Still at Odds with Conventional Galaxy Evolution: The Star Formation History of Ultra-Diffuse Galaxy Dragonfly 44

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ABSTRACT

We study the star formation history (SFH) of the ultra-diffuse galaxy (UDG) Dragonfly 44 (DF44) based on the simultaneous fit to near-ultraviolet to near-infrared photometry and high signal-to-noise optical spectroscopy. In fitting the observations we adopt an advanced physical model with a flexible SFH, and we discuss the results in the context of the degeneracies between stellar population parameters. Through reconstructing the mass-assembly history with a prior for extended star formation (akin to methods in the literature) we find that DF44 formed 90 percent of its stellar mass by \( z \approx 0.9 \) (\( \sim 7.2 \) Gyr ago). In comparison, using a prior that prefers concentrated star formation (as informed by previous studies of DF44’s stellar populations) suggests that DF44 formed as early as \( z \approx 8 \) (\( \sim 12.9 \) Gyr ago). Regardless of whether DF44 is old or very old, the SFHs imply early star formation and rapid quenching. This result, together with DF44’s large size and evidence that it is on its first infall into the Coma cluster, challenges UDG formation scenarios from simulations that treat all UDGs as contiguous with the canonical dwarf population. While our results cannot confirm any particular formation scenario, we can conclude from this that DF44 experienced a rare quenching event.

Key words: galaxies: evolution – galaxies: dwarfs

1 INTRODUCTION

Matching predictions to observations of how, and when, galaxies assemble serves as an important test for our greater understanding of cosmology and baryonic physics. Modern theories that suggest galaxy evolution is determined by the growth of their dark matter haloes, as well as the regulation of their gas processes (e.g., White & Frenk 1991; Schaye et al. 2010; Davé et al. 2012; Wechsler & Tinker 2018), have successfully replicated some observed relations between galaxy properties – for example, the tight connection between stellar mass and halo mass (i.e., the SMHM relation; Moster et al. 2010). A number of outstanding issues remain, however. A particularly challenging problem is explaining the increasing number of galaxies that cease forming stars (i.e., ‘quench’) over time (Renzini 2006; Faber et al. 2007). While simulations correctly predict scaling relations for massive galaxies (e.g., the mass–metallicity relation; MZR, and star formation main sequence), there are still fundamental discrepancies at lower stellar masses.

In the low mass regime, observations have shown that quenched galaxies associated with massive host haloes are rare (Geha et al. 2012), such that quenching at \( z < 1 \) is thought to predominantly be a result of environmental effects (e.g., Boselli & Gavazzi 2006; Fillingham et al. 2018; Mao et al. 2021). Rather than remain quenched, recent studies instead suggest that isolated quiescent dwarfs may in fact oscillate between ‘star forming’ and ‘quenched’ states (e.g., Polzin et al. 2021). Yet cosmological simulations typically over-predict the abundance of quiescent field dwarfs (e.g., Dickey et al. 2021).

The recently discovered ultra-diffuse galaxies (UDGs) potentially exemplify our limited understanding of the true diversity of galaxy evolution and quenching. UDGs were initially noted for their surprisingly large sizes given their low surface brightnesses (\( R_{\text{eff}} \geq 1.5 \) kpc and \( \mu_0(g) \geq 24 \) mag arcsec\(^{-2}\); van Dokkum et al. 2015) which, along with their red colours, distinguished them from classical low surface brightness (LSB) galaxies (e.g., Dalcanton et al. 1997).

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Several current cosmological model predictions suggest that conventional processes can explain the UDG population, thus maintaining standard dark matter halo occupancy relations (e.g., Tremmel et al. 2020). Such models typically focus on the mechanisms which increase the size of otherwise canonical dwarf galaxies to make them ‘ultra-diffuse’ (for a summary of UDG origins see Jiang et al. 2019a). Simulations have shown that unusual star formation or galaxy evolution processes can ‘puff up’ canonical dwarfs (e.g., high-spin scenarios, Amorisco & Loeb 2016; Rong et al. 2017; energetic star formation feedback, Di Cintio et al. 2017; Chan et al. 2018; Jackson et al. 2021) or dynamically redistribute their stellar populations (e.g., tidal heating and/or stripping; Jiang et al. 2019a; Liao et al. 2019; Carleton et al. 2019; Sales et al. 2020). Alternatively, UDGs may represent the tail of galaxy evolution processes, such that only minor differences in their evolution (e.g., when they infall or have major mergers) distinguish their final properties from normal dwarfs (e.g., Tremmel et al. 2020; Wright et al. 2021).

Despite these differences, nearly all models rely on environmental processes to explain the lack of star formation in the subset of UDGs that are quiescent (e.g., via ram pressure stripping; Yozin & Bekki 2015; Rong et al. 2017; Chan et al. 2018; Tremmel et al. 2020). Accordingly, all of the scenarios follow a dichotomy related to when UDGs infall into a cluster environment: whether the proto-UDGs surpassed the size-threshold prior-to or post infall, is tied to whether they infall ‘late’ or ‘early’. While UDGs are found both in the field and clusters, those that are quiescent are usually located in clusters (the few exceptions may be on backsplash orbits; e.g., Papastergis et al. 2017; Benavides et al. 2021). Explaining the origin of UDGs and the diversity of their properties in the context of their environments remains a key question in understanding galaxy formation and evolution.

Testing the predicted UDG properties (e.g., kinematics, Amorisco & Loeb 2016; stellar populations, Rong et al. 2017; Ferré-Mateu et al. 2018; globular cluster (GC) properties, Carleton et al. 2021; infall versus quenching times, Gunn et al. 2022) from these scenarios against the observed properties, however, has revealed a number of discrepancies. And while some UDGs are found with very large sizes ($R_{\text{eff}} > 4.5$ kpc), these exotic objects are beyond the predictions of most models (Di Cintio et al. 2017; Carleton et al. 2019). Along the same lines, models which accurately predict the distribution of UDG sizes fail to reproduce the distribution of sizes among normal dwarfs (e.g., Rong et al. 2017; Jiang et al. 2019a; Tremmel et al. 2020).

On the other hand, van Dokkum et al. (2015) proposed that some UDGs originate similar to today’s massive galaxies (and have sizes reflecting their massive haloes), but lost their gas early in their histories. As a result of their early quenching, these ‘failed’ galaxies did not build up the stellar mass expected for their haloes. This scenario deviates from the expected galaxy–halo connection, in that either these failed galaxies do not follow the SMHM relation or at least have a larger scatter than the standard relation.

A particularly interesting UDG is Dragonfly 44 (DF44) which is the largest galaxy in the original van Dokkum et al. (2015) sample, with $R_{\text{eff}} = 4.7 \pm 0.2$ kpc (van Dokkum et al. 2017). High S/N spectroscopy has revealed an extremely old and metal-poor stellar population ($\sim 2.3\sigma$ below the canonical dwarf MZR; Villaume et al. 2022), implying that DF44 quenched very early and over a short timescale. Moreover, while DF44 appears to have very low rotation (van Dokkum et al. 2019) characteristic of dwarf spheroidal galaxies, the stellar population gradients are ‘inverted’ compared to the gradients typical of dwarf spheroidals (Villaume et al. 2022). Regardless of whether DF44 has an over-massive halo or not (van Dokkum et al. 2017; Wasserman et al. 2019; Bogdán 2020; Lee et al. 2020; Saifolalahi et al. 2021), this UDG is inconsistent with the majority of UDG formation models.

Late-quenching (after infall into a dense environment) scenarios can be ruled out for DF44 given its old age (e.g., Rong et al. 2017; Chan et al. 2018; Liao et al. 2019; Jiang et al. 2019a; Jackson et al. 2021). Moreover, DF44’s low rotation conflicts with high-spin scenarios (e.g., Rong et al. 2017; although the rotation could increase at larger radii, Grishin et al. 2021). Yet, given the uncertainty in establishing the cluster infall time for an individual galaxy, we cannot preclude early-infall scenarios (e.g., Yozin & Bekki 2015; Liao et al. 2019; Carleton et al. 2019, 2021; Tremmel et al. 2020). While some evidence (e.g., Alabi et al. 2018; van Dokkum et al. 2019) suggests that DF44 is on its first infall into Coma, this is difficult to prove.

There is more to be learned, however, as UDG formation scenarios can be tested via their inferred star formation histories (SFHs). The time-scales of star formation reveal important epochs (e.g., mergers, infall, and/or quenching), which can be compared against observations. A number of studies have investigated the ages and mass assembly histories of UDGs, relying either only on broadband colours, or low to moderate S/N spectroscopy (e.g., Kadowaki et al. 2017; Ferré-Mateu et al. 2018; Gu et al. 2018; Pandya et al. 2018; Ruiz-Lara et al. 2018; Martín-Navarro et al. 2019; Buzzo et al. 2022, submitted). While these studies provide important first steps, comparisons with predictions are not necessarily straightforward. This is primarily because constraining the detailed shape of a galaxy’s SFH is a complex problem.

Several galaxy properties can conspire to alter the spectral energy distribution (SED) in similar ways (e.g., stellar age, metallicity, and dust), which are particularly difficult to disentangle with low spectral resolution data (e.g., with photometry alone; Bell & de Jong 2001). Recovering the SFHs for old stellar populations is particularly difficult – the integrated spectrum evolves non-linearly with age (Serra & Trager 2007) such that old populations appear relatively similar (for a complete discussion see the review by Conroy 2013). Moreover, a late burst of star formation can ‘outshine’ a (dominant) older population (e.g., Papovich et al. 2001; Allanson et al. 2009). While broad wavelength coverage is needed to precisely determine the dust absorption (and emission, with mid-infrared coverage), high resolution data of select spectral features are needed to precisely constrain the stellar metallicity and age. Both observations are necessary to break the degeneracy between these parameters (e.g., Vazdekis 1999; Trager et al. 2000). Using spectra that span a relatively wide wavelength range, full-spectrum fitting has proven to be effective in this respect (e.g., MacArthur et al. 2009; Sánchez-Blázquez et al. 2011). However, this technique requires a well-calibrated spectral continuum. Simultaneously fitting photometry and spectra can bypass this issue, as the photometry provides a means to fit the continuum and increases the wavelength coverage.

In fitting the data it is necessary to impose ‘prior knowledge’, such as the flexibility of the SFH. The choice of a prior for the shape of the SFH can significantly impact age estimates, particularly for older stellar populations, and for low resolution and/or low S/N data (as shown in, e.g., Maraston 2005; Leja et al. 2017, 2019; Han & Han 2018; Carnall et al. 2019). In order to draw connections between the

\[ 1 \text{ In practice it is generally easier to calibrate photometry to standard filters than to calibrate a spectrum.} \]

\[ 2 \text{ 'Prior' here is used in the Bayesian sense, where the probability of a model given the data (i.e., the 'posterior') is proportional to both the likelihood of the data (given the model) and the prior knowledge about the model.} \]
predicted and observed properties of UDGs it is necessary to give
due attention to the choice of a prior. While it is advantageous to use
flexible models together with physically motivated priors, a ‘good
prior’ is not necessarily known a priori. Therefore, results should
be discussed in the context of the prior used (which may not be as
‘uninformative’ as intended; e.g., Leja et al. 2019).

