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Implications of a Temperature-dependent Initial Mass Function. III. Mass Growth and Quiescence

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Abstract

The stellar initial mass function (IMF) is predicted to depend upon the temperature of gas in star-forming molecular clouds. The introduction of an additional parameter, $T_\text{IMF}$, into photometric template fitting suggests most galaxies obey an IMF top heavier than the Galactic IMF. The implications of the revised fit on mass function, quiescence, and turnoff are discussed. At all redshifts, the highest-mass galaxies become quiescent first with the turnoff mass decreasing toward the present. The synchronous turnoff mass across galaxies suggests quiescence is driven by universal mechanisms rather than by stochastic or environmental processes.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Initial mass function (796); Star formation (1569); Galaxy quenching (2040); Stellar mass functions (1612)

1. Introduction

Several of the strongest constraints on galaxy formation and evolution are provided by measurements of the stellar-mass function (SMF), or stellar mass distribution, of distant galaxies. Perhaps the most longstanding is the discovery that the most massive galaxies complete their growth earliest, one of several related effects collectively termed downsizing (Cowie et al. 1996; Fontana et al. 2006; Stringer et al. 2009; Fontanot et al. 2009). The existence of massive galaxies at high redshift requires high stellar baryon fractions (Finkelstein et al. 2015) or may even challenge the standard ΛCDM cosmological paradigm (Steinhardt et al. 2016; Behroozi & Silk 2018). The existence of massive quiescent galaxies at high redshift (Toft et al. 2014; Glazebrook et al. 2017; Schreiber et al. 2018; Tanaka et al. 2019; Valentino et al. 2020) may pose a similar challenge.

All of these results rely on measurements of galactic stellar masses. Most of the light from a galaxy is emitted by only the most massive stars, comprising a small fraction of the full stellar mass. The remainder of the stellar population must be inferred from assumptions that are difficult to test outside of our own Galaxy. As a result, the luminosity of a distant galaxy can be determined far more precisely than its stellar mass.

This is particularly true because of the advent of large photometric surveys, which only have accompanying spectroscopy for a small fraction of their objects. The Sloan Digital Sky Survey (Ahumada et al. 2020) contains spectra for ~0.5% of the $10^{9}$ objects with optical photometry. The largest multiwavelength survey with the infrared observations necessary to constrain stellar masses (cf., Bradač et al. 2014), COSMOS (Scoville et al. 2007), includes spectroscopy (Hasinger et al. 2018) for approximately 2% of the $10^{9}$ objects imaged (Laigle et al. 2016). Ultradeep surveys now contain $\geq 10^{5}$ objects at $z > 6$ (Bouwens et al. 2015, 2016; Steinhardt et al. 2020a), with very few spectra at these redshifts. Thus, for the vast majority of galaxies, stellar mass determination comes from photometric template fitting, a set of techniques for fitting model spectra to photometry in order to determine redshift and physical parameters.

Photometric template fitting relies on the assumption that these models successfully describe galaxies. Mathematically, there will always be a best-fit reconstruction for each galaxy over the allowed template space, regardless of whether the model space includes the true galaxy properties. However, if the model space is insufficient, that best-fit model will produce incorrect properties.

The most critical assumption for stellar mass determination is the stellar initial mass function (IMF), or the distribution of stellar masses in a zero-age stellar population. Because most of the stellar mass is inferred from only the rare, most massive stars, a small change in the shape of the IMF can produce a significant change in stellar mass. A change in IMF will also change the star formation rate (SFR), metallicity, age, extinction, and other inferred parameters.

The IMF has been historically assumed to be constant for all galaxies, as it can only be empirically measured in the Milky Way. That is, star formation in all galaxies, at all redshifts, is assumed to produce the same mass distribution that it does in the Milky Way. However, observational evidence also suggests that the IMF may not be universal (Conroy & van Dokkum 2012; La Barbera et al. 2013; Spiniello et al. 2014; Lyubenova et al. 2016; Lagattuta et al. 2017; van Dokkum et al. 2017). Further, physical models of star-forming clouds strongly

6 Because it is known that these models do not entirely describe galaxies, goodness-of-fit metrics are typically not used to reject mismatches except in extreme cases.
suggest that the distribution of stellar masses formed should depend on the temperature of the cloud, with a top-heavier IMF for higher temperatures (Low & Lynden-Bell 1976; Larson 1985; Bernardi et al. 2017; Jermyn et al. 2018).

Although direct observational measurements of gas temperatures are difficult, there is considerable indirect evidence to suggest that gas temperatures vary. Dust temperatures in star-forming galaxies are typically above 20 K, with higher dust temperatures found both toward high redshift and toward higher SFRs at fixed stellar mass and redshift (Magnelli et al. 2014; Schreiber et al. 2018; Kokorev et al. 2021). Although luminosity-averaged dust temperatures are not guaranteed to be reliable indicators of gas temperatures in star-forming regions, the gas temperatures inferred from the methods used in this work lie in a similar range and have similar redshift dependence and SFR dependence (cf., Steinhardt et al. 2022 for an extended discussion), although they are measured in entirely different ways.

