UV upturn versus UV weak galaxies: differences and similarities of their stellar populations unveiled by a de-biased sample

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ABSTRACT
The ultraviolet (UV) upturn is characterised by an unexpected up-rise of the UV flux in quiescent galaxies between the Lyman limit and 2500 Å. By making use of colour-colour diagrams, one can subdivide UV bright red-sequence galaxies in two groups: UV weak and upturn. With these two groups, we propose a comparison between their stellar population properties with the goal of establishing differences and similarities between them. We make use of propensity score matching (PSM) to mitigate potential biases between the two samples, by selecting similar objects in terms of redshift and stellar mass. Also, we take advantage of spectral energy distribution (SED) fitting results from MAGPHYS made available by the GAMA collaboration. The analyses are made by comparing the distributions from the SED fitting directly, as well as investigating the differences in correlations between their parameters, and finally by using principal component analysis (PCA). We explore important differences and similarities between UV weak and upturn galaxies in terms of several parameters, such as: metallicity, age, specific star formation rate, time of last burst of star-formation, to mention a few. Notable differences are those concerning \((g - r)\) colour, metallicity, and time since last burst of star-formation: UV upturn are redder in the optical, more metallic, and their last burst of star-formation happened earlier in time. These differences suggest that UV upturn systems have shorter star-formation histories (i.e. have been evolving more passively) when compared to UV weak galaxies. Consequently, these last seem to have a higher diversity of stellar populations.

Key words: galaxies: general – galaxies: elliptical and lenticular, cD – galaxies: stellar content – galaxies: abundances – ultraviolet: general – ultraviolet: galaxies

1 INTRODUCTION
The formation and evolution of galaxies has only been investigated for a little over 100 years and, in that time-frame, remarkable advances have been made. Hubble (1926) suggested that galaxies could be classified in two large groups: early- and late-type (ETGs and LTGs hereafter). The first comprises all the elliptical and lenticular systems, which are usually inhabited by aged stellar populations; whereas the latter encompasses spiral and irregular galaxies, being mostly composed by young and hot stellar populations.

It is in this context that the study of ETGs, as well as the so-called ultraviolet (UV) upturn phenomenon are embedded. Since ETGs are known to be mainly constructed by aged stellar populations, their radiation peaks in the visible region of the electromagnetic spectrum, strongly weakening towards lower wavelengths – i.e. UV. Therefore, ETGs are not expected to have any substantial emission in bluer ranges of the electromagnetic spectrum, as it would indicate hotter stellar populations (namely young stars).

Yet, some ETGs actually present a meaningful flux in the UV range of the spectrum, which has been reported for the first time by Code (1969) by observing the bulge of M31; that later became the ‘UV upturn of elliptical galaxies’ (e.g. O’Connell 1999). Hypotheses such as residual star-formation activity in ETGs (e.g. Stasińska et al. 2015; Evans et al. 2018; López-Corredoira & Vazdekis 2018) started to be considered as potential explanations (e.g. Yi et al. 2005; Kaviraj et al. 2007a,b; Pipino et al. 2009; Salim & Rich 2010; Bettoni et al. 2014; Davis et al. 2015; Haines et al. 2015; Sheen et al. 2016; Vazdekis et al. 2016, and references therein). Also, with the better understanding of stellar evolution, other rare stellar evolutionary phases started to be acknowledged as potential culprits for the UV upturn. Theories discussing the role of post-main-sequence stellar evolutionary phases have been proposed as early as 1971 (see Hills 1971). Suspects of prompting this phenomenon are blue horizontal branch (HB) stars and extreme HB (EHB) stars (Yi et al. 1997; Brown et al. 1998, 2000; Yoon et al. 2002).
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2004; Peng & Nagai 2009; Donahue et al. 2010; Loubser & Sánchez-Blázquez 2011; Schombert 2016, and references therein), as well as the asymptotic giant branch (AGB) family of stars: post-AGB, post-early-AGB, AGB manqué (e.g. Greggio & Renzini 1990; Brown et al. 1998; Deharveng et al. 2002; Donas et al. 2007; Han et al. 2007; Chavez & Bertone 2011; Rosenfield et al. 2012), and even ‘regular’ AGB stars (see e.g. Ortiz et al. 2019; Guerrero & Ortiz 2020, as references to the UV excess in AGB stars). Besides, quiescent galaxies can also suffer from boosts in their UV emission due to binary systems in interaction, which makes them likely suspects of causing the UV upturn (e.g. Zhang et al. 2005; Han et al. 2007, 2010).

A global characteristic that appears to be a consensus in the community is the role of metallicity and its impact in the UV upturn phenomenon (e.g. Faber & Worthey 1993; Yi et al. 1997; Jeong et al. 2012; Chung et al. 2013). Burstein et al. (1988) suggested a relation between the UV upturn and the intensity of Mg$_{2}$, which is supported by Boselli et al. (2005), Donas et al. (2007), and Bureau et al. (2011) but not backed by Loubser & Sánchez-Blázquez (2011). Moreover, some studies indicate that helium-enhanced populations might explain simultaneously the UV properties of globular clusters and the UV upturn (e.g. D’Antona & Caloi 2004; Lee et al. 2005; Kaviraj et al. 2007b; Piotto et al. 2007; Peacock et al. 2011; Schiavon et al. 2012; Chung et al. 2017; Gouldrooj 2018; Peacock et al. 2018). Some studies have even found the UV upturn in NGC 6791, an old open cluster (see Buson et al. 2006; Buzzoni et al. 2012).