In this work we simultaneously fit near-ultraviolet (NUV) to near-
infrared (NIR) photometry (nine bands) with high S/N (~ 96 Å−1)
(rest-frame optical spectroscopy (from KCWI, the Keck Cosmic Web
Imager). The same data set was used in van Dokkum et al. (2019) and
Villaume et al. (2022) to study the stellar kinematics and populations
of DF44. We adopt flexible SFHs in our fiducial model which do not
assume a certain shape with time. Moreover, we compare the results
between SFH priors of different degrees of ‘smoothness’ in order to
identify which results are fully constrained by the observations. We
address the unique stellar population properties of this UDG, and its
epoch of formation and quenching, in order to test models of UDG
formation.

The data are described in Section 2, and Section 3 details how we
fit the data with an advanced physical model. In Section 4 we discuss
the results, and put the results in the context of the literature. What our
results imply about the origins of DF44 in the context of theoretical
models is discussed in Section 5. A summary of the key results is
provided in Section 6. The SFHs of DF44 determined by this work are
listed in full in Appendix A. We provide additional details on
systematic biases and degeneracies between dust extinction and the flux
from old stellar populations in Appendix C.

2 DATA

Our data for DF44 include both rest-frame optical spectroscopy and
NUV to NIR photometry, shown in Fig. 1, and described in more
detail below. We assume the spectroscopic redshift measured by van
Dokkum et al. (2017): \( z = 0.02132 \pm 0.00002 \).

2.1 Spectroscopy

The spectroscopy is described in detail in van Dokkum et al. (2019)
and analysed further in Villaume et al. (2022); we summarise the
relevant details here.

Of particular note is the sky subtraction, as the sky is much brighter
than the UDG. Sky exposures were obtained 1.5 away from DF44 in-
termittently between DF44 observations. The wavelength-dependent
time variation in the sky spectrum was obtained from the spatially
collapsed individual sky spectra, as parameterised by principal com-
ponent analysis (PCA). The sky in each science cube was determined
from a linear combination of templates, where the bestfit sky spec-
trum for the given exposure was subtracted from each spatial pixel.
Additional details are provided in van Dokkum et al. (2019).

KCWI integral field spectroscopy was obtained for DF44 and spec-
tra were extracted in nine elliptical apertures after masking the ten
brightest point sources. The apertures were sized 9″ × 6″, to match
the UV photometry; see the following section. The integrated spec-
trum was determined through bootstrapping the individual spectra,
where we used the 50th percentile of the bootstrapped flux distribu-
tion and the average of the 16th and 84th percentile as the uncertainty.

With 17 hours of exposure on-target, the integrated spectrum reaches
a S/N ~ 96 Å−1 (see the third panel in Fig. 1).

The KCWI Medium slicer with BM grating was used, yielding a spectral resolution of \( R = 4000 \). After masking and interpolating
over regions badly affected by sky transmission, the spectrum was
smoothed to a resolution of 110 km s\(^{-1}\), for the purpose of later
comparing with templates at this resolution. The final spectrum is
shown in Fig. 1 (the unsmeared spectrum shown with grey lines),
covering 4578–5337 Å rest-frame, with notable absorption features
labelled. Also shown is the S/N of the spectrum as a function of
wavelength.

Given the challenge of precisely flux-calibrating the spectrum
(e.g., due to residuals from the spectral extraction), we instead rely
on the calibration of the photometry to provide constraints on the
SED continuum when fitting the galaxy properties and SFH (see
Section 3). For this reason we do not flux calibrate the spectrum,
and the continuum shape therefore reflects primarily the instrument
response function and not the galaxy SED. We then effectively flat-
ten the continuum by dividing through by a polynomial fit. In the
fitting routine we therefore need to marginalise over the shape of the
spectral continuum in comparing the models to the observations (see
Section 3.3).

Lastly, we chose to mask the spectrum between 4700–4750 Å
rest-frame where there is a broad dip in the spectrum that does not
appear in the models. We note that the blue end of the spectrum
(\( \lesssim 4800 \) Å) was not fitted by either van Dokkum et al. (2019) or
Villaume et al. (2022). Our results are not impacted by masking this
region of the spectrum, although the \( \chi^2 \) values are slightly higher
without masking.

2.2 Photometry

Photometry in all the broadband images was performed by measuring
fluxes within a 9″ × 6″ elliptical aperture, with a position angle of
65 degrees, to be consistent with the UV photometry reported by Lee
et al. (2020). As this is significantly larger than the image resolution
in all filters, no point spread function homogenisation was applied,
though appropriate aperture corrections are made to the Spitzer and
GALEX images to account for light lost outside the aperture due to
the point spread function. Details on the reduction and analysis of
each image is described in more detail, below. The photometric mea-
surements in each broad-band filter were corrected for foreground
extinction in the Milky Way in the direction of the Coma Cluster
using the website \texttt{http://argonaut.skymaps.info/usage} and
Table 6 of Schlafly & Finkbeiner (2011) with \( RV = 3.1 \).

2.2.1 Spitzer-IRAC Near-Infrared (NIR) Imaging

\textit{Spitzer}-IRAC (Fazio et al. 2004; Werner et al. 2004) observations of
DF44 were taken on 2017 May 12 starting at 07:19 (UT). Both 3.6
and 4.5 \( \mu \)m (channels 1 and 2, respectively) observations were taken.
50 medium-scale (median dither separation 53 pixels) cycling dither
pattern 100 second frames were taken in each channel. The total exposure time was 93.6 × 50 = 4680 s in channel 1 and 96.8 × 50 =
4840 s in channel 2.

We removed the ‘first-frame correction’ (to address imperfect bias
subtraction; see Section 5.1.10 of the IRAC Instrument Handbook).
The rectification of each individual data frame for history effects in
the IRAC arrays was performed in two steps that are explained
in detail in Pandya et al. (2018). In short, we first performed a per pixel correction that was based on IRAC idling time characteristics in the IRAC skydarks, matched to those that took place before our observations. The typical magnitude of the per pixel correction was about 4 kJy sr$^{-1}$ in channel 1 and 1 kJy sr$^{-1}$ in channel 2. The typical corrections are much smaller than the read noise error and we do not add any systematic magnitude uncertainties due to these first-frame corrections.

In the second step, a mean background is calculated for each frame, and a function fitted to these means is subtracted. The typical function consisted of a constant term plus terms that are declining exponentially with time. The uncertainties in these first-frame effect corrections are negligible compared to other sources of systematic error. We also formed a median image after doing a $3\sigma$ clipping from all the frames on the source in each channel and subtracted that median image separately in each frame. Such a median image will subtract the residual images that have been formed on the detector from previous observations. We determined that the uncertainty in the final magnitudes added by this step is less than 0.01 mag.

The DF44 frames include a point source on top of the faint galaxy. We used Spitzer Science Center provided software MOPEX, specifically the APEX and APEX-QA modules, to subtract this point source using point response function (PRF) fitting. The estimated uncertainty due to this step is about 0.5 micro-Jy in both channels.

We used the contributed Spitzer/IRAC software IMCLEAN (Jhora99 2021) to remove leftover column pulldown artefacts from the CBCD frames. We then used the Spitzer custom software package MOPEX to create mosaics of the 50 frames in each channel, using the default parameters and the North up, East left orientation. Before mosaicking we ran the overlap correction module to adjust for background offsets among the CBCD frames (one number per frame).
We used only the multiframe outlier rejection scheme in MOPEX to reject outlier pixels in the input frames.

Next we manually created masks of other sources (including point-like sources on the galaxy) in both channels with the custom software GIPSY (van der Hulst et al. 1992). We then measured the ‘sky background’ in five empty areas of sky close to DF44 in channels 1 and 2, and from the results we estimated an average sky background (0.00408 and 0.00415 MJy sr$^{-1}$ in channels 1 and 2, respectively) to be subtracted at the position of DF44, applying the mask and using Astropy Python library commands in a 9$''$ × 6$''$ (P.A. +65°) aperture centred on the coordinates given by van Dokkum et al. (2015): R.A. = 13$^h$00$^m$58$''$.0, Dec. = 26°58'35''. We corrected the results with the appropriate aperture corrections from the IRAC Instrument Handbook.

The uncertainty in aperture photometry was estimated by performing aperture photometry on several positions in empty sky and taking the rms scatter in these measurements. This gave 0.05 and 0.10 mag in IRAC channels 1 and 2, respectively. We estimated the uncertainty due to masking by replacing the pixel values under the masks by the average pixel values within the unmasked aperture, and performed the photometry again, and took the difference between this measurement and the measurement using the masks as the uncertainty. The channel 1 masking uncertainty is thus 0.14 mag, and 0.18 mag for channel 2.

The sky background subtraction uncertainty is estimated by taking the maximum difference in the sky background measurements in three areas of empty sky around DF44 in the images and adding them up. This method gives 0.01 mag and 0.11 mag as the sky uncertainty in channels 1 and 2, respectively.

The calibration uncertainty was estimated to be 2 per cent in IRAC channels 1 and 2, amounting to 0.02 mag in systematic uncertainty. There is an additional uncertainty of 9 per cent in channel 1 and 2 per cent fractional flux in channel 2 due to the uncertainty in integrated aperture flux correction factor (limiting case is infinite aperture). These convert to 0.09 and 0.02 mag in channels 1 and 2. In addition there is the point source subtracting uncertainty of 0.01 mag.

We list the final AB magnitudes for channels 1 and 2 and their respective uncertainties in Table 1.

### 2.2.2 Gemini GMOS g- and i-Band Imaging

DF44 was observed on 2017 May 12 with the Gemini Multi-Object Spectrometer (GMOS) for a total of 3000 s in both the g- and i-bands. The observations have been described by van Dokkum et al. (2016). We flux-calibrated the images with SDSS, accounting for a g − i colour term and using four SDSS catalogued stars in our images. The data were obtained in photometric conditions, and we adopt an absolute calibration magnitude uncertainty to be 3 per cent, amounting to 0.03 mag in the g- and i-bands, based on https://www.gemini.edu/instrumentation/gmos/calibrations. The sky background uncertainty was calculated as above for the IRAC channels, and amounted to 0.03 mag in the g-band and 0.09 mag in the i-band. Aperture photometry was performed using the coordinates from van Dokkum et al. (2015) and the Astropy Python library commands.

We list the final AB magnitudes for the g- and i-bands and the respective uncertainties in Table 1.

### Table 1. DF44 Photometry.

| Filter | $m_0$ (AB) | $\lambda_{\text{eff}}$ (Å) |
|--------|------------|--------------------------|
| UVOT UV1 | 23.40 ± 0.19 | 2516.7 |
| UVOT UV2 | 24.97 ± 0.41 | 2010.4 |
| GALEX NUV | 23.67 ± 0.35 | 2271.1 |
| GMOS g_G0301 | 20.02 ± 0.14 | 4687.6 |
| GMOS i_G0302 | 19.33 ± 0.18 | 7751.6 |
| WFC3 F606W | 19.80 ± 0.08 | 5813.0 |
| WFC3 F814W | 19.32 ± 0.19 | 7972.9 |
| IRAC1 | 20.09 ± 0.18 | 35439.4 |
| IRAC2 | 20.45 ± 0.24 | 44840.9 |

### 2.2.3 HST/WFC3/UVIS F606W and F814W imaging

Additional visual images of DF44 were taken on 2017 April 23 with the Hubble Space Telescope using the WFC3 camera and its UVIS detector and broadband filters F606W and F814W. van Dokkum et al. (2017) reported 5σ AB depths of F606W = 28.4 and F814W = 26.8 for DF44. A total of 2430 s and 2420 s were spent on the source in F606W and F814W filters. In both filters we calculated the sky mode in five different ‘empty’ regions of the sky and took an average and subtracted those values from the images. We also manually masked out point sources in the images. We used the image headers to calculate the conversion from electrons/s to AB magnitudes and performed elliptical aperture photometry within the same apertures as mentioned above for IRAC.