Jermyn et al. (2018) developed a theoretical prescription for a one-parameter family of IMFs at some gas temperature $T_{\text{IMF}}$. This work is the third in a series that studies the effects of fitting the COSMOS2015 (Laigle et al. 2016) catalog with templates derived from those IMFs. Paper I (Snepen et al. 2022) describes the fitting procedure, finding that nearly every galaxy is best fit with a $T_{\text{IMF}}$ higher than the Milky Way. Thus, nearly every galaxy is best described with an IMF which is bottom-lighter (or top-heavier) than our own. Paper II (Steinhardt et al. 2022) explores the implications of these results for star formation and the star-forming “main sequence.” This work describes the effects on SMFs and high-redshift cosmology.

The fitting procedure and data set are summarized in Section 2, with a full description given in Snepen et al. (2022). The updated stellar masses derived from the updated catalog and resulting shift in mass functions are described in Section 3. These results imply a much stricter mass hierarchy for quiescence than previous results. Whether the highest-redshift galaxies continue to produce tension with $\Lambda$CDM is described in Section 4.1. The broader implications of these results are discussed in Section 4.

2. Methodology

The template fitting presented here attempts to reproduce standard, existing techniques as closely as possible, with the sole exception of a single additional parameter that allows selection from a family of IMFs. Full details on the technique, selection, uncertainties, covariances between parameters, and a comparison with fits using a fixed IMF are given in Paper I (Snepen et al. 2022).

Fits are performed on the largest multiwavelength photometric data set available, the COSMOS2015 catalog (Laigle et al. 2016). Objects are measured in as many as 26 filters: 12 broad bands (NUV, u, B, V, r, i, z, Y, J, H, and IRAC channels 1 and 2), 2 narrow bands (NB711 and NB816), and 12 intermediate bands.

The resulting catalog is fit using the photometric template-fitting code EAZY (Brammer et al. 2008). The standard version of EAZY fits galaxy SEDs as a linear combination of 12 basis templates, drawn themselves as linear combinations of 560 Flexible Stellar Population Synthesis (FSPS; Conroy et al. 2009) synthetic spectra using different combinations of metallicity, extinction, and age but an identical IMF. Here, equivalent basis sets are produced using the Jermyn et al. (2018) IMF,

$$\xi(m) \propto \begin{cases} m^{-0.3} & m < 0.08 M_\odot \left( \frac{T_{\text{IMF}}}{20} \right)^2, \\ m^{-1.3} 0.08 M_\odot \left( \frac{T_{\text{IMF}}}{20} \right)^2 < m < 0.5 M_\odot \left( \frac{T_{\text{IMF}}}{20} \right)^2, \\ m^{-2.3} M_\odot > 0.5 M_\odot \left( \frac{T_{\text{IMF}}}{20} \right)^2. \end{cases}$$

where $T_0 = 20$ K, so at $T_{\text{IMF}} = T_0$, this produces a standard Kroupa IMF (Kroupa 2001). For each IMF, a set of 560 FSPS templates is constructed corresponding to the same combinations of age, star formation history, extinction, and metallicity as in the standard EAZY library. Those are then reduced to 12 basis templates, again using the same procedure as for the standard EAZY library. Fits are performed over a grid of IMFs, spaced every 1 K for 8 K $< T_{\text{IMF}} < 60$ K.

Thus, $T_{\text{IMF}}$ determines the top heaviness of the IMF, with the variabiliy of the IMF causally interpreted as being set by temperature in star-forming clouds. Given other theoretical prescriptions, other dependencies on temperature have been suggested, but the presented approach is agnostic to the theoretical model. A translation to other mass-scaling relations is seen in Snepen et al. (2022). Additionally, it should be noted that the IMF is derived from fitting the existing stellar population. Thus, $T_{\text{IMF}}$ does not probe the gas temperature in star-forming clouds at the time the observed light was emitted, but instead when the existing stellar population was formed.

The value of $T_{\text{IMF}}$ yielding the minimum reduced $\chi^2$ is chosen as the best-fit temperature for each object. For most of the high signal-to-noise objects, there is a single local $\chi^2$ minimum within the grid, which is also the global minimum. For the remainder of the catalog, mostly objects with fewer bands or low signal-to-noise ratio, there are multiple local minima or the only local minimum lies at 8 K or 60 K. These objects are discarded from the final catalog, with the exception of the population described in Section 2.1.

