *Monthly Notices of the Royal Astronomical Society* 522, no. 4: 5740–5757.