The uncertainties were estimated in the following way: we estimate a photometric calibration offset uncertainty of 0.03 mag, and the uncertainty due to background subtraction (estimated as above) is 0.05 mag in F606W and 0.13 mag in F814W. The uncertainty due to masked point sources within the aperture is estimated to be 0.03 and 0.01 mag in F606W and F814W. The uncertainty in performing aperture photometry was estimated as above and results in an additional 0.05 and 0.14 mag in F606W and F814W.

We list the final AB magnitudes for F606W and F814W and the respective uncertainties in Table 1.

### 2.2.4 Ultraviolet

The UV data reduction and analysis was presented in Lee et al. (2020). This consists of two filters observed with Swift UVOT (UV1 at 2600 Å and UV2 at 1928 Å), and GALEX NUV images. The UVOT data include a correction for red leakage and scattered light, where the correction (14 per cent) was comparable to the flux uncertainty. Again we list the final results in Table 1.

### 3 STELLAR POPULATION MODELLING AND FITTING

In this section we describe how we fit the DF44 observations using the fully Bayesian inference code Prospector (v1.0 Leja et al. 2017; Johnson et al. 2019, 2021b). The photometry and spectroscopy are fitted simultaneously, incorporating the information on the stellar properties and SFH from both data sets. In Section 3.1 we describe the advanced physical model, which includes a non-parametric SFH and a flexible dust attenuation law. We additionally include a white noise and spectral outlier model described in Section 3.2, and a spectrophotometric calibration model which marginalises out the
shape of the spectral continuum, in Section 3.3. A summary of the parameters and priors of our physical model is shown in Table 2. Section 3.4 briefly describes the sampling method.

Table 2. SFH parameters and priors. Notes: 1) Fraction of SFR in a given time bin, where the SFH is a piece-wise constant function with $N$ parameters ($N = 1$ free parameters). The prior is a Dirichlet function, controlled by the parameter $\alpha_D$, see Section 3.1.1. 2) Redshift, with a tight prior about the measured spectroscopic redshift, $z_{spec}$. 3) Total stellar mass is the integral of the SFH, which includes the mass lost to outflows. To convert to stellar mass remaining at the time of observation we regenerate the spectral templates and subtract the mass lost as calculated by FSPS. 4) The total stellar metallicity where scaled-Solar $\alpha$-abundance is assumed. 5) Parameters for the two-component Charlot & Fall (2000) dust absorption model, with an adjustable attenuation curve slope from Noll et al. (2009) with a UV bump based on Kriek & Conroy (2013). 6) Parameters for the Draine et al. (2007) dust emission model. 7) The uncertainty on the spectra can be increased by a given factor, with a likelihood penalty for factors giving reduced $\chi^2<1$. 8) An outlier pixel model can increase the errors for individual pixels by a factor of 50, to accommodate for poor matches between the data and spectral templates. 9) A fourth degree Chebyshev polynomial is fit (via optimisation) to the residual of the normalised ratio between the observed spectrum and the proposed model spectrum and multiplied out prior to each likelihood calculation. This effectively accounts for the lack of flux-calibration in the spectrum.

| Note | Parameter | Description | Prior |
|------|-----------|-------------|-------|
| SFH  | $f_{ni}$  | sSFR fraction. | Dirichlet($\alpha_D$) |
|      | $z_{obs}$ | Redshift | Uniform(min= 0.01, max= $z_{spec} + 0.01$) |
|      | log $M_*/M_\odot$ | Total stellar mass formed | Uniform(min= 8, max= 12) |
|      | log $Z/Z_\odot$ | Stellar metallicity | Uniform(min= -2, max= 0.19) |
|      | $\delta_{dust, diffuse}$ | Diffuse dust optical depth (eq. 2) | Uniform(min= 0, max= 1.5) |
|      | $\delta_{young/dust, diffuse}$ | Ratio of diffuse to birth-cloud dust optical depth (eq. 1) | Clipped Normal($\mu = 1$, $\sigma = 0.3$, min= 0, max= 1.5) |
|      | $n_{dust}$ | Diffuse dust attenuation index | Uniform(min= -2, max= 0.5) |
|      | $Q_{PAH}$ | Percent mass fraction of PAHs in dust | Uniform(min= 0.5, max= 7) |
|      | $U_{min,dust}$ | Minimum starlight intensity to which the dust mass is exposed | Uniform(min= 0.1, max= 25) |
|      | $\gamma_{dust}$ | Mass fraction of dust in high radiation intensity | LogUniform(min= 0.001, max= 0.15) |
| Noise model | spec_jitter | Multiplicative spectral noise inflation term | Uniform(min= 1, max= 3) |
|      | outlier spec | Fraction of spectral pixels considered outliers | Uniform(min= $10^{-5}$, max= 0.5) |
| Spectrophotometric calibration | $c_n$ | Chebyshev polynomial coefficients, $n = 4$ |

3.1 The physical model

The physical models are based on the stellar population synthesis (SPS) models from the Flexible Stellar Population Synthesis Library (FSPS; Conroy et al. 2009; Conroy & Gunn 2010) with MESA Isochrones and Stellar Tracks (MIST; Choi et al. 2016; Dotter 2016, based on the MESA stellar evolution code; Paxton et al. 2011, 2013, 2015, 2018), and MILES$^4$ spectral templates (Sánchez-Blázquez et al. 2006).

The dust is modelled with the two-component dust attenuation model from Charlot & Fall (2000), which separates the dust components between those associated with the birth-cloud, and a uniform dust screen. While we expect DF44 to have an old stellar population with very little dust content, we prefer to include a flexible dust model and marginalise over the parameters rather than assume a simplistic model. This avoids the assumption that dust attenuation in DF44 is the same as dust attenuation in the local Universe. The birth-cloud dust acts to only attenuate stellar emission for stars younger than 10 Myr,

$$
\tau_{dust, birth}(\lambda) = \delta_{dust, birth} \left( \frac{\lambda}{5500 \text{ Å}} \right)^{-1}
$$

(1)

while the diffuse-dust acts as a uniform screen with a variable attenuation curve (Noll et al. 2009),

$$
\tau_{dust, diffuse}(\lambda) = \delta_{dust, diffuse} \left( \frac{4.05}{\lambda} \right) \left( \lambda \frac{5500 \text{ Å}}{\lambda} \right)^n
$$

(2)

where $n$ is the diffuse dust attenuation index, $k'(\lambda)$ is the attenuation curve from Calzetti et al. (2000), and $D(\lambda)$ describes the UV bump based on Kriek & Conroy (2013). The diffuse dust is given a uniform prior (min= 0, max= 1.5). We note that the diffuse dust optical depth is related to the dust extinction via $A_{\lambda} = 2.5 \log_{10}(\epsilon) \tau_{dust}$, where $\tau_{dust}$ is the sum of the diffuse and birth dust components.

We use a joint prior for the ratio of diffuse to birth-cloud dust, rather than a direct prior on birth-cloud dust, to avoid degeneracies between the two parameters. The prior for $\delta_{young/dust, diffuse}$ is a clipped normal with $\mu = 1$, $\sigma = 0.3$, min= 0, and max= 1.5, which broadly follows results from the literature for massive galaxies while allowing some variation. Lastly the prior on the attenuation index is uniform (min= 0, max= 0.5).

Dust emission is calculated assuming energy conservation, i.e., all the energy attenuated by dust is re-emitted at infrared wavelengths (da Cunha et al. 2008). As our photometry is limited to $< 4.4 \mu$m

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$^4$ http://miles.iac.es/
Comparison of SFH priors between specific SFR (SFR per unit mass; first and second panels) and corresponding mass-weighted age (third panel). The $\alpha_D = 1$ SFH prior prefers solutions where the star formation is equally weighted between the time bins, hence we label it ‘extended’. In comparison, the $\alpha_D = 0.2$ SFH prior prefers solutions where the star formation is unequally distributed between time bins, which we label as ‘concentrated’. The sSFR is shown as a function of lookback time for ten random draws (thin lines) from the Dirichlet SFH priors with $\alpha_D = 1$ (extended; red) and $\alpha_D = 0.2$ (concentrated; blue). The medians and 68 per cent CRs of the prior are indicated with thick lines and shaded regions, respectively. The implicit mass-weighted age priors are shown in the lower panel, with vertical lines indicating the median, and shaded regions indicating the 68 per cent CRs.

(re-st-frame) there is no significant information in the SED constraining dust emission. We chose to include the full dust model and marginalise over the unconstrained parameters, rather than a more simplistic model, in order to avoid biasing the result.

The stellar metallicity is a free parameter; however we assume a constant metallicity for all the stars and for the entire history of the galaxy. This single metallicity has a uniform prior in the rest-frame (4.0–5.4 Gyr, 5.4–7.2 Gyr, 7.2–9.6 Gyr, and 9.6–12.6 Gyr), and the last bin covers 0.95$x_{\text{univ}}$–$x_{\text{univ}}$, where $x_{\text{univ}}$ is the age of the Universe at the time of observation. Defining the time bins this way reflects the non-linear evolution in the SEDs: the narrower time bins at recent lookback times allow a sufficient precision in capturing recent star formation, while the wider bins at later lookback times reflect the modest evolution of older stellar populations. The last time bin is included to permit a maximally old population.

Fitting SEDs to recover SFHs is an ill-defined problem, and prone to overfitting (e.g., Moutata & Pelat 2000; Moutata et al. 2004; Ocvirka et al. 2006a). In order to recover a physically plausible SFH it is common to invoke ‘regularisation.’ There a number of ways that this can be done, which differ in technical detail. One approach is to impose Gaussian-like priors on the SFH and/or the age-metallicity relation (e.g., as in the commonly used code STECKMAP; Ocvirka et al. 2006a,b), and another is to penalise sharp transitions in the SFH (e.g., the continuity prior; Leja et al. 2019). In this work we use a third method, which is to control the degree of concentration of fractional specific SFR (sSFR) between the time bins of the nonparametric function. While these approaches differ in detail, they all attempt to avoid nonphysical solutions by imposing constraints on the variability of the SFH over time.

We adopt a Dirichlet prior which includes a concentration parameter, $\alpha_D$, that controls the preference to distribute the fractional sSFR in one bin ($\alpha_D < 1$) or evenly between all bins ($\alpha_D \geq 1$), respectively. A detailed description of this prior is provided in Leja et al. (2017). Without direct physical motivation to inform a choice of $\alpha_D$, we consider both $\alpha_D = 1$ and $\alpha_D = 0.2$ as valid options, labelling them as ‘extended’ and ‘concentrated’ versions of the SFH prior. In comparing the results produced from these two choices of SFH prior, we explore the dependence of the results on the degree of regularisation.

Fig. 2 shows random draws (thin lines) for priors with $\alpha_D = 1$ (extended) and $\alpha_D = 0.2$ (concentrated), with the time bins as defined above. The median and 68 per cent credible regions (CRs) of the priors are shown with a thick line and shaded regions, respectively. The corresponding implicit prior on the mass-weighted age is shown in the bottom panel for reference. The mass-weighted stellar age ($t_{\text{age}}$, sometimes referred to as the mean stellar age, broadly describes the average formation time of stars in a given galaxy in units of lookback time) is calculated from the SFH:

$$t_{\text{age}} = \frac{\int_{t_{\text{obs}}}^{\infty} t \ SFR(t) \ dt}{\int_{t_{\text{obs}}}^{\infty} SFR(t) \ dt}$$

where $t_{\text{obs}}$ is the age of the Universe at the time of observation. The implicit age prior for an extended SFH is centred at half the age of the Universe with a 99.9 per cent CR between 3.08–9.98 Gyr, and thus is a strong prior against both very old and very young ages. In comparison, the concentrated SFH also peaks around half the age of the Universe (although offset given the varying widths of the time bins), but the prior is not as tight (99.9 per cent CR between 0.83–12.17 Gyr) such that old ages are less strongly disfavoured.