To try to stratify this patchwork of stellar populations in galaxies, one must investigate their spectral energy distributions (SEDs). The SED of a galaxy encodes the integrated light from all the emitting astrophysical objects inhabiting therein, with special remarks on stars, stellar remnants, and dust. Therefore, breaking the encryption of SEDs is key to analyse the influence of each of those components; properties such as stellar masses, ages, metallicities, and so forth can be retrieved from this technique (see Walcher et al. 2011; Comroy 2013, for reviews on the topic). Several previous works have attempted to analyse the potential prompters of the UV upturn; e.g. Hernández-Pérez & Bruzual (2013) developed a library rich in binaries and they further concluded that these are paramount to explain the phenomenon (Hernández-Pérez & Bruzual 2014). The analysis made by Lonoce et al. (2020) is based on absorption line features in the UV and it was applied to four massive ETGs fostering the UV upturn in the highest redshift ($z$) so far ($z \sim 1.4$); they concluded that only old stellar populations could explain such UV emission, without specifying the most likely culprits. Also, Werle et al. (2020) suggest that some galaxies presenting UV upturn can be influenced by accretion or minor mergers and their UV emission is due stellar populations younger than 1 Gyr; for their sample, this would explain the UV emission of nearly 20 per cent of the cases. On the other hand, they also believe that other UV upturn systems are mainly influenced by old and hot stellar populations (i.e. stars in the centres of planetary nebulae and white dwarfs) with an addition of EHB stars and binary systems in interaction; these account for approximately 80 per cent of their UV bright quiescent systems.

Apart from analysis of stellar populations, several works have tried to investigate this issue in different viewpoints. For instance, Burstein et al. (1988) suggested a link between the UV upturn and velocity dispersion, which has been supported by works that have determined that, in fact, the UV upturn is more frequent in more massive ETGs (e.g. Le Cras et al. 2016) and its dependence has been shown by Dantas et al. (2020). Also, many works investigated whether the strength of the upturn evolves in $z$ (e.g. Brown 2004; Rich et al. 2005; Ree et al. 2007; Boissier et al. 2018), as well as the fraction of ETGs nesting the UV upturn (Dantas et al. 2020). Others looked for environmental dependencies, such as Yi et al. (2011) and Ali et al. (2019), but could not provide a definitive answer to this issue, despite the predictions from helium-sedimentation theory discussed in Peng & Nagai (2009). All in all, there are many aspects to consider while investigating such a complex problem as the UV upturn, many of which bring to light contradictory results.

Given this context, the goal of this paper is to compare overall differences and similarities among UV bright red-sequence passive/retired galaxies (RSGs, namely UV weak and upturn galaxies), according to the paradigms of Yi et al. (2011) and Cid Fernandes et al. (2010, 2011). To that end, we have applied a propensity score matching (which was applied to stellar mass, log M$_{\ast}$, and $z$) to the RSG passive/retired sample described in Dantas et al. (2020) with the aim of strongly limiting the biases between them. It is important to highlight that the main results described in Dantas et al. (2020) concern the evolution in $z$ and log M$_{\ast}$ of the fraction of UV upturn systems; hence, this dependence is removed with the use of PSM. We make use of the value-added catalogues provided by the Galaxy Mass Assembly (GAMA) collaboration, in which results for SED fitting using MAGPHYS (da Cunha et al. 2008) are available. With these results at hand, we explore such similarities and differences, as well as their implications. To that end, we investigate their distributions directly or differences in correlations between the resulting parameters from SED fitting by making use of correlation maps (e.g. de Souza & Ciardi 2015). Finally, a principal component analysis (PCA) is applied with the goal of verifying the results from the previous analyses.

This paper is structured as follows. In Sec. 2 we briefly describe both the dataset and methodologies used in this paper; in Sec. 3 we present the stellar population properties of our sample and the differences and similarities between both UV classes; in Sec. 4 the discussion is extended; and in Sec. 5 we present some conclusions to this study. Extra material can be found in the Appendix. For all purposes, this work made use of the standard Λ-CDM cosmological model with the following parameters: {$H_0, \Omega_M, \Omega_\Lambda$} = {70km s$^{-1}$Mpc$^{-1}$, 0.3, 0.7} – as used by the GAMA collaboration (Baldry et al. 2018). Also, all masses herein used are in terms of solar masses (M$_{\odot}$) unless stated otherwise.

2 DATASET & METHODOLOGY

We make use of GAMA-DR3 database (Baldry et al. 2018)$^1$ aperture-matched with Sloan Digital Sky Survey 7th data release (SDSS-DR7, York et al. 2000; Abazajian et al. 2009)

$^1$ Available at http://www.gama-survey.org/dr3/schema/
and Galaxy Evolution Explorer GR6/plus7 (GALEX, Martin et al. 2005). The sample herein used is the same one used in Dantas et al. (2020, bold rows in Table 1 therein) – see ‘final sample’ with WHAN emission line diagram (Cid Fernandes et al. 2010, 2011) classification of retired/passive systems.

It is worth mentioning that the WHAN chart is an emission line diagnostic diagram that uses the equivalent width of Hα – EW(Hα) – and the line ratio of [NII] λ6583 and Hα (log[NII]/Hα). By using EW(Hα), it is possible to detect some of the ‘liry’ retired/passive population of galaxies – which cannot be done by using log[OIII] λ5007/Hβ (which is the case of the Baldwin-Phillips-Terlevich – BPT – diagram Baldwin, Phillips & Terlevich 1981).

Further details about the selection criteria and treatment applied are available in Dantas et al. (2020).

### 2.1 A control sample

This sample was de-biased by making use of propensity score matching (PSM, e.g. Rosenbaum & Rubin 1983; Ho et al. 2007). PSM is a technique that enables us to select similar systems in terms of the properties chosen; it has only been used a few times in Astrophysical studies so far (see de Souza et al. 2016; Trevisan et al. 2017, for other applications in Astronomy). By considering retired/passive UV upturn galaxies as our benchmark, we select a control sample of retired/passive UV weak systems that are the closest in terms of log $M_\star$ and $z$. The main results in Dantas et al. (2020) are the dependence of the fraction of UV upturn systems in terms of log $M_\star$ and $z$; therefore, we applied PSM considering these two parameters, to remove such dependence. To that end, we make use of the nearest-neighbor algorithm available in scikit-learn, a python package rich in several machine learning tools (Pedregosa et al. 2011). During the process, some UV weak galaxies – considered UV upturn ‘twins’ – were accounted for multiple times; in such cases, we only considered the system once. For that reason, the final sample for UV weak systems is lower than those of UV upturn galaxies, which is depicted in the column ‘After PSM’ in Table 1.

