Constraints on the star formation histories of galaxies in the Local Cosmological Volume

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ABSTRACT
The majority of galaxies with current star-formation rates (SFRs), \( SFR_0 \geq 10^{-3} M_\odot/\text{yr} \), in the Local Cosmological Volume where observations should be reliable, have the property that their observed \( SFR_0 \) is larger than their average star formation rate. This is in tension with the evolution of galaxies described by delayed-\( \tau \) models, according to which the opposite would be expected. The tension is apparent in that local galaxies imply the star formation timescale \( \tau \approx 6.7 \) Gyr, much longer than the \( 3.5-4.5 \) Gyr obtained using an empirically determined main sequence at several redshifts. Using models where the SFR is a power law in time of the form \( \propto (t - t_1)^{\eta} \) for \( t_1 \approx 1.8 \) Gyr (with no stars forming prior to \( t_1 \)) implies that \( \eta = 0.18 \pm 0.03 \). This suggested near-constancy of a galaxy’s SFR over time raises non-trivial problems for the evolution and formation time of galaxies, but is broadly consistent with the observed decreasing main sequence with increasing age of the Universe.

Key words: galaxies: star formation – galaxies: stellar content – galaxies: evolution – galaxies: formation – Galaxy: evolution – Galaxy: formation

1 INTRODUCTION

The formation and evolution of observed galaxies constitutes a cosmological boundary condition which must be fulfilled by any physically realistic theory of cosmological structure formation and evolution. A Milky Way (MW) type galaxy is generally thought to have begun forming \( \approx 12 \) Gyr ago (i.e. at time \( t_1 \approx 1.8 \) Gyr after the Big Bang, Planck Collaboration XIII 2016), reaching a maximum star formation rate (SFR)\(^1\) with the SFR subsequently decreasing (e.g. Mor et al. 2019).

The MW is a well-studied case, for which measurements of the phase-space, chemical, and age parameters of a large ensemble of disk stars reveal a complex star-formation history (SFH). It decreases from \( SFR \approx 10 - 20 M_\odot/\text{yr} \) about 10 Gyr ago to a minimum with \( SFR \approx 2.7 M_\odot/\text{yr} \) about 6 Gyr ago, reaching a local maximum of \( SFR \approx 8 M_\odot/\text{yr} \) about 3.5 Gyr ago and decreasing to a present-day value of \( SFR_0 \approx 1.3 M_\odot/\text{yr} \) (Mor et al. 2019). While the data may also be interpreted with a constant \( SFR \approx 4 M_\odot/\text{yr} \) over the past \( \approx 12 \) Gyr (yielding a present-day disk stellar mass of \( M_* \approx 4.8 \times 10^{10} M_\odot \)), a general trend of a decreasing SFR has also been found by Zonoozi et al. (2019) based on the shape of the galaxy-wide stellar mass function, and from an analysis of the kinematical imprint of star-formation in a clustered mode according to which the thick disk may have been formed from an elevated SFR about 10 – 12 Gyr ago (Kroupa 2002). Ruiz-Lara et al. (2020) map the SFH from > 12 Gyr ago until today, finding consistency with the analysis by Mor et al. (2019) and showing time-resolved evidence that it may have been modulated over the past 6 Gyr by the orbit of the Sagittarius satellite galaxy.\(^2\) In the context of Milgromian Dynamics (MOND, Milgrom 1983; Bekenstein & Milgrom 1984), the SFH of the MW is likely to have been significantly affected by its encounter with Andromeda (M31) about 7-10 Gyr ago (Zhao et al. 2013).\(^3\) The MW

\(^1\) SFR is the acronym used for star formation rate, while \( SFR \) is the associated physical parameter.

\(^2\) This raises the question of why orbital decay through dynamical friction between the putative dark matter haloes of the satellite and the MW has not yet merged the two (Kroupa 2015).