3.1.1 Non-parametric SFH

To characterise the SFH we use a non-parametric\(^5\) model of the form of a piece-wise constant function with $N = 12$ time bins. The benefits of such a flexible SFH (relative to parametric functions, e.g., declining exponential or log-normal) have been well characterised by Leja et al. (2019) and Lower et al. (2020), among others. The time bins are defined in lookback time, spaced so that the first seven bins correspond to 0–30 Myr, 30–100 Myr, 100–500 Myr, 500 Myr–1 Gyr, 1.0–2.0 Gyr, 2.0–3.0 Gyr, and 3.0–4.0 Gyr. There are four bins spaced logarithmically between 4 Gyr to 0.95$x_{\text{univ}}$ (4.0–5.4 Gyr, 5.4–7.2 Gyr, 7.2–9.6 Gyr, and 9.6–12.6 Gyr), and the last bin covers 0.95$x_{\text{univ}}$–$x_{\text{univ}}$, where $x_{\text{univ}}$ is the age of the Universe at the time of observation. Defining the time bins this way reflects the non-linear evolution in the SEDs: the narrower time bins at recent lookback times allow a sufficient precision in capturing recent star formation, while the wider bins at later lookback times reflect the modest evolution of older stellar populations. The last time bin is included to permit a maximally old population.

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Non-parametric here means that the SFH has no specified functional form.

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3.2 Noise and outlier models

A noise model is used to account for possible under- or over-estimates of the spectral uncertainties, where the noise is uniformly inflated (or deflated). This effectively modifies the spectral uncertainty by a multiplicative factor, but is counterbalanced by a penalty in the likelihood calculation for larger uncertainties. This down-weights spectra where the uncertainties are otherwise low, but there is a mismatch between the spectrum and the models. The minimum uncertainty in the photometry is 7%, and as we expect this to be large enough to account for deviations with the template SEDs, we do not include a noise model for the photometry in our model.

A mixture model is used to identify and mask pixels in the spectra which have large deviations from the model. The purpose here is to avoid being overly sensitive to outlier pixels in the spectrum. This is again relevant where the S/N is large and significant residuals can result from poor matches to the models where the model itself is inaccurate (due to differences in, for example, α-enhancement). PROSPECTOR uses the mixture model approach described in Hogg et al. (2010).

The spectral outlier model finds that less than 1 per cent of the pixels are inconsistent with the model templates beyond the specified uncertainty. Note that the spectral white noise model prefers to inflate the uncertainties by ~ 1–3 per cent, which is not unexpected given that the S/N of the spectrum is high, 40–140 (median 96) and that the models are not flexible enough to precisely match the metallicity- and α-abundance sensitive spectral features (i.e., the Mg triplet).

3.3 Spectrophotometric calibration

We rely on the calibration of the photometry to constrain the shape of the SED continuum. The PDF4 spectrum is not flux-calibrated such that neither the normalisation nor the shape of the spectral continuum provides information about the stellar properties. In fact, the spectrum was flattened prior to fitting (see Section 2.1). For this reason we ignore the shape of the spectrum when computing the likelihood of the SED model (relative to the spectrum). We do this by following the routine provided through PROSPECTOR which fits (via optimisation) a polynomial to the residual between the spectrum and the model, which is then multiplied to the model. We use an \( n = (\lambda_{\text{max}} - \lambda_{\text{min}})/100 \text{ Å} \sim 8 \) order Chebyshev polynomial, which is flexible enough to remove the broad continuum shape without over-fitting absorption features (e.g., Conroy et al. 2018). We test our results using several different orders of the polynomial, and find that we are generally insensitive to the choice of \( n \) as long as \( n > 4 \) (otherwise the dust attenuation pdf is skewed).

3.4 Sampling

The complete model includes 19 free parameters (11 of which describe the shape of the SFH), which are summarised in Table 2. We follow the sampling procedure outlined in Johnson et al. (2021b) (see also Tacchella et al. 2021), using the dynamic nested sampling algorithm DYNESY⁶ (Speagle 2020) to efficiently sample the high-dimensional parameter space of the model and build posterior pdfs. This approach provides full posterior distributions of the model parameters together with their degeneracies. A useful primer on Bayesian methods can be found in van de Schoot et al. (2021).

Throughout this work we report the uncertainties as 68 per cent CRs (which corresponds to the 16th to 84th percent range) of the posterior pdfs as the majority of the distributions are non-symmetric.

3.5 Simultaneously fitting the photometry and spectroscopy

In fitting both the photometry and spectroscopy we consider the log-likelihood of the model, conditioned on the observation, to be the sum of the two individual likelihood functions:

\[
\ln L(d_s, d_p | \theta, \phi, \alpha) = \ln L(d_s | \theta, \phi, \alpha) + \ln L(d_p | \theta)
\]  

(4)

where \( d_s \) is the spectroscopic data, \( d_p \) is the photometric data, the parameters \( \theta \) describe the physical model used in PROSPECTOR, the parameters \( \phi \) describe the spectroscopic noise model (Section 3.2), and the parameters \( \alpha \) include the spectro-photometric calibration (Section 3.3). The parameters of the physical model are summarised in Table 2. We apply no relative weighting between fitting the spectroscopy and photometry in assessing the match between the observations and SEDs.

The basic likelihood calculation is effectively a \( \chi^2 \) calculation for both the spectral and the photometric data. We alter the likelihood calculation for the spectroscopy to include the noise model and outlier model described in Section 3.2, following the procedure outlined in Appendix D of Johnson et al. (2021b).

4 RESULTS

Given the sensitivity of modelling ages of old stellar populations, and their dependence on both the flexibility of the assumed SFH and the choice of SFH prior (e.g., Leja et al. 2017, 2019), we present the results for two ‘extremes’ of the SFH prior: i) an ‘extended’ SFH, preferring equal distribution of fractional sSFR between the time bins (\( \alpha_2 = 1 \)), and ii) a so-called ‘concentrated’ SFH, preferring an unequal distribution of fractional sSFR between time bins (\( \alpha_2 = 0.2 \)). The difference between these priors is discussed in Section 3.1.1.

In assuming the SFH is extended, there is a preference for ages

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⁶ https://dynesty.readthedocs.io/en/latest/
Figure 3. Summary of the fitting results for DF44. The observed data (black) is compared to the bestfit models (red, extended SFH prior; blue, concentrated SFH prior) and the 68 per cent CR of 500 randomly drawn models from the posteriors (red/blue shaded). The corresponding posteriors are shown in Figs. 5 and 4. (a) The observed (circles) and bestfit (diamonds and squares) photometric points, where the $\chi^2/N_{\text{data}}$ of the bestfit SED is listed and (b) shows $\chi^2$ of the bestfit points. (c) The observed uncertainties shown in grey) spectrum and bestfit spectra (multiplied by the spectrophotometric calibration polynomial). The light grey region indicates the spectral region masked throughout the fitting process. (d) The $\chi^2$ of the bestfit spectra as a function of wavelength. (e) The relative change of the bestfit models, i.e., the ratio of the two bestfit spectra. (f) The spectrophotometric calibration polynomials.

Overall the fits to the photometry are similar between the two SFH priors; the extended SFH model has marginally smaller residuals at NUV wavelengths. Similarly, the bestfit model spectra (multiplied by the spectrophotometric calibration polynomial) compared to the spectroscopy are nearly identical, with differences only at the $<1$ per cent level. Given the degeneracy between age, dust, and metallicity, the subtle differences in these features lead to the differences in the predicted stellar population parameters.
4.1 Star formation history and stellar population parameters at $z=0$

Fig. 4 shows the median (solid line) and 68 per cent CR (shaded) of the posterior pdfs for the sSFR, and corresponding SFR and mass-assembly history. Similarly, the median (dashed line) and 68 per cent CRs (hatched) for the explicit and implicit priors are shown (see also Fig. 2). The SFHs of the bestfit models (shown in Fig. 3) are indicated with open crosses. The median (dashed line) and 68 per cent CRs (hatched) for the priors are shown for reference. Note that the cumulative mass and mass-weighted age priors are implicit, as they are derived from the sSFR prior. Dotted lines are drawn at 50, 70, and 90 per cent of the cumulative mass for reference. The last 100 Myr are shaded grey to indicate that the SFH is affected by artefacts such as HB stars (see text).

A curious feature of both SFHs is the rise in SFR within the last 100 Myr (corresponding to the first two time bins and shaded grey in Fig. 4: by 1.8–2.4 dex). Although residual star formation appears to be common for massive early type galaxies, where ~0.5 per cent of their mass formed within the last 2 Gyr, the fraction decreases at lower stellar masses, consistent with galaxy ‘downsizing’ (e.g., Salvador-Rusinol et al. 2020). The recent rise in DF44’s SFH accounts for ≤1 per cent of the total stellar mass, assuming either SFH prior. While DF44 shows no indication of recent star formation from the photometry, and similarly lacks emission lines in the spectrum, it is possible that Hα emission (perhaps related to star formation ignited by a late infall in to the Coma cluster) recently stopped. This is perhaps unlikely, however, given the lack of blue regions within the galaxy. Lee et al. (2020) concluded, based on the difference in NUV and UVW2 bands, that the light traces older stars (on ~ Gyr time-scales, as opposed to young stars which evolve on the order of ~ Myr time-scales). The ‘recent burst’ is not a consequence of an artefact in the KCWI spectrum; the same feature is apparent when fitting the MaNGA data from Gu et al. (2018). Rather, we expect this recent star formation to be an artefact of the stellar models not being flexible to the contribution of blue horizontal branch (HB) stars (discussed in Appendix B1) or non-solar Mg-abundances.

We none the less test the sensitivity of the models to the presence of a very young stellar population by re-defining the time bins of our SFH, only allowing for star formation older than 1 Gyr. This places a strong prior against recent star formation (SF) to counteract the inability of the SPS models to correctly model the influence of the blue HB stars. In excluding star formation younger than 1 Gyr, the models are better able to recover the shape of the SED, particularly in the NUV, but are marginally worse in matching the spectrum. With this revised model we recover SFHs equivalent to that of our primary

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\footnote{Additional testing of the prior-sensitivity of the SFH showed that using $\alpha_D = 0.5$ (mildly concentrated) produced parameter values between the results from $\alpha_D = 0.2$ and $\alpha_D = 1$, as expected. The mass-weighted age was found to be 11.9 Gyr, which indicates that the very old age is not overly sensitive to the choice of the $\alpha_D$ value.}
Figure 5. Posteriors of selected fitted and derived parameters (indicated with an asterisk) for the fits shown in Fig. 3. Contours are shown smoothed with a $n = 1$ Gaussian kernel, where red (blue) contours show the fits with an extended (concentrated) SFH prior. Black lines denote the expected results given the analysis by Villaume et al. (2022) for $\log(Z/Z_\odot)$ and stellar mass from van Dokkum et al. (2016) and Saifollahi et al. (2022). Grey shaded regions indicate the uncertainties on these values. The median and uncertainties from the 68 per cent CR for our results are listed along the top of the one-dimensional histograms.