Fig. 1 depicts the classification of the sample used in this work according to Yi et al. (2011). Fig. 2 displays UV upturn systems as well as UV weak galaxies before and after PSM in a chart of $z$ per log $M_\star$; the final $z$ range goes from 0.06 to 0.30. The distribution of log $M_\star$ and $z$ for both UV weak and UV upturn systems, before and after PSM, can be seen in Fig. 3.

### 2.2 SED fitting

In terms of stellar population properties, we have made use of the results from MAGPHYS (da Cunha et al. 2008) available in the homonym MagPhys data management unit (DMU) from GAMA-DR3 (Baldry et al. 2018). The GAMA team performed the SED fitting by making use of 21 photometric bands, spanning from the UV to the far-IR/submillimetre: FUV, NUV, $ugriz$, ZYJHK, W1234, PACS100/160, SPIRE 250/350/500 (Driver et al. 2018) and treated them with the lambdaadar code (Wright et al. 2016). Additionally they use Bruzual & Charlot (2003) simple stellar population templates combined with Chabrier (2003) initial mass function (IMF) and Charlot & Fall (2000) dust models. Since Magphys is a parametric SED fitting code, the star-formation history (SFH) is parametrised; the details on the SED fitting procedure can be found in Baldry et al. (2018); Driver et al. (2018).

#### 2.2.1 Dust masses

In this Section we briefly present some results for dust in our sample. We have not de-reddened the sample in terms of internal extinction albeit using SED fitting results, which may cause some contamination from reddened green-valley galaxies (e.g. de Meulenaer et al. 2013; Sodré et al. 2013). To as-

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**Table 1.** Number of objects of each UV class (according to Yi et al. 2011) before and after PSM.

| Galaxy UV class | Before PSM | After PSM |
|-----------------|------------|-----------|
| UV upturn       | 87         | 87        |
| UV weak         | 118        | 51        |

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**Figure 1.** Colour-colour diagram for NUV-$r$ versus FUV-NUV with the classifications according to the prescription of Yi et al. (2011). The straight black lines depict the two out of the three criteria of Yi et al. (2011): NUV-$r$=5.4 and FUV-NUV=0.9. This image depicts the colour-colour diagram after the PSM.

**Figure 2.** Scatter-plot depicting the UV upturn and weak systems. The latter is shown twice: before (in light brown) and after PSM (in strong red); the reference objects – i.e. those nesting UV upturn – are in dark brown.

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3 DIFFERENCES AND SIMILARITIES: A VIEW ON STELLAR POPULATIONS

In this section we present the main results of our analysis. For analysing correlations, we make use of Spearman’s correlation rank (Spearman 1904). It is worth mentioning that UV and UV-optical colours, and the 4000 Å break are also discussed in this Section albeit not being products of SED fitting. The parameters chosen for this analysis are the following:

i. \( D_n4000 \): 4000Å break.
ii. UV and UV-optical colours: FUV-NUV, FUV-\( r \), and NUV-\( r \);
iii. \( \langle \log t_{\text{SFR}} \rangle \): average log of age weighted by light (using \( r \)-band);
iv. \( \langle \log t_{\text{burst}} \rangle \): average log of age weighted by mass;
v. \( \langle Z/Z_\odot \rangle \): average metallicity in solar units;
vi. (SFR): star formation rate in the last 0.1 Gyr;
vii. (sSFR); specific star formation rate in the last 0.1 Gyr;
viii. (\( t_{\text{form}} \)): median age of the oldest stars in the galaxy;
ix. (\( t_{\text{last}} \)): median time since last burst of star formation;
x. (\( f_{\text{burst}} \)): fraction of stellar mass formed in the corresponding time-scale;
xii. (\( t_{\text{burst}} \)): fraction of stellar mass formed in the last 2 Gyr;
xiii. (\( \langle t \rangle \)): median star-formation timescale (parameter originated from the fact that MAGPHYS is a parametric code);

3.1 Direct comparison

In Dantas et al. (2020) we have found that UV upturn systems presented redder (\( g-r \)) optical colour when compared to their UV weak counterparts. Therefore, here we start our
Figure 6. Distributions of six parameters which resulted from SED fitting (see text for more details). From left to right: the first row depicts \((\log t)_m\) and \((\log t)_r\); the second, \((t_{\text{form}})\) and \((t_{\text{last}})\); the third, \((\text{sSFR})\) and \((\text{sSFR})\); and, finally, the fourth, \((Z/Z_{\odot})\) and \((\gamma)\). UV weak and upturn galaxies are depicted in light and dark brown, respectively. The corresponding \(\tilde{x}\) are in the respective colours marked in dashed lines, except for \((\text{sSFR})\), in which both \(\tilde{x}\) coincide; in this case, the UV upturn systems are marked by a continuous line to allow for both \(\tilde{x}\) to be seen overlapped. For \((\text{sSFR})\), a straight line at -11.31 is marked, which is considered to be a standard cut to separate passive galaxies from the star-formation main sequence (see e.g. Davies et al. 2019a). Additionally, the skewness \((s)\) of each distributions can be seen in their respective legend box.

By revisiting this phenomenon and checking whether this behaviour repeats itself in a controlled scenario (by making use only of retired/passive UV bright RSGs after PSM). The results are depicted in Fig. 5, which shows that UV weak systems are more skewed to the left than UV upturn galaxies; their medians \((\tilde{x})\) follow the trend. In fact, the behaviour seen in Dantas et al. (2020) can be reassessed in this study, even after the sample being controlled. This is an interesting finding, as the distribution of \(\log M_{\star}\) is basically the same for both systems and \((g - r)\) being correlated to \(\log M_{\star}\) (e.g. see Fig. 20, Kauffmann et al. 2003).

Following the depiction of the \((g - r)\) colour, in this Section we present the direct comparison of the distributions of the parameters from SED fitting depicted in Fig. 6. The sub-figures display the Gaussian kernel distribution for each parameter analysed for both types of galaxy, according to their UV class. Additionally, the skewness of each distribution is available in their respective legend box. Skewness \((s)\) is a measure of the asymmetry of a distribution; for those with longer tails to the right, \(s\) is positive, negative otherwise, and null for symmetric cases (for details on the topic, the reader is referred to Groeneveld & Meeden 1984).