For each object at any $T_{\text{IMF}}$, EAZY outputs a best-fit and a photometric redshift $z_{\text{phot}}$ and a linear combination of basis templates to the observed photometry. Typically the photometric redshift is similar for all $T_{\text{IMF}}$, as it is mainly constrained by spectral breaks rather than by the shape of the SED. Galactic parameters including stellar mass, SFR, metallicity, and age are then constructed as a (luminosity-weighted) linear combination of the basis templates. For the comparisons shown in this work, star-forming and quiescent galaxies are separated using a $\text{UVJ}$ diagram. Rest-frame $U$, $V$, and $J$ fluxes are calculated from the best-fit reconstructed spectrum, shifted to the rest frame using the calculated photometric redshift and integrated over the relevant filters.

As described in detail in Paper II, most galaxies in COSMOS are best fit with $T_{\text{IMF}} \gtrsim 25$ K, compared with a Galactic IMF at $T_{\text{IMF}} = 20$ K. Further, the best-fit stellar mass, SFR, and other parameters are sensitive to changes in $T_{\text{IMF}}$ on this scale (Snepen et al. 2022, Figure 8). Thus, the best-fit properties of most objects in COSMOS change significantly following the introduction of $T_{\text{IMF}}$ into the fitting process. The remainder of this paper focuses on the ways in which this alters SMFs and the implications for our understanding of stellar-mass growth and quiescence.
with an unphysically high $T$ regions. The extremely high $0.95 < \chi^2_{\text{IMF}} < 1.05$. At every mass, there is a clear local minimum at a similar $T_{\text{IMF}}$. In addition, the slope changes with mass, and a small outlier population of the most massive star-forming galaxies galaxies (red, dashed) are best fit with an unphysically high $T_{\text{IMF}}$. A plausible explanation is that the local minimum between 30 K and 35 K indicates gas temperatures in star-forming regions. The extremely high $T_{\text{IMF}}$ would then indicate an additional breakpoint in the stellar-mass distribution coming from a lack of very high-mass stars, a possible indication of turnoff.

2.1. Well-measured Objects with Multiple Minima

Most objects without a single, clear global minimum in $\chi^2(T_{\text{IMF}})$ have a complex landscape due to large measurement uncertainties and correspondingly poorly constrained fits. However, there is also a small class of well-measured objects, typically high-mass star-forming galaxies, without a single global minimum. These objects typically exhibit a general trend of an improved fit toward high, physically unreasonable values of $T_{\text{IMF}}$. In addition, there is a local $\chi^2$ minimum at a value of $T_{\text{IMF}}$ similar to other star-forming galaxies at the same redshift. A stacked $\chi^2$ landscape (Figure 1) shows the change in overall slope of $\chi^2(T_{\text{IMF}})$ toward high mass. This implies a combination of two effects, one common to all star-forming galaxies and a second preferentially occurring at high stellar mass.

A change in $T_{\text{IMF}}$ results in an IMF of similar shape to a Kroupa IMF, but with break masses in different locations. Because starlight is dominated by high-mass stars, in effect, measurements of $T_{\text{IMF}}$ are predominantly measurements of the higher-mass break mass. Finding that star-forming galaxies have a similar $T_{\text{IMF}}$ essentially indicates that they have similar breaks in their stellar-mass distribution.

However, changes in the stellar population can be produced not only by a change in the IMF, but also by a change in the star formation history (SFH). In principle, the IMF and SFH are not only by a change in the IMF, but also by a change in the star formation history (SFH). In principle, the IMF and SFH are entirely degenerate. Given any choice of IMF, an SFH can be constructed to match any stellar population. The highest-mass stars with the shortest lifetimes can be used to determine the recent SFR. The IMF is then used to construct a full stellar population at that SFR. Subtracting this population, the next highest-mass objects in the remaining population are then used to construct the SFR at an earlier time. Iterating will produce a binned SFH, which can be combined with the assumed IMF to construct the present stellar population. This approach has been used to determine extragalactic SFHs (Panter et al. 2003; Sánchez et al. 2019), assuming a Galactic IMF.

A particularly poor choice of IMF could be ruled out because producing the observed stellar population would require a the SFH to be negative at some times. However, given the other significant uncertainties, a statistically significant rejection of a plausible IMF is unlikely.

Here, the stellar population is decomposed by allowing the IMF to vary rather than the SFH. The standard EAZY methodology assumes a delayed-tau SFH (Brammer et al. 2008), with the stellar population ages in this work allowed to range from 0.02 to 20 Gyr (Sneppen et al. 2022). Thus, a high-mass break in the stellar population is assumed to correspond to a high-mass break in the IMF and therefore a very high $T_{\text{IMF}}$. However, the same lack of very high-mass main-sequence stars can also be produced by a rapid decline in SFR in the recent past, with the time since that decline corresponding to the main-sequence lifetime at the break mass. In that case, instead of a high $T_{\text{IMF}}$, such a break would be a possible indicator of very recent star formation turnover.