Results (at times $>1$ Gyr), with statistically consistent but less dust and metallicity, and slightly higher stellar mass. Interestingly, with the extended SFH prior, the revised age estimate is $\sim$2.4 Gyr older. With the concentrated SFH prior, the revised age estimate is unchanged from that of our main result. As such, we conclude that the presence of the ‘recent burst’ of SF does not affect our conclusion that DF44 formed and quenched very early in the history of the Universe.

Fig. 5 shows the posteriors for the normalisation of the diffuse dust attenuation curve, stellar metallicity, stellar mass, and mass-weighted age. The parameters marked with an asterisk are not directly fit in our physical model, but derived from the posterior distributions. We calculate the dust extinction following equations (1) and (2) in the V-band, where we use $\lambda = 5500$ Å. We note that ‘total stellar mass formed’ is a free parameter in our model, which we convert to ‘stellar mass’ by subtracting the mass lost throughout the SFH, as calculated by FSPS. The median and uncertainties of the marginalised posteriors for extended (concentrated) SFH priors are:

\[
\begin{align*}
\tilde{\tau}_{\text{dust}, \text{ diffuse}} &= 0.24^{+0.03}_{-0.05} \left( 0.20^{+0.04}_{-0.03} \right), \\
* A_V &= 0.51^{+0.11}_{-0.13} \left( 0.45^{+0.10}_{-0.08} \right), \\
\log(Z/Z_\odot) &= -1.18^{+0.01}_{-0.01} \left( -1.27^{+0.03}_{-0.02} \right), \\
* \log(M/M_\odot) &= 8.23^{+0.02}_{-0.06} \left( 8.33^{+0.03}_{-0.03} \right), \\
* t_{\text{age}} / \text{Gyr} &= 10.20^{+0.34}_{-0.48} \left( 13.06^{+0.02}_{-0.04} \right),
\end{align*}
\]

as labelled above the one-dimensional histograms. In both cases DF44 has a very old, modestly dusty, and metal-poor stellar population.

Contrary to our expectation that old (e.g., Péroux & Howk 2020)
and metal-poor (e.g., Galliano et al. 2018) populations are devoid of dust (see also Barbosa et al. 2020), DF44 appears to have a non-negligible amount: the normalisation of the diffuse-dust attenuation curve is $\tau_{\text{dust, diffuse}} \geq 0.2$ and $A_V \geq 0.5$. The origin of such dust is not clear, however, Buzzo et al. 2022 (submitted) recently measured similar extinction values from optical to mid-infrared photometry for a sample of quiescent UDGs. The overall shape of the SED constrains the dust content, however there are degeneracies with both metallicity and age. If we instead fix $\tau_{\text{dust, diffuse}} = 0$ and re-fit DF44 (with an extended SFH prior), the posterior pdfs are statistically consistent with that of our main result, although we note that the age increases (as expected) by $\sim 0.23$ Gyr. In Appendix B2 we discuss the fit to just the photometry, which prefers an even dustier solution ($\tau_{\text{dust, diffuse}} \sim 0.36$ and $A_V \sim 0.8$, although the photometry provides no direct constraint for the metallicity, and little constraint for the age). While the spectroscopy breaks the degeneracy between dust and metallicity, the degeneracy with age remains; adding either more dust or a stellar population older than $\sim 3$ Gyr lowers the flux at wavelengths $< 5000$ Å (see Appendix C). Additional observations in the mid-infrared would provide better constraints on the dust content, as age and dust affect the flux in opposite directions at this wavelength range.

Other than $\tau_{\text{dust, diffuse}}$, the posteriors of the dust model parameters largely reflect their priors -- which is to be expected given the lack of constraining data. None the less, to check that our results do not depend on the particular dust model, we also fit the data with the dust model of Gordon et al. (2003) based on the SMC Bar (thought to have similar dust properties to dwarf elliptical galaxies, i.e., without a UV bump in the extinction curve), and find no change to our result. A degeneracy between the dust normalisation and stellar mass can be seen in the joint posterior in Fig. 5, where an increase in dust suggests a higher stellar mass. As a point of comparison, a solid black line indicates the estimated stellar mass from van Dokkum et al. (2016), and a dotted black line indicates that measured by Saifollahi et al. (2022) with uncertainties reflecting the systematics of the model fitting. Both of our fits produce stellar masses lower than (and statistically inconsistent within their 68 per cent CRs) with the van Dokkum et al. (2016) value, but consistent with Saifollahi et al. (2022). Given that the photometry included in our fits is measured within an aperture, and thus does not include all of the light of the galaxy, it is not unexpected that the stellar mass we recover underestimates that from the literature.

There is a $\sim 0.1$ dex difference in log($Z_\star/Z_\odot$) between the fits with an extended or concentrated SFH prior, where the sense of the metallicity difference is consistent with that of the age difference ($\sim 2.9$ Gyr) with respect to the age–metallicity degeneracy. This indicates that we are not able to fully break the age–metallicity degeneracy with the data at hand. While in Fig. 5 we show the stellar ‘isochrone’ metallicity measured by Villaume et al. (2022) as a black dashed line for comparison, there are several caveats to their comparison which are discussed in the following section.

At this point the dichotomy of DF44 being ‘old’ or ‘very-old’ is subject to the choice of SFH prior. We remind the reader that the extended SFH prior behaves analogously to regularisation methods used throughout the literature. While the concentrated SFH prior provides more flexibility to better recover the short and early star formation expected for DF44, it is not necessarily a ‘good’ prior; we provide no physical information for the shape of the SFH. We simply tune the prior such that it prefers to distribute the SF within fewer time bins (see Section 3.1.1).

This prior-dependency problem is exacerbated with less complete or lower S/N data sets. As a brief example, in Fig. 6 we compare the stellar metallicities and ages determined through fitting both the spectrum and photometry (diamond), with that fitted to only the photometry (circle) for the extended SFH prior (points marked with an ‘E’). While the NUV–NIR photometry provides information on the dust in DF44 (see Appendix B), the age estimate is more heavily weighted by the SFH prior than are the full spectrum fitting results. Accordingly, the photometry-only fit gives a median age $\sim 3.4$ Gyr younger than the fit to the spectrum and photometry together.\footnote{If instead of the non-parametric model, we assume the SFH follows a delayed exponential form (a common parametric model adopted within the literature) we find similar results. With a logarithmically uniform prior on the $\tau$-folding time, $\tau$, and linearly uniform prior for the delay time, $t_{\text{age}}$, the implicit age prior has a complex form with 16th, 50th, and 84th percentiles of 1 Gyr, 3.8 Gyr, and 8.4 Gyr respectively – preferring younger ages than the extended SFH prior results. The implicit age skews even younger if instead $\tau$ is linearly sampled. Fitting the photometry of DF44 suggests the age is $\sim 8.2$ Gyr, and slightly less dusty than using the extended SFH model. Fitting both the photometry and spectroscopy suggests the age is $\sim 13.6$ Gyr, and slightly less dusty and more metal poor than our main result. We note that the photometry-only results with the delayed parametric model appear particularly sensitive to the S/N – if we inflate the photometric uncertainties by a factor of two, the age posterior decreases by $\sim 2$ Gyr. The same is not true when using the non-parametric models.}

![Figure 6. Comparison of stellar metallicity and age for DF44 from this work, Gu et al. (2018), and Villaume et al. (2022) (the latter using the same spectroscopic data set as ours). Both results from the literature derived values using alf, and thus are not directly comparable to our results using Prospecr (see text). Black coloured points show mass-weighted ages, while orange points show luminosity-weighted ages. Marker shapes indicate the data used in fitting the stellar properties. Dashed lines connect results obtained from the same study. We mark the results from this work derived with an extended SFH with an ‘E’, or with the concentrated SFH with a ‘C’.


4.2 Which SFH prior is preferred?

There is little statistical evidence to decide whether the results from either SFH prior better reflects the ‘true’ properties (or SFH) of DF44. The distributions of SED models shown in Fig. 3 are similar between the fits with each prior, and the models have similar residuals.

There are subtle differences, however, particularly around the Hβ and Mg II features where the concentrated SFH gives a (statistically) lower χ². The Hβ line is sensitive to recent star formation (and to HB stars, as discussed in Section 4.1), while Mg II is to sensitive the α-abundance of the stellar population. The FSM models that we use are currently limited to fixed solar α-abundance. However, Villauume et al. (2022) found that DF44 has [Mg/Fe]= 0.11 ± 0.06 through fitting the same spectrum of DF44 as this work with the full-spectrum fitting code alf (Conroy et al. 2018), which includes response functions to measure the non-solar chemical abundance variations. Given the relationship between both features and the age of the stellar population, this points to the need to include more complex stellar populations variables, e.g., α-abundance, in models in order to break this degeneracy.

Fig. 6 compares the stellar metallicities and ages measured for DF44 by this work, Villauume et al. (2022), and Gu et al. (2018). Both previous studies fitted rest-frame optical spectra of DF44 with the full-spectrum fitting code alf. We caution that there are fundamental differences between alf and PROSPECTOR which make their results only broadly comparable: e.g., the inclusion of non-solar abundance patterns (as mentioned above), and alf fits a single-age stellar component (with a uniform prior with minimum age of 1 Gyr) rather than an SFH. That said, the luminosity- and mass-weighted ages should be comparable given that DF44 is old.

Villauume et al. (2022) fitted the same KCWI spectrum as this work, while Gu et al. (2018) fitted a MaNGA spectrum which covers a broader wavelength range (including several additional age diagnostics: Hδ, Hγ, Ca II H and K, and G-band). The MaNGA spectrum has S/N ~ 8 Å⁻¹, however, which is only ~ 12 per cent the S/N of the KCWI spectrum. Despite differences in data, the two studies both found the age of DF44 to be ~10.5 Gyr, although the stellar metallicities are formally discrepant. Notably, Gu et al. (2018) also considered the g − r colour of DF44 from Dragonfly imaging, and re-weighted their posteriors, which considerably lowers their metallicity value (and is then consistent with Villauume et al. 2022 owing to its large uncertainty).

Considering that we fit DF44 in a completely independent way compared to these studies, it is at least encouraging that the results are fairly similar. Significant variations among age and metallicity measurements for the same object, measured between different studies, is not unique to DF44. In Appendix B4 we outline two additional examples and discuss the reasons behind their differences.

The comparison shown in Fig. 6 demonstrates the difficulty in measuring the stellar properties of old stellar populations, related both to limitations of data and modelling. As discussed in the previous section, a solution is within reach as the inclusion of a variable α-abundance or the addition of mid-IR photometry would help to break degeneracies between the stellar population properties.

We conclude that DF44 has an age of ~10–13 Gyr. Without clear statistical evidence to favour one SFH model over the other, throughout the remainder of this work we present both sets of results. In the next section, we discuss the implications of such a large sized galaxy having formed the bulk of its stellar mass very early.

5 DISCUSSION

In this work, we sought to measure the detailed SFH of DF44 as a means to distinguish between UDG formation scenarios, which predict a variety of quenching times (i.e., SFHs). The consistent narrative among theoretical simulations is that UDGs are contiguous with the canonical dwarf population. However, Villauume et al. (2022) established that DF44 is dissimilar to canonical dwarf galaxies with respect to both the stellar population gradients, stellar metallicity, and kinematics. In measuring the SFH of DF44 we can further test this scenario.

