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Research Status of the Star-Forming Galaxy Main Sequence (Postprint)

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Abstract

Observations have revealed that a tight correlation exists between the star formation rate (SFR) and stellar mass (M_*) of star-forming galaxies (SFGs) (i.e., $\lg \text{SFR} - \lg M_*$, termed the “main sequence relation”), with a scatter of approximately 0.2–0.4 dex. The main sequence relation is of paramount importance for constraining theoretical models of galaxy evolution and constitutes one of the fundamental relations describing galaxy evolution. In recent years, with the rapid development of large-scale observational facilities and data processing techniques, theoretical models of galaxy formation and evolution have become increasingly sophisticated, enabling astronomers to achieve numerous significant advances in the study of the main sequence relation. We first introduce the techniques for measuring galaxy SFR and the methods for selecting SFGs, which facilitates subsequent analysis of the causes of systematic biases in the main sequence relation. We then present the latest observational progress on the main sequence relation: the relation flattens at the high-mass end, possibly due to the transition between cold and hot accretion modes in galaxies/dark halos resulting in reduced cold accretion; the dependence of the main sequence scatter on stellar mass exhibits a U-shaped pattern, likely because stellar feedback at the low-mass end and active galactic nucleus feedback at the high-mass end introduce diversity in the star formation histories of galaxies with comparable stellar masses; and the discrepancy between theoretical and observational zero points of the main sequence relation at intermediate and high redshifts remains highly controversial. Finally, we provide a summary and outlook for research on the main sequence relation.

Full Text

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Research Progress on the Star-Forming Main Sequence

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Abstract

Observations have revealed a relatively tight correlation between star formation rate (SFR) and stellar mass (M_*) for star-forming galaxies (SFGs), expressed as $\log \text{SFR} \propto \log M_*$ and known as the “main sequence,” with a typical scatter of $0.2 \sim 0.4$ dex. The main sequence relation plays a crucial role in constraining theoretical models of galaxy evolution and represents one of the fundamental relationships describing galaxy evolution. In recent years, with rapid advances in observational facilities and data processing techniques, theoretical models of galaxy formation and evolution have become increasingly sophisticated, enabling astronomers to achieve significant progress in understanding the main sequence. We first introduce techniques for measuring galaxy SFR and methods for selecting SFGs, which helps analyze potential systematic biases in main sequence determinations. We then present recent observational progress: the main sequence “flattens” at the massive end, possibly due to a transition between cold and hot accretion modes that reduces cold gas supply; the scatter of the main sequence shows a U-shaped dependence on stellar mass, likely because stellar feedback at the low-mass end and AGN feedback at the high-mass end create diversity in star formation histories among galaxies with similar masses; and the systematic discrepancy between theoretical and observational zero points at intermediate and high redshifts remains controversial. Finally, we summarize and provide an outlook for future research on the main sequence.

Keywords: star-forming galaxies; main sequence; galaxy formation; galaxy evolution

2. Measuring the Star-Forming Main Sequence

The process of deriving the main sequence from observational data involves several key steps. First, raw data must be analyzed to calculate SFR and M_* for galaxy samples. Second, SFGs must be selected from the complete galaxy sample to determine the main sequence relation. Both the determination of galaxy SFR and the selection of SFGs significantly influence the final results [?, ?]. Different methodologies employed in these steps introduce systematic differences that can lead to variations in the derived main sequence, affecting our understanding and interpretation of this fundamental relation.

2.1 Methods for Measuring Galaxy Star Formation Rates

Observational estimates of integrated galaxy SFR rely on spectroscopic data, with several commonly used SFR indicators [?]. The most traditional method utilizes $H\alpha$ emission lines [?, ?]. Young, massive stars produce copious ionizing photons that ionize surrounding gas. Hydrogen atoms emit characteristic lines when transitioning from higher to lower energy levels, including the prominent $H\alpha$ line at $0.656 \mu\text{m}$. The relationship between $H\alpha$ line intensity and ionizing photon rate was established by Osterbrock and Ferland [?], and with a given initial mass function (IMF), this photon rate can be converted to SFR. However, $H\alpha$ -based SFR measurements are highly sensitive to dust extinction, as ionizing photons may be absorbed by dust before ionizing hydrogen atoms, leading to underestimated SFRs. The $H\alpha$ line traces stars formed within the past 10 Myr.

The most direct method employs ultraviolet (UV) observations [?]. Young, massive stars (primarily O and B types) emit strongly in the UV. With a specified IMF, UV radiation can be converted to SFR, making it the most direct probe of star formation. Like $H\alpha$, UV measurements are also susceptible to dust attenuation, which absorbs UV light and leads to underestimated SFRs, requiring dust correction. This method traces stars formed over the past $10 \sim 200$ Myr.

Infrared (IR) observations provide another approach [?, ?]. After UV radiation from young stars is absorbed by interstellar dust, the dust re-emits this energy in the IR. IR observations can therefore infer a galaxy's SFR. However, not all UV photons are absorbed by dust, and the absorption fraction depends heavily on a galaxy's dust content and distribution, making this determination challenging. Assuming complete UV absorption and IR re-emission yields a lower limit on the true SFR. This method traces stars formed over $0 \sim 100$ Myr.

Increasingly, studies combine multiple wavelength measurements (e.g., UV+IR, $H\alpha$ +IR) [?, ?, ?] to account for both dust-affected and dust-free components, providing more accurate SFR estimates. Lutz [?] concluded in a far-IR review that combining far-IR and UV data represents the most effective current method for determining galaxy SFR. Additional techniques using X-ray and radio observations exist but are less common. Spectral energy distribution (SED) fitting methods [?, ?] that incorporate stellar population synthesis models (e.g., BC03 [?]) with parameterized star formation histories represent another approach.