Such an interpretation would fit nicely with the additional evidence presented in Section 4.4. For the remainder of this work, rather than excluding these objects from the catalog, the choice is made to include them using the best-fit properties at the local minimum of $T_{\text{IMF}}$ between 20 K and 45 K. A choice to use the far higher value of $T_{\text{IMF}}$ would result in significantly lower stellar-mass estimates. Thus, either using the higher value of $T_{\text{IMF}}$ or excluding this sample entirely would only strengthen the conclusions regarding high-mass turnover in the following sections. However, because this is only a small population, those conclusions are not sensitive to this choice.

3. Effects on Stellar Masses and Quiescence Mechanisms

3.1. Effects of IMF “Temperature” on Stellar Masses

The best-fit $T_{\text{IMF}}$ at nearly every redshift is not 20 K, corresponding to a Galactic IMF, but rather higher (Figure 2). It might be expected that a top-heavier IMF will always produce a lower stellar mass, because massive stars have a smaller mass-to-light ratio, and therefore, a distribution with more massive stars also has a smaller mass-to-light ratio. However, changing the temperature of the IMF might also change other parameters that are degenerate with the stellar mass (as detailed in Paper I).

Figure 1. Average $\Delta \chi^2(T_{\text{IMF}})$ at various masses for star-forming galaxies at $0.95 < z < 1.05$. At every mass, there is a clear local minimum at a similar $T_{\text{IMF}}$. In addition, the slope changes with mass, and a small outlier population of the most massive star-forming galaxies (red, dashed) are best fit with an unphysically high $T_{\text{IMF}}$. A plausible explanation is that the local minimum between 30 K and 35 K indicates gas temperatures in star-forming regions.

Figure 2. Mean best-fit $T_{\text{IMF}}$ for quiescent (red) and star-forming (blue) galaxies as a function of redshift. Light shading indicates the 1σ spread of individual observations, with dark shading indicating the uncertainty on the mean. Quiescent galaxies are at redshifts cooler than their star-forming counterparts, but both populations typically require top-heavier IMFs than a Galactic IMF. The Anderson–Darling test statistic quantifies that within any redshift bin of width $\Delta z = 0.25$ from $z = 0$ to $z = 2$, the two distributions yield a $p$-value of less than $10^{-16}$ to be drawn from the same underlying distribution, and a $p$-value <0.1% from the smaller sample at $z \sim 2.5$. At higher redshifts, the mean temperature of both populations increases.
Thus, it is first necessary to recompute individual stellar masses from templates for the objects with sufficient signal to noise to constrain them. Subsequently, the effects on the entire stellar-mass distribution can be estimated from those best-fit stellar masses in order to correctly understand how that distribution changes with the introduction of $T_{\text{IMF}}$.

3.2. Uncertainties and Eddington Bias

The resulting stellar-mass distribution exhibits many of the properties reported in previous studies, which assumed a Galactic IMF. However, stellar masses determined from template fitting have large uncertainties. It is therefore necessary to model this uncertainty in order to determine the true, underlying SMF from the observed stellar-mass distribution.

The observed SMF can be thought of as the true SMF convolved with some error function, changing the shape of the SMF. Because what is measured is the distribution of objects above the stellar-mass completeness cut, this creates a high-mass bias in observed SMFs, which is a form of the Eddington bias. Here, this bias is corrected using the methodology presented in Ilbert et al. (2013). Assuming that the true SMF follows a Schechter function and the scatter follows the same distribution determined by Ilbert et al. (2013), a best-fit error-convolved Schechter function is calculated for the observed SMF, which can then be easily deconvolved to obtain an estimate of the true SMF. In practice, the effect of this error convolution is primarily that the observed mass function is overestimated at the high-mass tail, which deconvolution corrects. Thus, the correction will appear most significant at high redshift, as the detection threshold becomes closer to the maximum observed mass.

3.3. Revised Mass Completeness Cut

Constraining an additional parameter ($T_{\text{IMF}}$) compared with previous fits requires additional information and therefore a stricter signal-to-noise-ratio cut (detailed in Paper I). This cut will affect the stellar-mass distributions observed, as it rejects less luminous and therefore typically less massive galaxies. Thus, the mass distribution is no longer complete to the same degree at the same masses as in previous COSMOS studies (Davidzon et al. 2017). Therefore, for further analysis, the mass completeness cut is reevaluated at all redshifts.

The mass completeness is estimated at fixed redshift by determining the highest masses observed at the flux in the $K$ band, which separates the cut and accepted objects. A threshold of $K = 0.5 \mu$ Jy yields a clear delimiter between the cut and accepted object for all redshifts with a $>95\%$ true-positive rate and $<10\%$ false-negative rate.

Because $T_{\text{IMF}} > 20$ K, the inferred stellar masses have decreased. Thus, at every redshift, the typical stellar mass and thus the stellar-mass distribution in this work lies below those of previous studies. Thus, there are two effects that change the mass completeness in opposite directions. The requirement for a higher signal-to-noise ratio leads to a brighter completeness limit. However, the higher $T_{\text{IMF}}$ means that the same flux comes from a lower inferred stellar mass. In practice, the former effect is more significant, and therefore using a variable IMF, the stellar-mass completeness threshold is higher at most redshifts.