In the first row, the Gaussian kernel density distributions of \((\log t)_m\) and \((\log t)_r\) are displayed; they show that the stellar populations inhabiting UV upturn systems are systematically older than those in their UV weak counterparts – \((\log t)_r\) medians display a difference of only \(\sim 0.32\) Gyr. The analysis heretofore will consider only \((\log t)_r\) in order to avoid duplicate analysis.

Nonetheless, in the second row, the values of \((t_{\text{form}})\) for both systems show that the oldest stellar populations of both systems have very similar ages (see the proximity of \(\tilde{x}\) in dashed lines). \((t_{\text{form}})\) is higher for UV upturn than for UV weak systems, which apparently points to a gap of \(\sim 0.44\)
Gyr\(^2\) between the last starbursts of the two systems; although the shape of distributions of \(t_{\text{burst}}\) are similar. Yet, UV weak objects seem to have a longer tail towards low-end values.

The differences between both classes in terms of age \((\log t)_{s}\) and \((\log t)_{m}\) and \(t_{\text{burst}}\) are very small in terms of our current precision for age estimations (e.g. Dotter et al. 2011, which is around 1–2 Gyr). Therefore, one should consider these differences with the according caveats. Yet, to probe whether the ages are actually different between both classes, we analysed the distribution of \(D_4,4000\) (defined by Bruzual A. 1983) – which is available in Fig. 7. \(D_4,4000\) is known to be correlated to age and metallicity and it is an empirical measurement retrieved from the spectra (observed by the GAMA survey), conveying less errors, specially for values \(\geq 1.3\), which is the case here (e.g. Kauffmann et al. 2003; Mateus et al. 2006). The analysis indicates that UV upturn galaxies have higher values of \(D_4,4000\) in terms of their \(\bar{x}\) and \(s\) of the distribution, when compared to their UV weak counterparts. Therefore, the age and metallicity (which will be discussed further in this Section) gaps seems to be confirmed by the differences in \(D_4,4000\).

In the third row, \(\langle sSFR\rangle\) and \(\langle SFR\rangle\) are presented. The shape of the distributions for \(\langle SFR\rangle\) is similar for both UV classes, except for the low-end of UV weak systems, that shows a bump that is absent in their upturn counterparts. It is interesting that according to this marker UV upturn systems have a higher rate of star-formation in the last 0.1 Gyr than compared to their weak counterparts. For \(\langle sSFR\rangle\) the shapes of both systems are very different, but their \(\bar{x}\) is exactly the same at -11.47. A straight line in black has been added at \(\langle sSFR\rangle=-11.31\), which is a standard cut to separate star-forming\(^2\) from passive systems (e.g. see Fig. 2C in Davies et al. 2019a). It is possible to see that many of the galaxies of our sample possess \(\langle sSFR\rangle>-11.31\); in fact 34 UV upturn and 15 UV weak systems from the post-PSM sample have \(\langle sSFR\rangle>-11.31\), which constitutes roughly 30–40 per cent of each galaxy class. These results are not completely reliable, as the SED fitting is done by making use of Bruzual & Charlot (2003) models, which highly bias the UV fit towards young stellar populations. These results are not in accordance with all the measures taken to avoid star-forming effects, such as the photometric criteria according to Yi et al. (2011), the emission lines criteria according to Cid Fernandez et al. (2010, 2011), and the amount of dust as seen in Fig. 4. Therefore, the results for \(\langle SFR\rangle\) and \(\langle sSFR\rangle\) are not completely trustworthy, and they must be evaluated cautiously.

To further investigate the results for \(\langle SFR\rangle\), we compared the \(\langle SFR\rangle\) and \(\langle f_{\text{burst}}\rangle\) in timescales varying from \(10^6\) to \(2 \times 10^9\) yr; these results are available in in Fig. 8 and Table 2. Again, these values are low and should be evaluated cautiously. Throughout all timescales (except for \(10^7\) and \(10^8\) yr, in which the results are all the same and null for both types of systems), the median values of all \(\langle f_{\text{burst}}\rangle\) are higher for UV weak systems when compared to their UV upturn counterparts. The distribution of \(\langle f_{\text{burst}}\rangle\) for \(10^6\) yr is more spread over small values, whereas for the other timescales \(\langle f_{\text{burst}}\rangle\) is essentially null \((5 \times 10^{-4})\), with some outliers. This indicates that, albeit the small values of \(\langle f_{\text{burst}}\rangle\), fluctuations in SED fitting indicate that UV weak systems have been forming a few more stars than those of UV upturn galaxies throughout time. This is also an inkling that \(\langle SFR\rangle\) alone is not enough to explain the differences between both groups of galaxies. By using \(\langle sSFR\rangle\), one mitigates some of the associating issues, but other parameters still remain important to disentangle their similarities and/or differences, such as \(\langle f_{\text{burst}}\rangle\). Additionally, considering the effects of making use of stellar population templates that favour star-forming effects (i.e. Bruzual & Charlot 2003), instead of taking into account the blue emission from rare/evolved stellar evolu-

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\(^2\) The differences in both \((\log t)_{s}\) and \(t_{\text{burst}}\) were linearised to accurately depict the differences of both classes of galaxies.

\(^3\) Or in other words, the so-called ‘star-formation main sequence’ of galaxies.
Figure 8. Averaged star-formation rate ($\langle SFR \rangle$, left column) and fraction of stellar mass formed in bursts ($\langle f_{\text{burst}} \rangle$, right column) respectively over the following periods: $10^6$, $10^7$, $10^8$, $10^9$, and $2 \times 10^9$ yr. The results herein depicted represent both UV weak and UV galaxies (in light and dark brown respectively). In all scenarios, $\langle SFR \rangle$ is very similar between both UV classes. In the first row $\langle f_{\text{burst}} \rangle$ is distributed over a range of values and a kernel density is depicted; the dotted and dashed lines depict the density for UV upturn and UV weak systems respectively. $\langle f_{\text{burst}} \rangle$ for other timescales are essentially null with some outliers; in these cases the kernel density cannot be computed.