\(^3\) The plane or disk of satellite galaxies orbiting the MW (Kroupa et al. 2005), as confirmed by the most recent Gaia proper motion data (Pawlowski & Kroupa 2020), appears to be strongly correlated with the plane of satellite galaxies around M31 (Ibata et al. 2013) by both being polar relative to the MW and having their
SFH is thus not likely that of an unperturbed self-regulated secularly-evolving disk galaxy. The other large galaxy in the Local Group, M31, had $SFR \approx 5 M_\odot/\text{yr}$ from 14 to 8 Gyr ago, with a dip to $SFR \approx 1 M_\odot/\text{yr}$ about 8–6 Gyr ago, a maximum near $5 M_\odot/\text{yr}$ about 5–1.5 Gyr ago and a decline to $SFR_\odot \approx 0.1 M_\odot/\text{yr}$ or less (Williams et al. 2017, the quoted values comprise only the region of M31 mapped by the PHAT survey). It appears that the SFHs of the MW and M31 may be correlated, as the initial larger values, the minima and maxima appear to be broadly in-phase.

On the other hand, the Triangulum galaxy (M33) is a near-flaccotent disk galaxy in the Local Group without a significant bulge and appears to have evolved largely without significant perturbations. Its SFR has increased significantly until the present time, with $SFR_\odot \approx 0.5 M_\odot/\text{yr}$, while about 10 Gyr ago, $SFR \approx 0.04 M_\odot/\text{yr}$ with evidence for an acceleration and then minimum about 5 Gyr ago (Javadi et al. 2017). This SFH may be related to its orbit around M31 (Patel et al. 2017). The Large Magellanic Cloud (LMC) also shows an increasing SFR until today with a dip about 5 Gyr ago (Meschin et al. 2014). This SFH cannot be representative of an isolated self-regulated disk galaxy because the LMC is strongly interacting with the Small Magellanic Cloud and also with the MW. It may be noteworthy that all four major galaxies of the Local Group discussed above share a similar depression in their SFHs roughly 5 Gyr ago. The evidence from the larger galaxies in the Local Group concerning the shapes of their SFHs is thus somewhat ambiguous and is mired by the Local Group members being subject to relatively strong encounters. The rather strikingly symmetrical arrangement of matter within the Local Group appears to be additionally troubling (Pawlowski et al. 2013).