Previous analyses of DF44 found that its stellar population is old, having an age of ~ 10 Gyr (see Fig. 6; Gu et al. 2018; Villauume et al. 2022). In this work we have shown that DF44 formed the majority of its mass early, where we consider the galaxy ‘quenched’ after it forms ~ 90 per cent of its mass. In using an extended SFH prior we obtain a lower limit of the quenching epoch of z ~ 0.9 (~ 6.3 Gyr after the Big Bang). Alternatively, in using a concentrated SFH prior (motivated by the results of Villauume et al. 2022), we recover an extremely early quenching epoch of z ~ 8 (~ 0.6 Gyr after the Big Bang). In either case we find that DF44 is old, the distinction being that a concentrated SFH prior suggests that it is very old. Without clear statistical evidence to favour one prior over the other (see Section 4.2) we instead focus on providing a qualitative comparison of the implications of the two results.

For either of our two results, the bulk formation of DF44 occurs during an epoch where the evolution of galaxies in dwarf-scale dark matter haloes (≤ 10¹¹ M⊙) significantly differs from that of galaxies in more massive haloes. The mass assembly histories expected for average galaxies with dark matter halo masses between 10¹¹–10¹³ M⊙ are shown in Fig. 7, from the empirical model of Behroozi et al. (2019). The mass assembly history of DF44 (as shown in Fig. 4) is shown for comparison.

While the current stellar mass of DF44 falls within the range expected for the z = 0 canonical central dwarf population, and its halo mass is in the neighbourhood of ~ 10¹¹ M⊙ (e.g., van Dokkum et al. 2016, 2019; Wasserman et al. 2019; see also Bogdán 2020), its mass assembly history is not necessarily compatible with this.

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9 Comparing the Bayesian evidence of the two fits (as derived from the nested sampling described in Section 3.4) we find a strong preference (according to the Jefferys scale, see for example Kass & Raftery 1995) for the concentrated SFH prior (ln Z_concentrated = 62590 is much larger than ln Z_extended = 62542), where here Z is the Bayesian evidence. However, this likely reflects the fact that the old age of DF44 is more disfavoured by the extended SFH prior (see Section 3.1.1) more than a preference of the data itself.

10 While FSPS does include an option to set the fraction of blue HB stars, for technical reasons we cannot include it as a free parameter in our models.

11 The stellar ‘isochrone’ metallicity (distinct from that which includes the response function for individual elements) [Z/H] values from Villauume et al. (2022) and Gu et al. (2018) were provided via private communication.

12 Villauume et al. (2022) considered the presence of a second young population (aged 1–3 Gyr), which lowers their age estimate by 0.6 Gyr but is consistent with their fiducial fit.
The expected size growth was determined from the stellar mass assembly histories of Behroozi et al. (2019) and the size–mass relation of Sales et al. (2020).

These values were taken from Figures 2 and 11 of Tremmel et al. (2020). We note that other simulations and SAMs which invoke tidal heating (e.g., Carleton et al. 2019; Jiang et al. 2019a; Liao et al. 2019; Sales et al. 2020) with slightly different prescriptions (i.e., cuspy vs. cored dark matter haloes, Carleton et al. 2019; Jiang et al. 2019a; Liao et al. 2019; Sales et al. 2020) from the empirical histories of Behroozi et al. (2019) and the size–mass relation of Sales et al. (2020).

While Tremmel et al. (2020) show that some objects reach the nominal sizes of UDGs prior to infall into a cluster, in order to reach the large end of UDG sizes requires the additional effect of tidal heating from the cluster environment. With the extended SFH prior, the quenching time of DF44 is reasonably consistent with the tidally heated RomulusC UDGs.

Certainly tidal heating is happening on some level to some galaxies in clusters. Evidence of such has been observed among proto-UDGs in clusters (e.g., Grishin et al. 2021). Carleton et al. (2019) interpreted the radial alignment of UDGs in Coma (Yagi et al. 2016, which includes DF44) as evidence that these galaxies have been tidally influenced. While we cannot discount the tidal heating scenario in explaining the size and quenching times of DF44, this scenario conflicts with other properties of DF44.

Measurements of the kinematics and dynamics of DF44 indicate that it has not been in the cluster environment long enough to be impacted by tidal effects. Its position in phase-space points to a place it has not been in the cluster environment long enough to be impacted by tidal heating (Mowla et al. 2017). Together with the above points, the SFH provides evidence that DF44 certainly quenched prior to cluster infall. This would suggest that its progenitor was larger than a dwarf galaxy or that a process unrelated to environment caused an expansion. This interpretation is
consistent with the conclusion of Saifollahi et al. (2022), who find that the elevated GC populations at a given stellar mass ($N_{\text{GC}}/M_\star$) of large UDGs (including DF44) are inconsistent with scenarios which explain the sizes of UDGs via redistributing the stars to larger radii (i.e., tidal interactions, stellar feedback, or high-spin). Villaume et al. (2022) similarly ruled out such scenarios given DF44’s ‘inside-out’ stellar population gradients. Therefore, how DF44 quenched is the crucial question to answer to understand its origins.

From simulations, only Wright et al. (2021, based on RomulusC; Tremmel et al. 2020) have proposed a scenario, ‘early major mergers’\textsuperscript{18}, in which UDGs can form and quench\textsuperscript{19} without relying on environmental quenching mechanisms. The UDGs in RomulusC had their star forming gas and star formation moved outwards from the central cores of the galaxies to larger radii by major mergers \textasciitilde8–11 Gyr ago. For most of the simulated UDGs, star formation continued in the galaxy outskirts, while the central core passively dimmed, leading to negative radial age gradients.

Considering that DF44 quenched \textasciitilde7 Gyr ago, this may suggest that a major merger is responsible for (or at least concurrent with) its quenching – and that there would be a flat age gradient. The central (< 0.5 kpc) SFH predicted for RomulusC UDGs is broadly consistent with DF44’s SFH when assuming an extended SFH prior, although not when assuming a concentrated prior (which quenches much earlier). Villaume et al. (2022) measured a flat-to-negative [Mg/Fe] gradient out to \textasciitilde2.5 kpc, which taken as a proxy for an age gradient is not strictly inconsistent with this scenario.\textsuperscript{20}

Further work is needed in order to establish whether DF44 is the product of an early major merger. For instance, the mechanism that quenches \textasciitilde5 per cent of the RomulusC UDGs is not fully described, providing no point of comparison with DF44’s SFH or stellar population gradients. Moreover, when this quenching occurs, or whether the galaxies remain quenched, is unclear. While Wright et al. (2021) and Van Nest et al. (2022) explored the predictions of ‘early major mergers’ in differentiating average UDGs and non-UDGs, the fact that DF44 is a rare case warrants more detailed comparisons.

The results of this work show that DF44 has been shaped by some rare galaxy evolution process, no matter whether the ‘true’ SFH resembles our result with an extended or concentrated SFH prior, or

\textsuperscript{18} We note that Saifollahi et al. (2022) refer to this scenario as ‘lack of late mergers’.

\textsuperscript{19} Less than 5 per cent of the simulated UDGs with masses $M_\star > 10^8 M_\odot$ are quenched, in the sense that they are gas poor. This population is dominated by galaxies that have had an interaction with a more massive halo and/or AGN activity.

\textsuperscript{20} While Villaume et al. (2022) measured a flat age gradient, they note that given the limitations of modelling granular differences in old stellar populations, the [Mg/Fe] gradient is more sensitive to age variations.
falls somewhere in between. As was shown in Fig. 7, the early SFR of DF44 is more typical of normal (MW-like) star forming galaxies at $z > 3$ (Rinaldi et al. 2021). The implication is that it is not the early, extreme SFH that makes DF44 unusual among $z = 0$ galaxies, but rather its sudden quenching. Given the lack of galaxies like DF44 in cosmological simulations, this would imply that galaxy evolution models are not capturing the true diversity of quenching mechanisms.

In fact, cosmological simulations already struggle to reconcile the opposing stellar mass–effective radius constraints for objects like DF44 in the context of the broader galaxy population. A common problem among cosmological simulations is that they do not accurately reproduce the population of normal sized dwarfs (e.g., Chan et al. 2018; El-Badry et al. 2016; Lupi et al. 2017; Tremmel et al. 2020; Benavides et al. 2021; see also Jiang et al. 2019a). Since this points to issues in the implementation of star formation and related feedback, the evidence from this work and Villaume et al. (2022) that there are objects like DF44 that require even more intense star formation feedback exacerbates this problem.

Analytic and semi-analytic models can avoid such issues to some degree. With respect to size, several UDG formation scenarios apply empirical distributions (e.g., Carleton et al. 2019; Sales et al. 2020) but they are then subject to the likely bias of ‘getting out what they put in’ (see Jiang et al. 2019b). With respect to star formation and feedback, Danieli et al. (2021) analysed the large number of GC candidates hosted by NGC 5846_UDG1 (Forbes et al. 2021) with a model that connects the evolution of a galaxy with its dark matter halo and GC populations (Trujillo-Gomez et al. 2019) to show that it is plausible that clustered supernova feedback could significantly increase the mass loading factor of gas outflows. However, these models miss an important component of galaxy evolution – the impact of the different environments a galaxy moves through over its lifetime. DF44’s very early quenching and relatively late infall into the Coma cluster invokes the question of what has it been doing for the last ~ 10 billion years? Given the potential ‘pre-processing’ by group environments or filaments that can affect everything from the size of a galaxy’s dark matter halo, to its SFH and present-day GC population, makes it vital to understand this aspect of galaxy evolution in general.

5.2 DF44 in context

The prior-dependence of the SFH for old stellar populations, even with high-S/N data, means that further work is needed to understand what ‘good’ SFH priors are for these systems. The problem is ampliﬁed at lower S/N, where the prior will have a stronger influence on the posterior pdfs (see Appendix B3 for an example). Consequently, it is not straightforward to compare results between studies in the literature. With this caveat in mind, we also show in Fig. 8 the quenching times and sizes of UDGs from three studies (Ferré-Mateu et al. 2018; Ruiz-Lara et al. 2018; Martín-Navarro et al. 2019), and for comparison high- and low-luminosity dwarfs in Coma (squares and diamonds, respectively; Ferré-Mateu et al. 2018). Arrows attached to these points indicate that they are perhaps upper limits, given potential biases from the use of regularised SFHs (akin to the extended SFH prior used in this work; see the discussion in Appendix B4). We note that the UDGs from the literature are shown with effective radii from the catalogue of Alabi et al. (2020) when possible, where DF44 was found to have a size of 3.74 ± 0.23 kpc in the Subaru/Suprime-Cam R-band.

Regardless of potential biases in the SFHs, there are still interesting conclusions to draw from this data set. DF44 stands out as an outlier among the largest observed UDGs with an early quenching time, for any of the discussed quenching times or sizes. On the other hand, the UDG DGSAT I stands out with both the largest size and latest quenching time among the literature values shown in Fig. 8, and it is also the only non-cluster member. Unlike the rest of the UDGs, DGSAT I is similar to a subset of the ROMULUSC UDGs which follow a trend in size–quenching time in distinct disagreement with the standard expectations of tidal heating. Its size is also well outside of what is plausible for the concentrated SFH scenario, or normal expectations of size growth given its late quenching time.

While it is outside the scope of this work to examine DGSAT I in detail, it is relevant to this discussion in that it further provides evidence that multiple observed objects, all of which are ‘UDGs,’ in fact have distinct formation pathways.