It is noteworthy that the analysis made by Werle et al. (2020) makes use of an updated version of Bruzual & Charlot (2003) models (Charlot & Bruzual, in preparation) which accounts for many of those stellar evolutionary phases underestimated, specially for the last $10^6$ yr.

...tionary phases, it is quite possible that these results are overestimated, specially for the last $10^6$ yr.

It is noteworthy that the analysis made by Werle et al. (2020) makes use of an updated version of Bruzual & Charlot (2003) models (Charlot & Bruzual, in preparation) which accounts for many of those stellar evolutionary phases underestimated in Bruzual & Charlot (2003). Therefore, their results account for a diminished influence from young stellar populations in order to explain the UV upturn phenomenon when compared to our results, specially in what concerns the values of $\langle SFR \rangle$ and $\langle sSFR \rangle$.

The forth and last row of Fig. 6 shows the distributions...
of \( \langle Z/Z_\odot \rangle \) and \( \langle \gamma \rangle \). The first depicts a quite different shape in their distributions; UV weak galaxies seem more skewed towards lower values than UV upturn systems. The latter shows the distributions of \( \langle \gamma \rangle \), a parameter resulting from \textsc{magphys} due to its parametric characteristics; the results show that, in this case, \( \langle \gamma \rangle \) is more skewed to the right for UV weak systems.

All in all, it is worth mentioning that the most important results depicted in the direct comparison analysis are the gaps in \( \langle t_{\text{burst}} \rangle \) and \( \langle Z/Z_\odot \rangle \).

### 3.2 Correlation maps

Correlation maps allow us to see a myriad of relations in a very compact framework (see de Souza & Ciardì 2015, as a reference of data visualisation in Astronomy). In fact, by using heatmaps and cluster-maps, we have gained access to 36 effective values of \( \rho \) for each UV class. This also means that instead of discussing each and every \( \rho \) we will focus the discussion on relevant results. Additionally, with the use of dendrograms (see Fig. 9), it is possible to see an hierarchical rearranging of chosen parameters and their respective correlation.

It is worth mentioning that we do not discuss the correlations for \( \log M_*, \) (sSFR), or \( \langle f_{\text{burst}}^{2Gyr} \rangle \) in dedicated sections; the reasons are simple, as \( \log M_* \) has been used to mitigate the biases in our sample; (sSFR) is not considered a main feature for this particular analysis; and most values of \( \langle f_{\text{burst}}^{2Gyr} \rangle \) are null. They are discussed when relevant in the following subsections.

#### 3.2.1 UV and UV-optical colours

One of the main results of this analysis is the change in correlations between UV and UV-optical colours and the other parameters retrieved from the SED fitting. By simply looking at the tree last rows of Tables A1 and A2, it is noticeable \( \rho \) changes from \( \sim 0 \) to mild values \( \rho \approx 0.2 \) \( \sim 0.3 \). Yet, only FUV-NUV and FUV-\( r \) colours are clustered together in both cluster-maps represented in Fig. 9; NUV-\( r \) becomes a ‘pivoting’ parameter, switching between similar groups in each UV class (i.e. weak or upturn).

Of course, all these colours are used to perform this UV classification (Fig. 1). Therefore, we must take into account their correlations/anti-correlations, instead of their actual values. Also, the discussion between the correlations between these colours and the other parameters will not repeated in the further subsections. We further explore these colours in Fig. 10.

#### 3.2.1.2 FUV-\( r \):

The changes for this colour are more subtle. For UV upturn systems, the trend is an overall anti-correlation with the other parameters, which makes sense, since the magnitudes of the \( r \)-band will tend to be lower (i.e. be brighter in the optical) when compared to the FUV. However, it is worth pointing to some differences between their UV weak counterparts, with remarks on the values of \( \rho \) estimated for \( \langle \log t \rangle_r, \) (sSFR), \( \langle t_{\text{form}} \rangle , \) and \( \langle t_{\text{burst}} \rangle \). For (sSFR), \( \rho \) changes from no correlation (\( \rho = -0.02 \)) for UV upturn to a weak anti-correlation for UV weak systems (\( \rho = -0.21 \)); for the other three timescale parameters, they change from a weak-to-mild anti-correlations to weak-to-mild correlations – i.e. their signal in fact changes between both types of systems –, with highlights on \( \langle t_{\text{form}} \rangle \).

#### 3.2.1.3 NUV-\( r \):

This colour presents significant changes between both groups of galaxies. It is robust for (sSFR) and \( \langle t_{\text{form}} \rangle \) though. For the other timescale parameters, \( \langle \log t \rangle_r \), and \( \langle t_{\text{burst}} \rangle \), \( \rho \) is stronger for UV weak systems and non-existent for the upturn counterparts. For \( \langle Z/Z_\odot \rangle \) \( \rho \) is negative and weak for UV weak systems, yet positive and mild for UV upturn counterparts. All in all, differently from FUV-NUV – which show a clear systematic change between UV weak and upturn galaxies –, here some correlations seem more important for UV upturn systems, whereas others for weak systems.

#### 3.2.2 Time-scales

The different timescales to which we refer here are \( \langle \log t \rangle_r, \) \( \langle t_{\text{form}} \rangle \), and \( \langle t_{\text{burst}} \rangle \). All of them are clustered in both UV weak and upturn cluster-maps, which is an expected result, since they are not linearly independent. All the cross-correlations between them are strong, i.e. \( \rho > 0.6 \) for all UV bright RSGs, except for \( \langle t_{\text{form}} \rangle \) versus \( \langle t_{\text{burst}} \rangle \) for UV weak systems, in which \( \rho = 0.42 \), which is a mild-to-strong value. Regarding the other parameters, all of these three anti-correlate with (sSFR) and \( \langle f_{\text{burst}}^{2Gyr} \rangle \) for both UV weak and upturn galaxies, remarkably the following pairs: \( \langle t_{\text{form}} \rangle \) and (sSFR), \( \langle t_{\text{burst}} \rangle \) and \( \langle f_{\text{burst}}^{2Gyr} \rangle \), \( \langle \log t \rangle_r \), and \( \langle f_{\text{burst}}^{2Gyr} \rangle \).