In order to improve our understanding of the formation and evolution of galaxies, larger and representative samples are needed. Delgado-Serrano et al. (2010) used Sloan Digital Sky Survey (SDSS) data to show that the vast majority of galaxies with stellar masses $M_\ast > 1.5 \times 10^{10} M_\odot$ are star-forming disk galaxies in the Local Universe as well as 6 Gyr ago, with elliptical galaxies comprising an unchanging 3–4% of the studied ensembles. The observational study by De Propris et al. (2014) of merger rates using close pairs indicates blue galaxies to have a small merger incidence, less than that expected in standard-cosmology. De Propris et al. (2014) find “Galaxies in these close pairs are likely to have undergone a series of previous encounters and close passes” which poses a problem for the expected rapid merging due to dynamical friction on the large and massive dark matter haloes (Kroupa 2015; Oehm et al. 2017). De Propris et al. (2014) conclude “At face value our findings minimize the importance of major mergers and interactions for galaxy evolution and argue that most galaxy evolution takes place via internal and secular processes.” Based on a survey of major disk galaxies within a distance of $\approx 8$ Mpc, Kormendy et al. (2010) find about half of the sample of 19 massive disk galaxies have no evidence for a classical bulge, raising the question “How can hierarchical clustering make so many giant, pure-disk galaxies with no evidence for merger-built bulges?” Comparing models of hierarchical galaxy formation with SDSS data, Shankar et al. (2014) conclude “Despite the observational uncertainties, the data tend to disfavour hierarchical models characterised by strong and impulsive disc instabilities, strong gas dissipation in major mergers, short dynamical friction time-scales.” In “The Impossibly Early Galaxy Problem”, Steinhardt et al. (2016) note $10^{12–13} M_\odot$ dark matter halos to be overabundant at $z = 6 – 8$ than expected if hierarchical assembly through mergers were to be valid. Mergers may thus be playing a lesser role in galaxy evolution than currently thought. The vastly dominating class of disk galaxies may thus be simpler than thought. Indeed, a principal component analysis of the galaxies selected with 21 cm-observations implies star-forming galaxies are governed by one parameter only, making such galaxies simpler than expected (Disney et al. 2008). Disk galaxies are well-known to obey well-defined Milgromian laws (Milgrom 1983; Bekenstein & Milgrom 1984), such as the baryonic-Tully-Fisher relation (McGaugh 2012) and the radial-acceleration relation (Lelli et al. 2017) – for a review, see (Famaey & McGaugh 2012). In view of this documented simplicity of galaxies, it is also important to quantify if the SFHs typically increase or decrease with time, because this question is intimately linked to the cosmological matter cycle and budget. By compiling many different surveys of star-forming galaxies with $M_\ast > 10^7 M_\odot$, Speagle et al. (2014, hereafter SP14) found them to form a well defined tight $SFR$ vs $M_\ast$ correlation, which is known as the main sequence of galaxies (e.g. Davé 2008; Renzini & Peng 2015; Popesso et al. 2019). With increasing cosmological redshift $z$, the main sequence evolves to larger $SFR$ for a given $M_\ast$. The tight correlation of the main sequence across cosmic time and the apparent simplicity of galaxies can be distilled into the understanding that while simple, galaxies tend to evolve according to ‘delayed-$\tau$’ models: After first increasing from an age, $t$, of the Universe of about $t = 3$ Gyr (10.8 Gyr ago), after $t \approx 6.5 – 7.5$ Gyr their SFRs decrease as their gas is consumed through star formation (fig. 10 in SP14). These studies suggest that the SFHs of galaxies can be described by the delayed-$\tau$ model (Eq. 4 below) and consequently that the present-day $SFR$ of a typical galaxy $^2$, $SFR_\odot$, needs to be smaller than the average value $SFR_\ast$, i.e.

$$\frac{SFR}{SFR_\odot} > 1. \quad (1)$$

Davé (2008) suggests this to be broadly consistent with dark-matter-based hydrodynamical simulations. Galaxy-formation simulations in Milgromian gravitation based on single-cloud collapse with negligible further gas accretion

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1 The reader is referred to the discussion in SP14 concerning the expected stochastic evolution of galaxies due to mergers as predicted in the standard dark-matter based models of structure formation, versus the more deterministic models such as through cold accretion of gas (Kereš et al. 2005; Davé 2008). Following SP14, it is implicitly assumed here that “galaxies simply follow a common, deterministic track”.

2 ‘Typical galaxy’ means a galaxy which has not suffered a major encounter within the past few dynamical times such that its SFH is approximately that of an unperturbed galaxy.
also lead to such a general behaviour, albeit with a much larger $\text{SFR}/\text{SFR}_\text{Ho}$ (Wittenburg et al. 2020).

In order to improve knowledge of galaxy formation and evolution, it is useful to also consider the ensemble of galaxies in the nearby Universe. Peebles & Nusser (2010) compare structure formation models to the spatial distribution of galaxies in the Local Cosmological Volume, defined by the sphere with radius 8 Mpc, finding significant tension between the predicted and observed distribution of major galaxies. Here, The Catalogue of Neighbouring Galaxies (Sec. 2) is used to address if $\text{SFR}_\alpha < \text{SFR}$. In Sec. 3, it is shown that galaxies in the Local Cosmological Volume pose a challenge to this generally accepted understanding. Sec. 4 presents a discussion and the conclusions.