That DF44 attained a similar stellar mass and size as the other large galaxies, but much earlier, supports the idea that it is either the product of unconventional galaxy evolution processes, or it was interrupted from becoming a much more massive galaxy by some catastrophic quenching event. Speculation of the latter has also been drawn on the basis of the wide range of GC counts among UDGs, and the range of implied dark matter halo masses (with some having little to no dark matter). This is the first time this diversity has been shown in the SFHs of the galaxies’ field star populations.

6 SUMMARY

In this work we simultaneously fit NUV to NIR photometry and high S/N rest-frame optical spectroscopy of the UDG DF44 with an advanced physical model. Our model includes non-parametric SFHs, a flexible dust attenuation law, a white noise model, and an outlier model, which we fit to the observations in a fully Bayesian framework with PROSPECTOR.

We find that DF44 formed the majority of its stellar mass (> 90 per cent) early, although how early is sensitive to the choice of the SFH prior and degeneracies between stellar population parameters. Using an extended SFH prior akin to similar studies in the literature (which strongly favours ages of half the age of the Universe, and therefore disfavours very old ages) we find that DF44 formed by $z \geq 0.9$. If we instead adopt prior knowledge from DF44’s stellar population gradients that the DF44 formed early and rapidly quenched (Villaume et al. 2022), such that its SFH is concentrated within a short timescale, we find that DF44 assembled as early as $z \approx 8$. Neither of these priors encode physical information of the shape of the SFH based on a priori knowledge, and thus neither are necessarily ‘good’ priors. Further work is needed to understand what ‘good’ SFH priors are for such old galaxies from a theoretical standpoint. Even with the high-S/N spectral data used in this work ($\sim 96 \, \AA^{-1}$) the data showed no statistical preference for either result. Improved age constraints are possible with the inclusion of observations in the mid-infrared in that this would pin down the dust attenuation, which in the NUV is degenerate with the contribution of old stellar populations. Improvements in the models (e.g., including variable $\alpha$-abundance) to replicate old and complex stellar populations are also needed.

DF44’s early and short SFH determined from this work, together with previous results that DF44 is very metal poor for its mass, and that stellar population gradients indicate ‘inside-out’ formation (unlike kinematically- and morphologically-similar dwarfs; Villaume et al. 2022), points towards an unusual origin, likely distinct from the canonical dwarf population. UDG formation scenarios outlined in simulations only predict the SFH and size of DF44 through invoking prolonged environmental effects, yet we conclude that DF44
quenched prior to accretion into the Coma cluster. While analysis of the Romulus25 simulation by Wright et al. (2021) proposes early major mergers as a means to produce UDGs in the field, it is not yet clear if the properties of DF44 are fully consistent with this scenario. Instead, DF44 may be a ‘failed galaxy’ with its initial size, or whatever processes that expanded it, being unrelated to its environment. In Summary, early quenching an late infall taken together rules out most UDG formation scenarios except for the failed-galaxy and early-major-mergers (with the caveats above). Additional work is needed to explain the old quiescent UDGs from a theoretical standpoint, while reproducing the observed stellar properties beyond general size–mass trends.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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percentiles of the distributions, where we note that the 50th, 50th, 50th...
APPENDIX B: SYSTEMATIC BIASES IN MEASURING SFHS

B1 SFH biased by blue horizontal branch stars

The use of integrated light to reconstruct stellar populations has the caveat that multiple types of stars can share spectral signatures. This is the case for young, massive main-sequence stars and old, metal poor stars on the blue side of the horizontal branch (HB); both act to amplify the equivalent width of the Balmer lines. A population of blue HB stars produces a flux shortward of 3000 Å which increases with decreasing metallicity due to a hotter main-sequence turnoff. Neglecting to include a blue HB population in models can contribute less than around 10 per cent of the total stellar mass.

with metallicities similar to DF44: NGC 2808 has [Fe/H] = −1.29 and (B − R)/(B + V + R) = −0.49 (bluer HB), and NGC 6218 (M12) has [Fe/H] = −1.32 and (B − R)/(B + V + R) = 0.97 (redder HB). Given that GCs are reasonable approximations of SSPs, we expect an early single burst of star formation only. Fits to the spectra of NGC 2808 and NGC 6218, over the same wavelength range as DF44, following the procedure described in Section 3, are shown in Fig. A1. The top panels summarise the comparison between the observations (black lines), and models (coloured lines). Similar to Fig. 4, the bottom panels show the sSFR, SFR, and mass assembly histories. An extended SFH was assumed, and the total stellar mass was fixed to $10^8 M_\odot$.

In both cases we find an increase in the SFR within the last 100 Myr, although to a larger extent for the GC with the blue HB stars (by $1.5^{+0.5}_{−0.3}$ dex for NGC 6218, and by $2.6^{+0.4}_{−0.3}$ dex for NGC 2808). In addition, we see that both SFHs are early and short-lived, although there are modest levels of star formation at $> 2$ Gyr, which likely results from the models being unable to precisely match the high S/N spectra ($\sim 180$ and $\sim 480$, respectively). We conclude from this comparison that some component of the recent SF burst we measure for DF44 could plausibly be related to a population of blue HB stars.

B2 Fitting the spectroscopy and photometry together vs separately

Figs. B1 and B2 show the results of fitting the models to observations of DF44, where we include the following input: i) using only the photometry (yellow), ii) using only the spectroscopy (green), and iii) using both the photometry and spectroscopy (red), and assuming an extended SFH prior. We note that the stellar mass is fixed (to the value reported by van Dokkum et al. 2016) for the spectrum-only fit as the continuum was subtracted from the spectrum.

Similar to Fig. 3 discussed in Section 4, in Fig. B1 the observations (black lines and markers) are shown relative to the bestfit models (coloured lines and markers, where the colours denote which observations were fit). Shaded coloured regions indicate the 68 per cent CRs from sampling the posterior pdfs, where the grey shaded region indicates the uncertainties in the spectrum.

Table A1. Summary of SFH results. The fraction of SF and the cumulative fraction of stellar mass formed are listed for each time bin of the non-parametric SFH model. The 16th, 50th, and 84th percentiles of the posterior (i.e., the 68 per cent CR) are listed. We note that the 50th percentiles of the fractional SFH do not necessarily sum to unity. The SF time-scales listed in Table 3 are interpolated from these step functions.

| Time bin (Gyr) | SF Fraction | Cumulative fraction of $M_*$ | Concentrated SFH prior | Cumulative fraction of $M_*$ |
|---------------|-------------|-----------------------------|------------------------|-----------------------------|
| $10^{-9}$ – 0.03 | 0.0703 | 0.0795 | 0.0967 | 1.0000 | 1.0000 | 1.0000 | 0.0042 | 0.0082 | 0.0099 | 1.0000 | 1.0000 | 1.0000 |
| 0.03 – 0.10 | 0.0050 | 0.0152 | 0.0240 | 0.9986 | 0.9988 | 0.9989 | 0.0016 | 0.0181 | 0.0221 | 0.9995 | 0.9996 | 0.9998 |
| 0.10 – 0.50 | 0.0007 | 0.0014 | 0.0061 | 0.9980 | 0.9983 | 0.9986 | 0.0000 | 0.0000 | 0.0004 | 0.9974 | 0.9977 | 0.9980 |
| 0.50 – 1.00 | 0.0014 | 0.0031 | 0.0049 | 0.9972 | 0.9979 | 0.9983 | 0.0000 | 0.0001 | 0.0002 | 0.9974 | 0.9975 | 0.9979 |
| 1.00 – 2.00 | 0.0003 | 0.0015 | 0.0039 | 0.9964 | 0.9970 | 0.9975 | 0.0000 | 0.0000 | 0.0001 | 0.9973 | 0.9974 | 0.9978 |
| 2.00 – 3.00 | 0.0014 | 0.0046 | 0.0086 | 0.9949 | 0.9962 | 0.9970 | 0.0000 | 0.0000 | 0.0001 | 0.9971 | 0.9974 | 0.9978 |
| 3.00 – 4.01 | 0.0011 | 0.0089 | 0.0158 | 0.9917 | 0.9932 | 0.9955 | 0.0000 | 0.0000 | 0.0005 | 0.9969 | 0.9973 | 0.9977 |
| 4.01 – 5.36 | 0.0091 | 0.0145 | 0.0435 | 0.9833 | 0.9886 | 0.9925 | 0.0000 | 0.0001 | 0.0004 | 0.9964 | 0.9971 | 0.9973 |
| 5.36 – 7.16 | 0.0166 | 0.0702 | 0.1351 | 0.9591 | 0.9790 | 0.9847 | 0.0000 | 0.0002 | 0.0016 | 0.9943 | 0.9969 | 0.9971 |
| 7.16 – 9.57 | 0.0722 | 0.1548 | 0.3310 | 0.8543 | 0.8993 | 0.9606 | 0.0000 | 0.0000 | 0.0022 | 0.9917 | 0.9950 | 0.9969 |
| 9.57 – 12.80 | 0.3036 | 0.3726 | 0.5208 | 0.5596 | 0.6872 | 0.8085 | 0.0000 | 0.0000 | 0.0008 | 0.9851 | 0.9938 | 0.9958 |
| 12.80 – 13.47 | 0.0583 | 0.1918 | 0.3111 | 0.0179 | 0.0618 | 0.1116 | 0.9678 | 0.9714 | 0.9737 | 0.9822 | 0.9916 | 0.9947 |

Downloaded from [http://www.noao.edu/ggc1lib](http://www.noao.edu/ggc1lib).
Both bestfit SED models match the photometry with reasonable $\chi^2_{\text{bestfit}}$. In comparison, the UV flux is significantly overestimated when fitting only the spectroscopy. Since the UV provides information about recent star formation, and the UV to optical colours constrain the dust attenuation, we do not expect to constrain these properties from the spectrum alone.

A comparison of the observed spectrum with the bestfit models is also shown in Fig. B1, with the $\chi^2_{\text{bestfit}}$ as a function of wavelength, and the spectrophotometric calibration polynomial (see Section 3.3). The ratio of the two bestfit models, shown flattened by dividing through by a polynomial, shows that the fits are similar at the 2 per cent level. The only notable differences between the two bestfit models are around the H$\beta$ line and Mg II features at $\sim 5285$ Å – 5305 Å (observed-frame). The positive ratio of the H$\beta$ line between the spectrum-and-photometry fit over the spectrum-only fit is consistent with the UV flux being constrained for the former, such that the absorption line is preferentially shallower. The difference in the Mg II lines reflects the difference in metallicities predicted for each fit, as well as the inability of the (fixed scaled-solar abundance) models to be flexible to such features.

Fig. B2 compares the basic stellar properties (normalisation of the diffuse dust attenuation curve, $V$-band extinction, stellar metallicity, stellar mass, and mass-weighted age) for the fits to the three sets of observations. This figure is akin to Fig. 5, discussed in Section 4. For
Figure B1. Comparison of fits with the spectrum and photometry (red), spectrum only (green, with mass fixed to the value from van Dokkum et al. 2016), and photometry only (yellow), assuming an extended SFH prior. The observed data (black) is compared to the bestfit models (coloured lines) and the 68 per cent CR of 500 randomly drawn models from the posteriors (shaded coloured regions). The corresponding posteriors are shown in Fig. B2. (a) The observed (circles) and bestfit (diamonds and triangles) photometric points, where the reduced $\chi^2/N_{\text{data}}$ of the bestfit SED are listed. (b) The $\chi^2 (\text{data} - \text{model})/\sigma$ of the bestfit photometric points. (c) The observed spectrum (uncertainties shown in grey) and bestfit spectra (multiplied by the spectrophotometric calibration polynomial). The hatched grey region indicates the spectral region masked throughout the fitting process. (d) The $\chi^2$ of the bestfit spectra as a function of wavelength. (e) The relative change of the bestfit models, i.e., the ratio of the two bestfit spectra. (f) The spectrophotometric calibration models, with 68 per cent CRs shown as shaded regions.