#### 3.2.3 \( \langle Z/Z_\odot \rangle \)

The values of \( \rho \) are robust in the lack of correlation with (sSFR) and \( \langle t_{\text{burst}} \rangle \) (i.e. for both groups of galaxies). Yet, differences are remarkable when looking at \( \langle \log t \rangle_r, \) \( \langle t_{\text{form}} \rangle \), and \( \langle f_{\text{burst}}^{2Gyr} \rangle : \rho \approx 0 \) for UV upturn systems, but are mild \( (0.2 < \rho < 0.4) \) for their weak counterparts. It is remarkable that these trends are not the same for all time-scales herein used, being non-existent for UV upturn galaxies, but only changing to mild values \( \langle \log t \rangle_r \), and \( \langle t_{\text{form}} \rangle \) – remaining robust and absent for \( \langle t_{\text{burst}} \rangle \). These results are easily seen in Fig. A1 due to the order of the parameters that remain the same – differently from those of Fig. 9 that change due to the clustering features of the top and lateral dendrograms.

### 3.3 Principal component analysis

In this Section, we explore the differences and similarities between UV weak and UV upturn galaxies by making
use of PCA. It is a technique suitable for analysing high-dimensional datasets. The concept behind PCA is the projection of these datasets in lower dimensions by minimising the loss of information as much as possible (e.g. Abdi & Williams 2010; Jolliffe & Cadima 2016). It has been widely used by the astronomical community in the analyses of several different problems (e.g. Jee son-Daniel et al. 2011; Chen et al. 2012; de Souza et al. 2014; Pace et al. 2019).

In order to obtain these results, we made use of the PCA functionality available in the scikit-learn python package (Pedregosa et al. 2011). The results used are the outputs of the attribute components_, which can be positive or negative; we make use of the absolute values to facilitate its visualisation⁴. It is worth mentioning that, since PCA is sensitive to scale, we have standardised all the variables before applying it (which is a common practice to PCA users; see Sec. 2C in Jolliffe & Cadima 2016).

Fig. 11 displays the results of the PCA analysis with 5 principal components (PCs), which describe the variance of over 95 per cent of both samples (95.1 per cent for UV upturn and 96 per cent for UV weak). The partial contributions of each PC can be seen in the titles of each sub-plot of the same image.

The results show that there are no outstanding differences between the two types of systems in the first two PCs. The main contributors for the variance of PC1 and PC2 are similar, i.e. (log t)$_s$, (t$_{term}$), and (t$_{last}$) are the three main parameters for both UV weak and upturn galaxies for the variance of PC1. The contribution of (log t)$_s$ for the variance are similar for both types of galaxies in PC1 (and this continues to be true throughout all the other PCs), which indicates that the differences between ages might not be significant. In a secondary level of PC1, FUV-NUV is important for UV upturn systems, whereas NUV-r plays an important role for the variance of their weak counterparts. This is in agreement with the analysis previously made for the UV and UV-optical colours (differences in correlation parameters between both groups of galaxies, and their dispersion seen in Fig. 10). Also, the difference in variance for ⟨Z/Z$_⊙$⟩ is eye-catching; this is also in accordance to the results seen in Sec. 3.1.

A similar trend occurs in PC2, in which FUV-r and FUV-NUV are the main contributors for the variance for both UV weak and upturn systems. In fact, it is only in PC3 that these main contributors change a lot: NUV-r become very important for the variance in UV upturn galaxies, whereas ⟨sSFR⟩ and ⟨t$_{term}$⟩ matter the most for UV weak systems. It is worth mentioning that in PC3 there is an important gap for ⟨Z/Z$_⊙$⟩, which is important for UV upturn systems and nearly nonexistent for UV weak galaxies. PC4 shows, again, that the contributions seem similar for both groups of galaxies, with an important contribution of ⟨Z/Z$_⊙$⟩ for both. Finally, PC5 depicts differences between the parameters that mostly contribute to the variance among both types of galaxies, being NUV-r the most important for UV weak galaxies, whereas ⟨E(Gyr)$^{\frac{r}{t_{burst}}}$⟩ for UV upturn systems.

In other words, the analysis made with PCA highlights that the main components responsible for the variance of both types of galaxies are basically the same, which is expected as these systems are in fact similar. They are both in the red-sequence, are classified as retired/passive systems according to their emission line features, possess the same range of log $M_*$ and z, and so forth. Therefore, their differences are more subtle, which can only be seen in a secondary level of PC1, and then at other less important components (such as PC3).

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⁴ By making use of the absolute values, no loss of information happens, as the signal estimated for components_, is roughly a choice of methodology.
Figure 10. UV and UV-optical colours (FUV-NUV, FUV- \( r \), and NUV- \( r \) respectively) against the following physical parameters (from top to bottom): \( \langle \log t_r \rangle \), \( \langle t_{\text{form}} \rangle \), \( \langle t_{\text{last}} \rangle \), \( \langle Z/Z_\odot \rangle \), \( \langle s\text{SFR} \rangle \), and \( \langle f_{2\text{Gyr}} \rangle \). UV weak and UV upturn systems are respectively depicted by light and dark brown markers, as well as grey and red 2D-Gaussian kernel density curves – with the exception of the last row, which has many values at zero, preventing the kernel density to be estimated. The labels depict the corresponding values of \( \rho \) for UV upturn (\( \rho_{\text{up}} \)) and UV weak galaxies (\( \rho_{\text{wk}} \)).
4 MAIN RESULTS

In this Section, we briefly expand the discussion of the main results presented in Sec. 3.

In terms of the direct comparison of the distribution of the parameters of UV weak and UV upturn galaxies, an overall characteristic that is very important to observe is that $s$ for UV upturn systems is systematically higher than their UV weak counterparts. This behaviour is true for cases, either when $s$ positive or negative; the only exception is for $\langle SFR \rangle$, when the opposite occurs, but it then disappears when it is pondered by log $M_\star$ (i.e. $\langle sSFR \rangle$). Yet, when further investigating the distributions of $\langle SFR \rangle$ combined with $\langle f_{\text{burst}} \rangle$ across several timescales, it is possible to see that UV weak systems have systematically higher $\langle f_{\text{burst}} \rangle$, when compared to UV upturn galaxies.