2 THE GALAXIES IN THE LOCAL COSMOLOGICAL VOLUME

The Catalogue of Neighbouring Galaxies (Karachentsev et al. 2004) and its update (Karachentsev et al. 2013) are used to extract the K-band luminosities and the SFRs based on integrated Hα and far ultraviolet (FUV) measurements for galaxies within a distance of $\approx 11$ Mpc. The catalogue also lists limit flags on the FUV- and Hα-based SFR values. If a SFR value is marked with such a flag, it is excluded from the here presented analysis (but including flagged SFR values does not significantly affect the results). This gives a sample of 870 galaxies, from 1145. From these 870 galaxies, 267 have only far ultraviolet (FUV)-based SFR values, 128 have only Hα based SFRs, and 475 have both measurements available. Thus, 14.7% and 30.7% galaxies lack FUV- and Hα-based SFR measurements, respectively.1 The K-band luminosity values are converted to $M_*$ using a mass-to-light ratio of 0.6 (Lelli et al. 2016).

For galaxies which have both SFR measurements available, $\text{SFR}_\alpha = (\text{SFR}_{\text{FUV}} + \text{SFR}_{\text{Ho}})/2$ is adopted. Their SFRs based on integrated Hα and FUV measurements are depicted in Fig. 1. The condition $\text{SFR}_\alpha \geq 10^{-3} M_*/\text{yr}$ leaves 386 galaxies. For the galaxies which only have the FUV- or Hα-based SFR measurements, $\text{SFR}_\alpha = \text{SFR}_{\text{FUV}}$ or $\text{SFR}_\alpha = \text{SFR}_{\text{Ho}}$, respectively (these galaxies do not appear in Fig. 1). Applying the cut $\text{SFR}_\alpha \geq 10^{-3} M_*/\text{yr}$ leaves 109 and 88 galaxies which have only $\text{SFR}_{\text{FUV}}$ or $\text{SFR}_{\text{Ho}}$ data, respectively.

Galaxies with $\text{SFR}_\alpha < 10^{-3} M_*/\text{yr}$ are not considered in the present analysis for the following four reasons (Karachentsev & Kaisina 2013 provide an in-depth discussion of these issues):

1) The $\text{SFR}_\alpha$ values may be affected by a pronounced top-light galaxy-wide initial mass function (gIMF) such that $\text{SFR}_\alpha < \text{SFR}_{\text{FUV}}$. Pfennig-Altenburg et al. (2009); Pfennig-Altenburg & Kroupa (2009) and sec. 4.3 in Ježábková et al. (2018) provide a detailed discussion of this gIMF behaviour, with the resolved dwarf galaxy DDO 154, which has a corresponding lack of massive stars, being a case in point (Watts et al. 2018). Indeed, the ratio of the gIMF theory is based on calculating the gIMF by integrating over all star-forming events in a galaxy. These are localised in molecular cloud over-densities (cloud cores) containing at least a few binaries. The integrated galactic initial mass function (gIMF) is thus the galaxy-wide integral over all freshly formed embedded clusters. The reader is referred to Kroupa et al. (2013) and Hopkins (2018) for a discussion of this problem.

2) Related to the systematically changing gIMF just discussed, it has been customary to describe star formation throughout a galaxy as being stochastic, an approach discussed in detail in Elmegreen (1997, 1999). Dwarf galax-

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1 The catalogue data are publicly available here: https://www.sao.ru/lv/lygdb/tables.php. The version updated on May 8th, 2020 is adopted here.
ies with low SFRs may lead to an undersampling of the gwIMF, but only if a central tenet of the IGIMF theory is adopted, namely that stars form in embedded clusters which dictate the available mass for the stellar population per cluster, leading to a difference in various SFR tracers (da Silva et al. 2014). Related to the suggestion that star formation is stochastic, Kennicutt & Evans (2012) discuss the possibility that dwarf galaxies may be prone to temporal variations of their SFRs. Applebaum et al. (2020) study the effect of a stochastic gwIMF on the formation and evolution of dwarf galaxies with cosmological simulations.