3.4. Turnoff Fractions and Ordering

The best-fit $T_{\text{IMF}}$ for star-forming galaxies is higher than that for quiescent galaxies at every redshift. As a result, the decrease in stellar mass compared with previous measurements is also greater for star-forming galaxies. This shift in the relative masses of star-forming and quiescent galaxies might help to explain a puzzling feature of previous turnoff studies at high redshift. The typical growth of star-forming galaxies is monotonic in mass; increasing mass at fixed redshift results in higher SFR but lower sSFR (Noeske et al. 2007; Peng et al. 2010; Speagle et al. 2014; Steinhardt et al. 2014; Schreiber et al. 2018). The same is true of hierarchical merging, in which smaller halos virialize before larger ones (cf., Press & Schechter 1974; Sheth et al. 2001), and of several results that have been described as downsizing (Cowie et al. 1996; Fontana et al. 2006; Stringer et al. 2009; Fontanot et al. 2009), showing that in several ways more massive galaxies evolve more rapidly than their less massive counterparts.

However, the quiescent fraction of galaxies as found using a Galactic IMF instead shows that the first galaxies to turn off, at $z > 2$, lie in the middle of the mass distribution, around $10^{10.5} M_\odot$ (Davidzon et al. 2017, Figure 12). At the same redshift, nearly all galaxies at both higher and lower stellar masses are still star-forming. Further, the star-forming main sequence appears to be universal (Steinhardt & Speagle 2014), with nearly all star-forming galaxies at the same stellar mass growing at the same rate at any given time. If turnoff is a natural result of the process that drives star formation, by the same principle one should expect turnoff to occur at a similar time in an ensemble of galaxies of a given stellar (or halo) mass at any fixed redshift. Thus, at most masses, nearly none or nearly all galaxies should be quiescent, with the mass range currently undergoing turnoff being the sole exception. However, studies using a Galactic IMF instead find that a mixture of star-forming and quiescent galaxies at the same stellar mass is most typical (Ilbert et al. 2013; Davidzon et al. 2017). For example, the quiescent fraction of $M \sim 10^{11} M_\odot$ galaxies lies between $20\%$ to $80\%$ from $z = 4$ to $z = 0.8$ in those studies.

At lower redshift, however, there is a different, far simpler picture. The highest-mass galaxies turn off first, and at every redshift, nearly all of the most massive galaxies have become quiescent. Lower-mass galaxies are predominantly star-forming. This result follows expectations from observations of the star-forming main sequence and mass downsizing. It suggests that turnoff is a natural extension of a galaxy’s evolution as it exits the high-mass end of the star-forming main sequence, rather than an independent event that can happen to galaxies at any stage of their lifetimes.

Using the best fit from a family of IMFs strengthens this picture. Quiescent galaxies have a nearly Galactic IMF so that their best-fit stellar masses will be similar to previous studies. However, star-forming galaxies have higher $T_{\text{IMF}}$, with $T_{\text{IMF}}$ further increasing toward higher redshift (Steinhardt et al. 2020b). Thus, the best-fit stellar masses for star-forming galaxies will be systematically lower than in previous studies. Further, they will systematically shift relative to the quiescent population. Thus, the quiescent fraction will increase at high mass.

Within the range covered by this study ($z \lesssim 2$), this produces an even sharper picture than using the Laigle et al. (2016) catalog on the same data set (Figure 3). At all redshifts where the quiescent fraction can be measured directly allowing a best-
fit IMF, the most (stellar) massive galaxies at each redshift are nearly all quiescent and the least massive nearly all star-forming.

### 3.4.1. Extrapolation to Higher Redshifts

At $z > 2$, COSMOS2015 presents an entirely different picture of quiescence than both COSMOS2015 and the variable-IMF fits at $z < 2$. The Davidzon et al. (2017) fits find that the most massive galaxies at $2.5 < z < 3.0$ are star-forming (reproduced in Figure 4) and that the quiescent fraction peaks at $\sim 10^{10.5}M_\odot$ in the middle of the distribution. As described above, this result is difficult to reconcile with the star-forming main sequence, with downsizing. So, it is natural to consider whether using a best-fit IMF might solve this “problem” by reducing star-forming stellar masses more than quiescent ones and yielding the more intuitive result found at lower redshifts.

COSMOS2015 has a large-enough sample to constrain the quiescent fraction out to $z = 3$ without additional assumptions. However, there are a few quiescent galaxies at those redshifts with sufficient signal to noise to constrain the IMF, and thus the quiescent fraction cannot be measured at those redshifts using the techniques in this paper. Instead, it is necessary to extrapolate to these redshifts based on a comparison between stellar masses using Galactic and best-fit IMFs at lower redshifts.