However, it is important to mention that the simple stellar population templates of Bruzual & Charlot (2003) do not include many of the rare evolved stellar stellar evolutionary phases known to be UV bright (e.g. HB, and EHB stars), as discussed in Sec. 1. This is an important caveat, which makes that most of the UV emission be fitted by making use of young stellar populations. This is certainly impacting on the estimates of some parameters, including $\langle SFR \rangle$ and $\langle sSFR \rangle$. For more accurate results, this analysis needs to take into account templates that consider these types of stellar populations.

Important results are those regarding $(g-r)$, $(Z/Z_\odot)$, ages, and $\langle t_{\text{last}} \rangle$. UV upturn systems appear to be older than their weak counterparts for both $\langle \log t \rangle$ and $\langle \log t \rangle_m$; also, $\langle t_{\text{last}} \rangle$ presents a median gap of $\sim 0.44$ Gyr between both systems, which point to a longer period of passiveness for UV upturn galaxies. Combined with the results for $(Z/Z_\odot)$ – which show lower $\bar{x}$ values and considerably lower $s$ – and $D_{4000}$, it seems that UV upturn systems have shorter star-formation histories when compared to their UV weak counterparts (these results are in agreement with Werle et al. 2020). There are two possible scenarios that could explain this difference in star-formation histories:

i. UV upturn systems could have simply completed their star-formation processes earlier in time;

ii. or UV weak galaxies, for some reason, have been more efficient in accreting metal-poor gas from the intergalactic medium, bringing their median metallicities to lower values and forming a few more stars than their UV upturn counterparts.

Finally, it is worth mentioning that generally UV upturn systems seem to be less disperse than UV weak galaxies (e.g. see Fig. 10). These differences are supported by the correlations and PCA analyses (with highlights to PC1), which seems to be in agreement with the hypothesis that UV upturn systems appear to be evolving more passively when compared to UV weak galaxies. In other words, bigger dispersion of UV weak systems maybe linked to a higher diversity of stellar populations.

5 SUMMARY & CONCLUSIONS

We have analysed 87 UV upturn and 51 UV weak galaxies observed by the GAMA collaboration with aperture-matched data from SDSS-DR7 and GALEX GR6/plus7. To
produce the aforementioned sample, we have made use of the UV bright RSGs classified as retired/passive according to the WHAN diagram (which are described in further detail in Dantas et al. 2020) and applied PSM, mitigating the effects of the confounding variables (log $M$, and $z$). From this sample, we made use of the SED fitting results from MAGPHYS available in the value-added catalogues from GAMA-DR3, which were estimated by making use of 21 band-passes which span from the UV to the far-IR/submillimetre. With those at hand, we have analysed their similarities and differences by comparing the distributions of their SED fitting parameters, investigating their correlations, and checking their principal components through principal component analysis. Our conclusions are as follows.

1. First and foremost, both UV weak and UV upturn galaxies, according to this study are very similar. This can be easily seen in the PCA analysis as a whole, but also in the direct comparison of their properties.
2. Their differences are subtle and appear in a finer analysis, such as seen for instance by the secondary parameters for PC1 (FUV-NUV, NUV-r, and $(Z/Z_\odot)$).
3. UV upturn systems are redder in the $(g-r)$ optical colour when compared to their UV weak counterparts in the same conditions: both being classified as retired/passive systems and occupying the same range of log $M$, and $z$. These results are in agreement to the previous analysis made in Dantas et al. (2020) and are consistent with differences in age and metallicity.
4. Overall UV weak systems reach larger ranges (with longer tails over smaller values and lower skewness) generally over the SED fitting output parameters, notably age ($\langle \log t \rangle$, and $(\log t)_m$, $\langle t_{\text{turn}} \rangle$, and $(Z/Z_\odot)$). This is a hint that suggests that UV weak systems may have a larger assortment of stellar populations.
5. Stellar populations in UV upturn galaxies seem to be systematically older than their UV weak counterparts (their $\bar{x}$ shows a gap of $\sim 0.32$ Gyr), but the associated errors are too high to enable any strong assumption (which is confirmed by the PCA analysis). Also, the age of the oldest stars in both systems ($\langle t_{\text{turn}} \rangle$) is basically the same. Additionally, their time since last burst of star-formation ($\langle t_{\text{turn}} \rangle$) has a median gap of $\sim 0.44$ Gyr, indicating a potential longer passiveness of UV upturn systems. Yet, the contribution of total variance of $\langle t_{\text{turn}} \rangle$ in PC2 and PC3 in the PCA analysis shows different contributions in for these systems; there is a higher contribution to total variance for UV weak systems, which supports the idea of higher passiveness of UV upturn galaxies. These must be interpreted with the according caveats regarding our current limitations in terms of age determination, and the use of Bruzual & Charlot (2003) models, which do not properly account for the UV emission from rare/evolved stellar evolutionary phases.
6. An additional analysis made with $D_\ast$,4000 shows another gap between these two types of galaxies, which may help corroborate the the results for age and metallicity.
7. UV weak galaxies have been showing slightly higher mean values of $\langle t_{\text{turn}} \rangle$ throughout several timescales (from $10^7$ to $2 \times 10^7$ yr). This indicates that UV weak systems have been to some extent more efficient in forming new stars, albeit the closeness of (SFR) throughout the same timescales between UV weak and UV upturn systems. This is another indication of higher passiveness of UV upturn galaxies.
8. Correlation parameters between UV weak and UV upturn galaxies change considerably, which seems to be due to their difference in dispersion. Such dispersion is higher in UV weak systems and it seems to be caused by a wider variety of stellar populations in terms of ages and metallicities.
9. Also, UV upturn galaxies are richer in metals then their UV weak counterparts, which can be seen throughout the different analyses of this paper (which is consistent with the findings of Werle et al. 2020).