3) It is possible that the measured Hα and UV fluxes are affected by photon leakage, dust obscuration and reddening and other physical effects (Calzetti 2008, 2013). It is likely that these are relevant, but the authors of the research papers reporting evidence for systematic variations of the gwIMF in galaxies correct for these biases (Hoversten & Glazebrook 2008; Lee et al. 2009; Gunawardhana et al. 2011).

4) Many of the least-massive galaxies in the Local Cosmological Volume with $M_* < 10^7 M_\odot$ are satellite galaxies which stopped forming stars many Gyr ago (e.g. Grebel 1997; Grebel et al. 2003). Dwarf galaxies sufficiently far from major galaxies of this mass behave as disk galaxies (e.g. the dwarf galaxy DDO 210 which is barely more massive than a massive globular cluster and which has a Milgromian rotation curve, putting it on the baryonic-Tully-Fisher relation, Famaey & McGaugh 2012). Meanwhile, dwarf galaxies within the vicinity of major galaxies have lost their gas (Grebel et al. 2003).

Overall, dwarf and major star-forming galaxies thus appear to conform to the same basic physical evolution, although differences between the SFHs at the lowest-mass end are evident and remain to be understood (Albers et al. 2019). Galaxies with $SFR_{\odot} < 10^{-3} M_\odot/yr$ are therefore considered to have too insecure SFRs and are thus omitted from the present analysis. For the in-total 583 galaxies used in this analysis, the gwIMF is near to canonical (Gunawardhana et al. 2011; Jerábková et al. 2018).

In a companion paper (Høibøe et al., in prep.), The Catalogue of Neighbouring Galaxies is compared with the SP14 main sequence. The $(SFR, M_*)$ values are in excellent agreement at $M_* > 10^7 M_\odot$, showing that The Catalogue of Neighbouring Galaxies conforms to the compilation by SP14.

3 THE CURRENT VS THE AVERAGE SFR

3.1 Theoretical expectations

Assume a galaxy forms stars from time $t_1$ until time $t_2$, the latter being the present-day if the galaxy is still forming stars. The SFH can be written as $SFR(t) = SFR + \Delta SFR(t)$ such that the average SFR of any galaxy over the time scale $t_{sd} \equiv t_2 - t_1$ becomes

$$SFR = \frac{1}{t_{sd}} \left( \int_{t_1}^{t_2} SFR dt + \int_{t_1}^{t_2} \Delta SFR(t) dt \right),$$

(2)

with temporal deviations from $SFR$ satisfying,

$$\int_{t_1}^{t_2} \Delta SFR(t) dt = 0 M_\odot.$$  (3)

This implies that if $SFR_{\odot} = SFR$, any decreasing SFH must have had a compensating increase.

According to the analysis by SP14, the SFHs of galaxies can be described by “delayed-$\tau$" models of the form

$$SFR_{\odot}(t > t_1) = \frac{A_{sd}}{\tau^2} (t - t_1) \exp \left( -\frac{t - t_1}{\tau} \right),$$

(4)

where $A_{sd}$ is a normalisation constant and $\tau$ is the star-formation time scale, with $SFR(t \leq t_1) = 0 M_\odot/yr$. Note that the present-day SFR becomes

$$SFR_{\odot}(t_2) \equiv SFR_{\odot,0} \equiv \frac{A_{sd} x e^{-x}}{\tau},$$

(5)

The parameter $x$ signifies which phase of the SFH a galaxy is currently in — the SFH rises up to a peak at $x = 1$ before following an asymptotically exponential decline. With this SFH, the average SFR is

$$SFR_{\odot} = \frac{A_{sd}}{t_{sd}} \left[ 1 - (1 + x) e^{-x} \right].$$

(7)

Thus (see also fig. 10 in SP14),

$$\frac{SFR_{\odot}}{SFR_{\odot,0}} = \frac{e^x - x - 1}{x^2} \geq \frac{1}{2},$$

(8)

the value of $\frac{1}{2}$ being reached at $x = 0$ (very long $\tau$). The ratio (Eq. 8) is shown in Fig. 2 as a function of $x$, revealing that the regime in which $SFR/SFR_{\odot} > 1$ occurs for $x > 1.79$.