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Comparison, black lines indicate values measured in the literature; dashed lines indicate the stellar isochrone metallicity measured by Villaume et al. (2022), while dotted and solid lines indicate the stellar mass measured by van Dokkum et al. (2016) and Saifollahi et al. (2021), respectively. For reference, the prior on the age (which is implicit, as age is determined by the time bin widths and SFH) is shown as a black histogram.

The broadband NUV to NIR photometry (yellow) and continuum normalised spectroscopy (green) carry different information about the galaxy properties. The broad (yet coarse) photometry provides a tighter constraint on the dust attenuation, while the spectroscopy constrains the metallicity. The dust attenuation cannot be determined from the spectroscopy alone because of the lack of continuum information; the spectrophotometric calibration marginalises over the continuum shape, and is degenerate with both the stellar mass and dust attenuation. On the other hand, the metallicity is tightly constrained by the spectroscopy as there is detailed information among the numerous absorption lines.

Despite the formal consistency of the dust and metallicity parameters between these two fits (given the large uncertainties), the age
posterior PDFs are significantly different. The age posterior from the photometry largely traces the (implicit) prior. A tighter pdf for the stellar metallicity provides a more precise estimate of the age, as expected given the degeneracy between these two parameters.

Simultaneously fitting the photometry and spectroscopy (shown in red) constrains the full set of parameters. In the particular case of DF44, the results are largely informed by the spectroscopy, which covers a broad range in metallicity and age features—the inclusion of the photometry only modestly affects the posteriors. The stellar mass derived from the combined data sets is consistent with that of Saifollahi et al. (2022), while the photometry-derived posterior is skewed lower by $\sim 0.23$ dex, which is likely also related to the lower estimate for the stellar metallicity. The combined result shows DF44 to be very old, metal poor, and perhaps with some small amount of dust.

**B3 SFH biased by choice of prior**

Fig. B3 demonstrates the S/N dependence of the bias imposed by the choice of SFH prior, which in this case is an extended SFH in describing a very old stellar population. We refit the KCWI spectrum of DF44 with the extended SFH prior ($\alpha_D = 1$), successively increasing the uncertainties of the spectrum such that the S/N$_{spec} = 5, 10, 15$, and 20. The medians of the recovered PDFs are shown for the mass-weighted age (in lookback time), $t_{50}$ and $t_{90}$ (in time since the Big Bang), $\log(Z/\text{Z}_\odot)$, and diffuse dust, with error bars corresponding to the 68 per cent (thick and wide) and 95 per cent (thin and narrow).
CRs. Points mark the results from fitting the spectrum and photometry simultaneously (diamonds), the spectrum alone (squares, offset vertically for clarity), and the photometry alone (circles). The prior distributions are shown in the top panels. Note that because the implicit priors for the SFH time-scales depend on the widths of the SFH time bins (a step function), the distributions are not necessarily smooth.

The SFH time-scales are more heavily weighted by the SFH prior at low S/N. This is particularly true for $t_{90}$, which we use as a proxy of the quenching time. In contrast, neither the stellar metallicity nor the dust is significantly biased, or at least the offsets are well within the (large) uncertainties. While having a complete set of observations informs many of the galaxy properties, the choice of a ‘good’ SFH prior is important.

### B4 Comparing results between studies – prior and data dependence

Fig. B4 shows a comparison of the star formation time-scales of UDGs (circles) and dwarfs (squares and diamonds) for observations from the literature (for Coma galaxies in almost all cases). We compare the time at which we consider the galaxy quenched, $t_{90}$, with how extended the SFH is, $t_{50}$. The grey shaded region denotes the parameter space where ages ($t_{50}$) are older than the Universe (e.g., OGS1 from Ruiz-Lara et al. 2018). We show the results from the literature as upper limits given the possible biases in SFH time-scales discussed above related to the S/N, and choice of SFH priors.

Except for DF44, all the literature values were measured using the full-spectrum fitting code STECKMAP. Notably STECKMAP smooths the SFHs via (tunable) regularisation akin to Gaussian priors on the SFH and age–metallicity relations (see the discussion in Section 3.1.1). The details of the regularisation differ between all studies, where for example, Ruiz-Lara et al. (2015) present the outcome of averaging several results with various smoothing parameters. Martín-Navarro et al. (2019) show in their appendix A the difference in their regularised and un-regularised results to be ~ 1 Gyr in $t_{50}$ and ~ 0.4 Gyr in $t_{90}$.

Ferré-Mateu et al. (2018) compared their SFH time-scales derived from STECKMAP with those from an alternative fitting code, STARLIGHT, which does not impose regularisation but does require relative-flux calibrated spectra. Between the two fitting approaches, Ferré-Mateu et al. (2018) found consistent results in that the SFHs are extended and had similar quenching times. That said, STARLIGHT preferred starting star formation ~ 2 Gyr later, such that the ages were younger and star forming time-scales were shorter. In contrast, the ‘burstier’ prior used in this work produced earlier star formation and quenching.

Because of the difficulties in determining the ages of old stellar populations, even subtle differences in data or analysis can impact results beyond the expected uncertainties. As an example, we can compare measurements for two UDGs, DF26/Yagi93 and Yagi418, both studied by Ferré-Mateu et al. (2018) and Ruiz-Lara et al. (2018); the values are connected with dashed lines in Fig. B4. Each author used rest-frame optical spectroscopy (where Ruiz-Lara et al. 2018 reported higher S/N and had a wider wavelength coverage) and they used the same code (STECKMAP). However, the median mass-weighted
ages differ by ~ 1 Gyr (uncertainties were not reported, but the luminosity weighted ages are formally consistent). In both cases the higher S/N data provided a solution shifted in the expected direction (i.e., towards older and less-extended SFHs).

While DF44 appears to have (one of) the shortest SFHs and earliest quenching times, we caution that a detailed comparison should consider priors and the S/N. A poorly chosen SFH prior will have a stronger bias at a low S/N. For example, in using an extended SFH prior with the DF44 KCWI spectrum degraded to S/N = 20, we recover \( t_{50} \approx 2.9 \pm 0.5 \) Gyr and \( t_{90} \approx 7.1 \pm 1.2 \) Gyr (see Fig. B3 in Appendix B3), which overlaps with the lower end of UDGs in Fig. B4. This suggests that some of these objects could be older, and have less-extended SFHs.

Along the same lines, we do not include photometry-derived results in Fig. B4 as the comparison can be misleading given the different choices (and relative contributions) of SFH priors. In the preceding sections we have shown that the photometry-derived ages are younger than the spectroscopy- or combined-derived ages. There is a similar difference between the results of Pandya et al. (2018, with optical to NIR photometry; not shown in Fig. 8) and Martín-Navarro et al. (2019, with rest-frame optical spectroscopy, S/N ~ 10 Å\(^{-1}\)). Both studied the UDG DGSAT I, although using different fitting methods and assuming different SFHs. Pandya et al. (2018) fitted their photometry (via MCMC) to a delayed-exponential model, while Martín-Navarro et al. (2019) fitted their spectroscopy with stockmap. We note that in this example the priors are considerably different. For a delayed exponential model with linearly uniform priors with \( \tau = 0.1-10 \) Gyr and \( \tau_{\text{age}} = 1-14 \) Gyr, the implicit prior on the mass-weighted age has a median of 3.2 Gyr. In comparison, a constant SFH has a median age of half the age of the Universe, \( \sim 6.8 \) Gyr (see also the discussion in Johnson et al. 2021b). While the luminosity-weighted ages are similar (~ 3 Gyr), their mass-weighted ages are discrepant by > 1 Gyr (\( \tau_{\text{age}} \) in the delayed-exponential model is the onset of star formation, where for a \( \tau > 3 \) this corresponds to ages considerably younger than \( \tau_{\text{age}} \)). The metallicities are also discrepant by > 1 dex, although Martín-Navarro et al. (2019) found that DGSAT I is unusually \( \alpha \)-enhanced. Several studies have studied UDGs from photometry alone (e.g., Greco et al. 2018; Barbosa et al. 2020), and have similarly noted younger ages than spectroscopy-derived results.

We additionally note that Martín-Navarro et al. (2019) uses a set of SSP models different than used in both this work and the other UDGs studies discussed here. Neither the choice of SSP models or application of regularisation would explain the significant offset between the SFHs of DGSAT I and the other UDGs, however.

**Figure B4.** Star formation time-scales of UDGs (circles) and dwarfs (low luminosity and high luminosity galaxies; squares and diamonds, respectively) for observations from the literature. We approximate the quenching time as when 90 per cent of the stellar mass is in place (\( t_{90} \)), while the time-scale \( t_{50} - t_{90} \) gives a sense of the duration of star formation, i.e., how concentrated/extended the SFH is. Other than DF44, we show the points from observations with arrows indicating that they are upper limits (see text). Points are coloured according to their S/N, where DF44 has a mean S/N of 96 Å\(^{-1}\). Dashed lines connect points measured for the same object, but from different studies. Sources: Ferré-Mateu et al. (2018), Ruiz-Lara et al. (2018), and Martín-Navarro et al. (2019). The points from Ruiz-Lara et al. (2018) are shown with S/N > 32 Å\(^{-1}\), the median of the reported range in values.

**APPENDIX C: DEGENERACY BETWEEN DUST ATTENUATION AND FLUX FROM OLD STELLAR POPULATIONS IN THE NUV**

The normalisation of the dust attenuation curve (\( \tau_{\text{dust, diffuse}} \)) and the fraction of old stars, both parameters of our physical model, are degenerate at optical and UV wavelengths. As a brief example of this degeneracy, Fig. C1 shows the photometry for DF44 (black points) relative to three model SEDs with simple stellar populations (i.e., not the results of fitting the physical model described in Section 3). Taking the grey model as the ‘fiducial’ model, slight variations in age and dust are shown by the purple and cyan models, respectively. While the 2.8 Gyr age increase or 0.2 dex increase in diffuse dust produces an equivalent effect in the NUV, they have opposing effects at wavelengths > 1 \( \mu m \). Coloured markers show the expected photometry in two JWST filters in the mid-infrared, with S/N ~ 5 to reflect the average uncertainty of the IRAC data. In this example, the ‘old’ and ‘dusty’ models are slightly distinguishable in F560W (\( \Delta m_{\text{AB}} \approx 0.6 \sigma_m \)) but very different in F770W (\( \Delta m_{\text{AB}} \approx 3 \sigma_m \)). The inclusion of mid-infrared data to our data set would allow us to assess whether DF44 is as dusty as our results suggest or a product of the complex degeneracies between physical parameters (see Section 4.1).
Figure C1. A brief demonstration of the degeneracy between dust attenuation and age on the shape of SEDs. Top: Photometry of DF44 (black markers) and models (coloured lines) for three SSP populations. Photometric points corresponding to the ‘old’ (purple dashed) and ‘dusty’ (solid cyan) models are shown as measured by the JWST F560W and F770W filters (coloured markers), with S/N = 5. Bottom: The relative change between the fiducial (grey) and older or dustier models. While the effect of either increasing the age or dust acts similarly at wavelengths < 1 μm, the effect acts in the opposite sense in the mid-infrared.