Ideally, one would start by comparing the COSMOS2015 masses with those in this work. A typical offset could be measured at every $T_{\text{IMF}}$, perhaps separately for quiescent and star-forming galaxies if the offset is different at the same temperature for young and old stellar populations. Extrapolating the characteristic $T_{\text{IMF}}$ (cf., Sneppen et al. 2022, Figure 7) for star-forming and for quiescent galaxies out to $z = 3$, those temperatures and corresponding IMFs could then be used to produce offsets and adjust the Davidzon et al. (2017) SMFs for each population.

However, in addition to a change in the best-fit IMF, there are three other differences that can significantly alter inferred stellar masses. First, the COSMOS2015 catalog is based on the LePhare photometric template-fitting code, and this work uses EAZY. A comparison of LePhare and EAZY stellar masses for...
the COSMOS2020 catalog shows a $\sim$0.2 dex offset (Weaver et al. 2022). Second, COSMOS2015 fits galaxies with a Chabrier IMF, and the 20 K IMF used here is instead identical to a Kroupa IMF. This, too, predominantly produces a systematic shift in the inferred stellar mass, although in principle there could also be a slight dependence on the age of the stellar population. Finally, a small fraction of objects is best fit with significantly different redshifts, due to the reinterpretation of a Lyman break as a Balmer break, or vice versa. None of these is the effect of interest here. However, they potentially dominate a direct comparison of masses between COSMOS2015 and this work.

Fortunately, these other differences should affect both star-forming and quiescent galaxies similarly, whereas a change in $T_{\text{IMF}}$ does not. Thus, in order to determine the relative shift between star-forming and quiescent mass functions, it is sufficient to determine the relative shift due to the change in $T_{\text{IMF}}$ alone. Here, that shift is modeled as follows at each redshift:

1. The characteristic $T_{\text{IMF}}$ is determined separately via linear extrapolation for star-forming and quiescent galaxies at $2.5 < z < 3.0$. This produces $T_{\text{IMF}} = 35$ K for star-forming galaxies and 25 K for quiescent ones.
2. The median offset between the best-fit stellar mass at that $T_{\text{IMF}}$ and the stellar masses for those galaxies using a 20 K IMF is found (i.e., the offset illustrated in Figure 9 in Sneppen et al. 2022).
3. Those offsets are then applied to the Davidzon et al. (2017) SMFs at $2.5 < z < 3$.

The results of applying those offsets to the Davidzon et al. (2017) SMFs (Figure 4) show a significant qualitative difference. Whereas the Davidzon et al. (2017) quiescent fraction peaks in the middle of the distribution, this extrapolation produces a result similar to the low-redshift answer. The highest-mass galaxies turn off first, and all of the most massive galaxies have become quiescent. Lower-mass galaxies are predominantly star-forming.

Thus, the effects of allowing a best-fit IMF are potentially sufficient to restore the more intuitive, low-redshift answer.

If the low-redshift shape of the quiescent fraction is indeed the shape at all redshifts, a further implication is that turnover appears to be a one-time, permanent process rather than galaxies having several shorter periods of quiescence between rounds of star formation. Alternating periods of quiescence and growth would produce a lower-mass quiescent population, rather than having the simpler result that only the most massive galaxies are found to be quiescent. A one-time, permanent turnover as suggested by the variable-IMF fits is easier to reconcile with both the star-forming main sequence and downsizing, as it would simply mean that galaxies that all grow in the same way naturally turn off at the end of that growth. However, these results still do not suggest any specific physical mechanism for turnover.

### 3.5. Turnoff Mass and Quiescent Galaxy Selection

Following the introduction of $T_{\text{IMF}}$, virtually all of the highest-mass galaxies at fixed redshift are quiescent and virtually all of the lowest-mass galaxies are star-forming, with a sharp transition between the two. This transition is so sharp that it even provides an approximate selection method for quiescent galaxies: simply use the best-fit stellar mass, assuming that the highest-mass galaxies are most likely to be quiescent.

This is a far less sophisticated method than the ones in current use. Those include color selection criteria (Williams et al. 2009; Amorots et al. 2013), template fitting followed by selection of galaxies with low sSFR (Brammer et al. 2008; Laigle et al. 2016), and most recently, a variety of machine-learning approaches (Leja et al. 2019; Davidzon et al. 2019; Steinhardt et al. 2020b; Shahidi et al. 2020; Turner et al. 2021). With the exception of color selection, which is Boolean, the other criteria instead provide a score or ranking, which can then be turned into a probability that the galaxy is quiescent. For example, in template fitting, a lower sSFR corresponds to a higher likelihood of quiescence. A threshold is then typically selected, with objects above the threshold considered quiescent and below the threshold star-forming.