The observationally constrained galaxy main-sequence evolution analysed by SP14 suggests that the typical real star-forming galaxy undergoes an evolution beginning at $t_1 \approx 3$ Gyr and with $SFR_{\odot,0} > SFR_{\odot,max} > 2$. The maximum value of the SFR, $SFR_{\odot,max}$, is reached when $t - t_1 = \frac{1}{\tau}$.

Figure 2. The ratio between the average and present-day SFR, $SFR_{\odot}/SFR_{\odot}$ (Eq. 8) as a function of $\tau/\tau$. The shaded vertical band contains galaxies with $2.7 < \tau/\tau < 3.4$ (Eq. 9).
\[ SFR/SFR_o \geq 10^{-3} M_\odot/yr, \]

where the \( \tau \) at the time \( 6.5 < t/\text{Gyr} < 7.5 \) (fig. 10 in SP14) such that \( 3.5 < \tau/\text{Gyr} < 4.5 \). Since \( t_\text{sf} \approx 12 \) Gyr for the galaxies observed in the Local Group, these galaxies would be in the 2.7 < \( x < 3.4 \) phase of their evolution, i.e. in the falling part of their SFH. If the nearby galaxies concur to this evolution, then according to Fig. 2 they ought to have

\[ 1.5 < \frac{SFR}{SFR_o} < 2.3. \]  

Note that \( 2.1 < \frac{SFR}{SFR_o} < 2.6 \) if \( t_1 = 1.8 \) Gyr (i.e. if galaxies started to form stars 12 Gyr ago), worsening the problem.

### 3.2 The Local Volume

The sample of Neighbouring Galaxies (Sec. 2) can be used to assess the ratio \( \frac{SFR}{SFR_o} \), because these galaxies have well-measured \( M_\odot \) and \( SFR_o \) values. The present-day stellar mass of the galaxy defines the average SFR,

\[ \frac{SFR}{SFR_o} \approx \frac{\zeta M_\odot}{t_\text{sf}}, \]  

where \( \zeta \) accommodates mass loss through stellar evolution (\( \zeta \approx 1.3 \) according to a canonical single-burst stellar population, as evident in fig. 1 of Baumgardt & Makino 2003). Note that \( 1 < \zeta < 1.3 \) for a galaxy with a constant SFR and a canonical gwIMF, but \( \zeta \) also depends on the gwIMF and can reach values as large as 2-3 for extreme star-bursting, low-metallicity galaxies (according to the IGIMF theory, see e.g. Yan et al. 2017; Dabringhausen 2019; Yan et al. 2019). According to the IGIMF theory, the nearby galaxies used here are expected to have \( 1.0 < \zeta < 1.3 \). By adopting \( \zeta = 1.3 \) we are thus working conservatively – the expected smaller value would bring a larger conflict with the delayed-\( \tau \) SFHs (see below).

Both observationally derived values, \( SFR_o \) and \( SFR \), are compared in Fig. 3 for the galaxies with \( SFR_o \geq 10^{-3} M_\odot/yr \). Fig. 4 plots the empirical \( \frac{SFR}{SFR_o} \) ratios to test if Eq. 1 or 9 can be fulfilled by the data. It is apparent that the delayed-\( \tau \) SFH description cannot account for the data if \( t_\text{sf} = 12 \) Gyr and \( \tau \approx 4 \) Gyr. Reducing \( t_\text{sf} \) to 6 Gyr would allow the model to account for the data, but such short \( t_\text{sf} \) violates the observed ages of galactic disks, which suggest \( t_\text{sf} \approx 12 \) Gyr (e.g. Knox et al. 1999).