All the evidences point to the fact that UV weak and upturn galaxies, within the same range of log $M$, and $z$, are generally very similar, with few exceptions. The most important differences point to a higher passiveness of UV upturn galaxies and a higher diversity of stellar populations in UV weak systems. Potential explanations to why UV upturn systems have shorter star-formation histories are:

i. UV upturn galaxies may have concluded their star-formation before UV weak galaxies;
ii. or, for some reason, UV weak systems have been more efficient in incorporating pristine (metal-poor) gas from the intergalactic medium, stimulating them to create a few more stars than UV upturn galaxies.

Further studies are still required to assess the richness of stellar populations of both these systems as discussed at the end of Sec. 4, specially by taking into account stellar population templates that are rich in rare stellar evolutionary phases, such as HB, EHB, the entire AGB family of stars (post-AGB, post-early-AGB, and so on), as well as binary systems in interactions.

6 DATA AVAILABILITY

No new data were generated or analysed in support of this research. Instructions on how to acquire the data herein used are described in Sec. 2.

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The colours used in the figures herewith are colour-blind friendly and were retrieved from www.ColorBrewer.org.

Credits: Cynthia A. Brewer, Geography, Pennsylvania State University.

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APPENDIX A: ADDITIONAL PLOTS AND TABLES

A1 Correlations

We provide an additional image as a visual aid (Fig. A1), as well as tables with the values for the \( \rho \) for both UV weak and UV upturn systems (Tables A1 and A2). They ease the comparison between the results for both classes of UV bright galaxies, which have been mixed with the clustering effect in Fig. 9.

This paper has been typeset from a TeX/LaTeX file prepared by the author.
Figure A1. Heatmaps featuring the correlation results ($\rho$, Spearman 1904) between MAGPHYS resulting parameters. The UV upturn systems are in the left while the UV weak are in the right panel.

Table A1. Correlations table for the UV weak systems.

|                  | $\langle \log t \rangle$ | $\langle Z/Z_\odot \rangle$ | $\langle \text{sSFR} \rangle$ | $\langle t_{\text{form}} \rangle$ | $\langle t_{\text{last}} \rangle$ | $\langle f_{2\text{Gyr}} \rangle$ | FUV-NUV | FUV-r | NUV-r |
|------------------|--------------------------|-----------------------------|-----------------------------|----------------------------------|----------------------------------|----------------------------------|---------|-------|-------|
| $\langle \log t \rangle$ | 1.00                     | -0.36                      | -0.57                      | 0.73                             | 0.82                             | -0.74                            | -0.01   | 0.14  | 0.42  |
| $\langle Z/Z_\odot \rangle$ | -0.36                    | 1.00                       | 0.12                       | -0.24                            | -0.10                            | 0.21                             | -0.09   | -0.15 | -0.16 |
| $\langle \text{sSFR} \rangle$ | -0.57                    | 0.12                       | 1.00                       | -0.87                            | -0.25                            | 0.28                             | -0.00   | -0.21 | -0.42 |
| $\langle t_{\text{form}} \rangle$ | 0.73                     | -0.24                      | -0.87                      | 1.00                             | 0.42                             | -0.40                            | 0.01    | 0.20  | 0.42  |
| $\langle t_{\text{last}} \rangle$ | 0.82                     | -0.10                      | -0.25                      | 0.42                             | 1.00                             | -0.76                            | -0.06   | 0.08  | 0.36  |
| $\langle f_{2\text{Gyr}} \rangle$ | -0.74                    | 0.21                       | 0.28                       | -0.40                            | -0.76                            | 1.00                             | 0.32    | 0.16  | -0.32 |
| FUV-NUV | -0.01                    | -0.09                      | -0.00                      | 0.01                             | -0.06                            | 0.32                             | 1.00    | -0.14 |       |
| FUV-r | 0.14                     | -0.15                      | -0.21                      | 0.20                             | 0.08                             | 0.16                             | 0.82    | 1.00  | 0.38  |
| NUV-r | 0.42                     | -0.16                      | -0.42                      | 0.42                             | 0.36                             | -0.32                            | -0.14   | 0.38  | 1.00  |

Table A2. Correlations table for the UV upturn systems.

|                  | $\langle \log t \rangle$ | $\langle Z/Z_\odot \rangle$ | $\langle \text{sSFR} \rangle$ | $\langle t_{\text{form}} \rangle$ | $\langle t_{\text{last}} \rangle$ | $\langle f_{2\text{Gyr}} \rangle$ | FUV-NUV | FUV-r | NUV-r |
|------------------|--------------------------|-----------------------------|-----------------------------|----------------------------------|----------------------------------|----------------------------------|---------|-------|-------|
| $\langle \log t \rangle$ | 1.00                     | -0.08                      | -0.54                      | 0.81                             | 0.93                             | -0.72                            | -0.32   | -0.29 | 0.11  |
| $\langle Z/Z_\odot \rangle$ | -0.08                    | 1.00                       | 0.08                       | -0.06                            | -0.00                            | 0.03                             | -0.24   | -0.05 | 0.30  |
| $\langle \text{sSFR} \rangle$ | -0.54                    | 0.08                       | 1.00                       | -0.83                            | -0.31                            | 0.40                             | 0.22    | -0.02 | -0.37 |
| $\langle t_{\text{form}} \rangle$ | 0.81                     | -0.06                      | -0.83                      | 1.00                             | 0.63                             | -0.54                            | -0.27   | -0.12 | 0.27  |
| $\langle t_{\text{last}} \rangle$ | 0.93                     | -0.00                      | -0.31                      | 0.63                             | 1.00                             | -0.74                            | -0.32   | -0.33 | 0.05  |
| $\langle f_{2\text{Gyr}} \rangle$ | -0.72                    | 0.03                       | 0.40                       | -0.54                            | -0.74                            | 1.00                             | 0.32    | 0.24  | -0.12 |
| FUV-NUV | -0.32                    | -0.24                      | 0.22                       | -0.27                            | -0.32                            | 0.32                             | 1.00    | 0.75  | -0.34 |
| FUV-r | -0.29                    | -0.05                      | -0.02                      | -0.12                            | -0.33                            | 0.24                             | 0.75    | 1.00  | 0.29  |
| NUV-r | 0.11                     | 0.30                       | -0.37                      | 0.27                             | 0.05                             | -0.12                            | -0.34   | 0.29  | 1.00  |