The success of these criteria is often evaluated using a receiver operating characteristic (ROC) curve (Figure 5), which evaluates the tradeoff between false-positive and false-negative rates at different thresholds.

As a single summary metric, $\Sigma$ROC is a rank-sum test, similar to the Mann–Whitney U test. Although stellar mass is a far cruder selection than several methods in current use, the overall $\Sigma$ROC (or AUC) of $\sim$0.8 at a wide range of redshifts is competitive with several current techniques, indicating the surprising sharpness and completeness of the transition from lower-mass star-forming galaxies to higher-mass quiescent ones.

This sharpness also makes it natural to define a single transition, or turnover mass, $m_{\text{to}}$, between the two populations. Because the transition takes place in a relatively narrow mass range, most definitions of $m_{\text{to}}$ will provide similar results. Here, $m_{\text{to}}$ is defined as the mass at which the probability of quiescence is 0.5.

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9 This is typically called AUC, or area under the curve, in machine-learning literature.
exponential behavior is reasonably well approximated as linear in lookback time, corresponding to an exponential $m_{\text{to}} \propto e^{-\tau}$. Red line indicates best-fit: $\log (m_{\text{to}}/M_\odot) = (10.11 \pm 0.15) + (0.11 \pm 0.02) \tau$, $\chi^2$/dof = 10.5/5.

$m_{\text{to}}$ is defined in every redshift as the mass at which 50% of galaxies are quiescent in a smoothed fit.

The resulting $m_{\text{to}}$ decreases toward lower redshift (see Figure 6).

Further, $\log m_{\text{to}}$ is nearly linear in lookback time, with best-fit $\log (m_{\text{to}}/M_\odot) = (8.57 \pm 0.18) + (0.26 \pm 0.03)\tau$. This linearity of $\log m_{\text{to}}$ in lookback time is reminiscent of a similar linearity in $\log \, sSFR$ along the star-forming main sequence (Speagle et al. 2014). This is further support for the possibility that quenching might not be an external event that ends star formation, but rather should be thought of as the natural endpoint of the same feedback mechanisms that drive the star-forming main sequence.

4. Discussion

Most of the inferred properties for galaxies in previous studies have relied on the assumption that a Galactic IMF is universally applicable. However, when photometry is fit to models incorporating a family of possible IMFs, nearly every galaxy outside the local universe is instead best fit with one top-heavier than the Milky Way. This top heaviness is best described in terms of a single parameter, $T_{\text{IMF}}$, which is hoped to correspond to a typical gas temperature in star-forming clouds. A higher $T_{\text{IMF}}$ corresponds to a top-heavier, or more accurately bottom-lighter, IMF.

Although in aggregate galaxies exhibit $T_{\text{IMF}}$ ranging from $\sim 20-45$ K, at any fixed redshift the distribution is far narrower. Star-forming galaxies are best fit with a characteristic $T_{\text{IMF}}(z)$ which rises from $\sim 25$ K at $z \sim 0$ to nearly 35 K by $z = 2$. Quiescent galaxies have a lower characteristic temperature, which exhibits either only weak or negligible redshift dependence.

4.1. The Most Massive, Highest-redshift Galaxies

Because $T_{\text{IMF}}$ is generally the largest for the highest-redshift galaxies, the extrapolated differences between the stellar masses shown here and previous results using Galactic IMFs are also the most significant at high redshift. This is of particular interest because the most massive galaxies as measured using Galactic IMFs are sufficiently massive to challenge $\Lambda$CDM (Steinhardt et al. 2016; Behroozi & Silk 2018).

The fits in this work produce lower stellar masses at high redshift. However, because the most massive star-forming galaxies at any redshift exhibit lower best-fit $T_{\text{IMF}}$ (see Paper II), the decrease in stellar mass is smaller for the most massive galaxies. As a result, there is still a discrepancy between the theoretical halo-mass function and the SMF, which would result from a redshift-independent stellar-mass–halo-mass relation.

4.2. Recalibrating Simulations

One of the conclusions of this work is that the observed SMF at high redshift differs significantly from previous studies. Because prior mass functions were well reproduced by calibrated simulations of galaxy formation within halos (cf., Vogelsberger et al. 2020), this suggests that a new calibration may be necessary.

Such a calibration has not yet been done, although given the large number of free parameters in simulations, it seems most likely that such a calibration is possible. Should it prove impossible to reproduce our SMFs with calibrated simulations within $\Lambda$CDM, that would be good evidence of new tension between cosmology, template-fit galactic properties, and numerical simulations.

4.3. Quiescence Mechanisms

This difference in quiescent and star-forming IMFs is, at a minimum, yet another indication of the well-studied bimodality in observed galaxy properties, separating star-forming galaxies from quiescent ones. However, it should be stressed that unlike most temperature measurements, the best-fit IMF is backward looking.