As is evident from Fig. 3, in the Local Cosmological Volume, \( \frac{SFR}{SFR_o} \) is pushed to larger values because of the second upper sequence (evident at \( \log_{10} \frac{SFR}{SFR_o} = 2 \) in Fig. 5). By removing the data in the second sequence using 2\( \sigma \) clipping, an improved estimate of the ratio can be obtained for the majority of nearby star-forming galaxies. The dispersion of the ratios for the galaxies with \( SFR_o \geq 10^{-3} M_\odot/yr \) is calculated and all data which are further than 2\( \sigma \) from the average are taken out. This is repeated until the average ratio does not shift, removing the second sequence noted in Fig. 3. The clipped and non-clipped distributions are displayed in Fig. 5.

Prior to outlier rejection, the sample of 583 galaxies yields a median (mean) of \( \frac{SFR}{SFR_o} = 0.96 (1.11) \). Applying outlier rejection leaves 455 galaxies and yields a median (mean) of \( \frac{SFR}{SFR_o} = 0.84 (0.85) \). The dispersion is 0.243 dex, but given the number of galaxies, the uncertainty in the mean is formally only 0.011 dex. The

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1 The median and mean values and outlier rejection are calculated in log10 space.
uncertainty of the mean of \( \frac{SFR}{SFR_o} \) is calculated by
\[
\sigma = \frac{0.85}{2} \left( 10^{0.011} - 10^{-0.011} \right) \approx 0.02.
\]
For completeness, it is noted that including also the 586 galaxies with \( SFR_o > 10^{-3} M_\odot/\text{yr} \) which are marked in The Catalogue of Neighbouring Galaxies with a limit flag (2σ clipping leaves 472 galaxies from this sample), the median (mean) of \( \frac{SFR}{SFR_o} \) becomes 0.84 ± 0.02 (0.85 ± 0.02), which is not distinguishable from the main result.

There is a clear preference for \( \frac{SFR}{SFR_o} \) < 1, though given the possibility of systematics (e.g. in the mass-to-light ratio), \( \frac{SFR}{SFR_o} = 1 \) is possible, in which case \( x = 1.79 \) and \( \tau = 6.7 \) Gyr assuming \( t_{sf} = 12 \) Gyr. But the data certainly argue against \( \frac{SFR}{SFR_o} > 1 \).

### 3.3 A power-law SFH?

Which type of SFH might account for the observational data and in particular for the mean value of \( \frac{SFR}{SFR_o} \) clipped to be 0.85, or at least get the ratio down to 1? As an ansatz,
\[
SFR_{\text{incr}}(t > t_1) = A_{\text{incr}} (t - t_1)^\alpha,
\]
with \( SFR_{\text{incr}}(t < t_1) = 0 \) as before, \( \eta = -1 \) being the power-law index and \( A_{\text{incr}} \) the normalisation.

The present-day average and present-day SFR are, respectively,
\[
SFR_{\text{incr}} = \frac{A_{\text{incr}}}{1 + \eta} t_{\text{sf}}^\alpha,
\]
\[
SFR_{o,\text{incr}} = A_{\text{incr}} t_{\text{sf}}^\alpha.
\]
To get the correct total normalisation \( M_\star \) at the present time,
\[
A_{\text{incr}} = \zeta (1 + \eta) M_\star / t_{\text{sf}}^{1+\eta}.
\]
Thus,
\[
\frac{SFR_{\text{incr}}}{SFR_{o,\text{incr}}} = \frac{1}{1 + \eta} \leq 1.
\]

The uncertainty of \( \eta \) is
\[
\sigma_\eta = \frac{\eta_+ - \eta_-}{2}, \quad \text{where} \quad \eta_\pm = \frac{1}{0.85 \times 10^{0.011}} - 1.
\]

The mean value of \( \frac{SFR}{SFR_o} \) clipped is 0.85 ± 0.02 (Section 3.2), implying that \( \eta = 0.18 \pm 0.03 \). The true uncertainty is probably at least about 30 per cent larger since the value quoted here treats all data points with equal weight and ignores the observational uncertainties which are not provided by Karachentsev et al. (2004, 2013). Note that \( \frac{SFR_{\text{incr}}}{SFR_{o,\text{incr}}} = 1 \) can be recovered for the case \( \eta = 0 \), which implies that any individual galaxy has the same SFR at all times.

According to this model, the stellar mass growth of an isolated non-interacting galaxy would be
\[
M_\star (t - t_1) = \frac{1}{\zeta (1 + \eta)} (t - t_1) SFR (t - t_1).
\]
For the case \( \eta = 0 \), \( M_\star \propto (t - t_1) SFR (t - t_1) \).

At a given \( M_\star \), the SFR would decrease with an increasing age of the Universe, \( t \), because a galaxy with fixed \( M_\star \) needed a larger SFR to reach this mass in a shorter time when the Universe was younger.

As a quantitative example, consider galaxies with a fixed \( M_\star = 10^{10} M_\odot \) at different times in standard cosmology. Suppose these all started forming stars at \( t_1 = 1.8 \) Gyr (i.e. about 12 Gyr ago) according to \( \zeta = 1.3 \), \( \eta = 0 \). At \( t = 2.1 \) Gyr, \( z \approx 3 \) such that \( SFR (0.3 \text{Gyr}) = 43 M_\odot/\text{yr} \). At \( t = 6 \) Gyr, \( z \approx 1 \) and \( SFR = 3.1 M_\odot/\text{yr} \). These are broadly consistent with the evolution documented by SP14, namely that \( SFR \approx 32^{+24}_{-18} M_\odot/\text{yr} \) at \( z = 3 \) and \( SFR \approx 10^{+2.8}_{-3.6} M_\odot/\text{yr} \) at \( z = 1 \) (their fig. 8).

The specific SFR becomes
\[
sSFR(t - t_1) = \zeta (1 + \eta) \frac{1}{t - t_1},
\]
such that today \( (t - t_1) = 12 \) Gyr and with \( \zeta = 1.3, \eta = 0 \),
\[
sSFR(t - t_1) = 1.1 \times 10^{-10} \text{ yr}^{-1}.
\]
As a further consistency check, in the regime where the gwIMF is expected to be comparable to the canonical IMF (i.e. \( \zeta \approx 1.3 \)) and thus for \( M_\star = 10^{10} M_\odot \), the observational study by Ilbert et al. (2015) leads to \( sSFR = 1.23 \times 10^{-10} \text{ yr}^{-1} \) (their eq. 1 with \( z = 0 \), being in reasonable
agreement with Eq. 22. Note that the sSFR vs $M_*$ relation might not be constant as its slope would be given by the value $\zeta(SFR_0, Z)$ if the gwIMF depends on the SFR and metallicity, $Z$. According to the IGIMF theory, $\zeta > 1.3$ for galaxies with $SFR_0 > 10 M_*/yr$ (cf. Gunawardhana et al. 2011; Yan et al. 2017). The slope of the sSFR vs $M_*$ relation thus encodes the systematic variation of the gwIMF.

4 DISCUSSION AND CONCLUSION

The Catalogue of Neighbouring Galaxies (Sec. 2) provides a sample of star forming galaxies which are used here to test a robust expectation concerning galactic SFHs (Eqs. 1 and 9). This expectation comes from the general understanding that galaxies typically have decreasing SFRs now, and should thus have an average star formation rate exceeding the present value ($sSFR/SFR_0 > 1$). Within the context of the delayed-$\tau$ models (Section 3.1), the present results are indicative of a rather long star formation timescale of the same. However, stars for 12 Gyr, the average and present SFRs are nearly by SP14. The tension between their results and the local $\tau$ of the delayed-should thus have an average star formation rate exceeding 9). This expectation comes from the general understand-
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DATA AVAILABILITY STATEMENT

The data used stem from the Catalogue of Neighbouring Galaxies (Sec. 2).

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