Like most properties determined from photometry, $T_{\text{IMF}}$ measures a luminosity-weighted average. In practice, galaxies likely comprise a mixture of stellar populations formed at a range of different $T_{\text{IMF}}$ given that the typical star-forming $T_{\text{IMF}}$ is redshift dependent. So, describing galaxies with a single $T_{\text{IMF}}$ is analogous to describing them with a single best-fit age for their stellar population.

In both cases, these luminosity-weighted averages are dominated by the same population of the most massive stars still on the main sequence. Typical age measurements indicate that the luminosity-weighted stellar population is typically $\sim 10^8$ yr old in a star-forming galaxy and far older in a quiescent one. Thus, $T_{\text{IMF}}$ for a star-forming galaxy describes the IMF $\sim 10^8$ yr earlier than when the light is emitted, and $T_{\text{IMF}}$ for a quiescent galaxy describes the IMF during its last significant epoch of star formation.

As a result, the bimodality between the behavior of star-forming and quiescent $T_{\text{IMF}}$ does not merely indicate that the two populations are distinct. Rather, it shows that quiescent galaxies had already taken on distinct properties from star-forming ones, including a more Milky Way–like IMF, while they were still star-forming.

One possibility is that this might allow a search for quenching, rather than quenched, galaxies. Because the strong change in galaxy color from blue to red only happens $\gtrsim 500$ Myr after turnover (Wild et al. 2020), color selection only finds galaxies that have long since quenched. If star-forming galaxies begin to exhibit distinct properties even while still

[10] It is also quite possible that different star-forming clouds within the same galaxy at the same redshift may lie at a range of temperatures. If so, the true IMF for that galaxy may not correspond to any specific $T_{\text{IMF}}$, but rather a weighted sum of different IMFs that the fitting routine will approximate as a single IMF corresponding to a single, best-fit $T_{\text{IMF}}$. Steinhardt et al.
forming stars, it might be possible to select these galaxies while they are still quenching, providing far more information about possible mechanisms. A simple selection proposed here is to look for galaxies with star-forming colors but low $T_{\text{IMF}}$, more characteristic of quiescent galaxies. Further work might develop improved selection criteria.

The drop in $T_{\text{IMF}}$ also indicates that galaxies are actively forming stars at a high rate even as they begin quenching. If $T_{\text{IMF}}$ truly reflects gas temperature in star-forming regions, it also helps to distinguish between different possible mechanisms. For example, AGN heating would quench star formation by heating gas in star-forming regions, inhibiting the collapse into stars (Di Matteo et al. 2005). For the stars that are still able to form, they would be expected instead to form under warming conditions, so that quenching galaxies should instead exhibit $T_{\text{IMF}}$.

Perhaps an effect such as strangulation (Peng et al. 2015) would be more likely to produce the observed lower $T_{\text{IMF}}$ in the last stages of star formation. In such a scenario, increasingly cooler gas would form stars even more efficiently, eventually leading to the depletion of the remaining gas and quiescence.

4.4. Synchronized Turnoff and Implications for Uniform Models

Other possible mechanisms are difficult to reconcile with the apparent universality of the drop in $T_{\text{IMF}}$. It appears that nearly every quiescent galaxy exhibits a lower $T_{\text{IMF}}$, meaning that they were all in a similar state while quenching. Thus, it is likely that most galaxies quenched via a common mechanism.

A stronger form of this universality of quenching comes from looking at the quiescent fraction of galaxies as a function of mass and redshift. Although nearly every stellar mass in this work is lower than the one inferred for the same galaxy using a Galactic IMF, the masses of star-forming galaxies decrease more than those of quiescent galaxies because $T_{\text{IMF}}$ is generally higher. As a result, previous estimates of quiescent fractions are replaced by a far simpler picture: At every redshift, nearly all of the higher-mass galaxies are quiescent and nearly all of the lower-mass galaxies are star-forming. There is a narrow mass range in which galaxies are transitioning from star-forming to quiescent, and that mass range monotonically decreases toward lower redshift.

A key implication is that not only do all galaxies eventually become quiescent, but galaxies at the same stellar mass quench nearly all at the same time. This would appear to be inconsistent with proposed quenching mechanisms such as galaxy harassment (Cortese et al. 2006; Wetzel et al. 2013; Woo et al. 2015; Bluck et al. 2019) and galaxy mergers or resulting AGN heating (Mihos & Hernquist 1996; Di Matteo et al. 2005), which would be driven by local environmental differences.

Instead, it points to a story much more similar to that of the star-forming main sequence, which is similar to the natural endpoint of the other astrophysics and feedback mechanisms that drive the star-forming main sequence. This, again, would appear to be more consistent with strangulation (Peng et al. 2015; Henriques et al. 2019) or some other gradual depletion mechanism. At a minimum, it is another strong indication that quenching, like many other things in galaxy evolution, is driven by processes that apply to nearly all galaxies in similar ways, rather than by a stochastic, environmentally driven quenching mechanism.

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