2.2 Methods for Selecting Star-Forming Galaxies

Selecting SFGs to define the main sequence is itself part of the definition process. Several selection methods are commonly employed. Color-based selection is most frequently used observationally, including Lyman-break techniques, B-z versus z-K (sBzK diagram) [?, ?], U-V versus V-J (UVJ diagram) [?, ?, ?, ?, ?], and NUV-r versus r-J (NUVrJ diagram) [?, ?]. The fundamental principles of these methods are described in detail in the 2015 review by Gao et al. [?].

Another approach applies specific star formation rate (sSFR) thresholds, where

galaxies above the threshold are classified as SFGs and those below as quenched galaxies (QGs). These thresholds should vary with redshift in practice. The 2σ -clipping method provides an alternative: given a target functional form for the main sequence, galaxies outside $\pm 2\sigma$ of the fit are iteratively removed. Santini et al. [?, ?] employed this method in their 2009 and 2017 work.

Recent years have seen novel approaches to defining the main sequence. Renzini and Peng [?] identified the main sequence as the higher-SFR ridge line of a bimodal surface function in three-dimensional space of N_g -log SFR-log M_* , where N_g represents galaxy number counts. Sherman et al. [?] in 2021 used the distribution of sSFR across different mass bins to identify SFGs. These new methods generally require large galaxy samples to enable robust statistical studies.

3. The Star-Forming Main Sequence

Characterizing the star-forming main sequence requires at least three fundamental parameters: slope, scatter, and normalization. Consequently, research on the main sequence primarily revolves around these three aspects. We first summarize early understanding of the main sequence before discussing recent advances from four perspectives: the “flattening” phenomenon at the massive end and its underlying mechanisms; studies of the main sequence scatter; systematic offsets between theoretical and observational normalizations and their causes; and efforts to unify observational results.

3.1 Early Understanding of the Main Sequence

Two comprehensive works essentially represent the astronomical community’s basic understanding of the star-forming main sequence prior to 2015. Gao et al. [?] summarized measurements from nearly a decade of research on the main sequence across $0 \leq z \leq 7$. They found slopes ranging from $0.6 \sim 1.0$, with lower-redshift main sequences having shallower slopes and different slopes at low- and high-mass ends. The normalization (at $10^{10} M_\odot$) increased continuously with redshift, particularly dramatically between $z \sim 0 - 2$. The main sequence exhibited moderate scatter of 0.3 dex with little redshift evolution.

Speagle et al. [?] (hereafter S14) in 2014 homogenized 64 observational results from 25 post-2007 studies spanning $z \simeq 0 - 6$ to a uniform scale, then fitted the calibrated data to obtain the best-fit formula for the main sequence at that time. Their goal was to directly compare different observational results to determine the true main sequence and its evolution. They not only precisely determined the evolution of the main sequence but also quantified how different selection criteria affected it. They identified major factors ($> 25\%$ effect) on main sequence determination: choice of IMF, SFR indicator, stellar population synthesis model, star formation history, dust attenuation, extinction law, and SFG selection method. After accounting for these factors and homogenizing some (though others were difficult to quantify precisely), they derived the best-fit relation:

$$\log \text{SFR} = [(0.84 \pm 0.02) - (0.026 \pm 0.003) \times t] \log M_* + [(6.51 \pm 0.24) - (0.11 \pm 0.03) \times t]$$

where t is cosmic age in Gyr, valid for $9.7 < \log M_* < 11.1$ and $0 < z < 6$. After accounting for intrinsic scatter in SFR indicators, they found the true scatter of the main sequence to be ~ 0.2 dex rather than the previously assumed 0.3 dex.

3.2.1 Slope of the Main Sequence

Recent years have seen extensive discussion of the main sequence' s slope variation at the massive end and its underlying mechanisms. Some studies argue for a simple power-law relation ($\log \text{SFR} \propto \alpha \log M_*$) with constant slope across all masses, both at low [?, ?] and high redshifts [?, ?, ?]. However, other studies find the main sequence is not a simple power law: the slope remains constant at low masses but decreases above a characteristic mass M_0 [?, ?, ?, ?, ?], a phenomenon called “flattening” or “bending” at the massive end.

Whitaker et al. [?] in 2014 found that for $0.5 < z < 2$, the main sequence slope depends on stellar mass, being steeper at low masses ($\log \text{SFR} \propto \log M_*$) and flatter at high masses ($\log \text{SFR} \propto (0.3 \sim 0.6) \log M_*$). Schreiber et al. [?] in 2015 similarly observed flattening for massive galaxies ($M_* > 10^{10.5} M_\odot$), with the effect becoming more pronounced at lower redshifts. Lee et al. [?] in 2015 introduced a new fitting function to describe this behavior:

$$\text{SFR}(M_*) = \frac{\text{SFR}_{\max}}{1 + (M_*/M_0)^{-\beta}}$$

where β represents the low-mass-end slope, M_0 the transition mass, and SFR_{\max} the asymptotic SFR at high masses. This parameterization has clear physical meaning and can describe key features of the main sequence. Their fits found $M_0 \sim 10^{10} M_\odot$ ($10^{9.8} \sim 10^{10.3} M_\odot$) at different redshifts, consistent with Tomczak et al. [?]. Recent work by Popesso et al. [?, ?, ?] has also observed bending at the massive end.

Three main explanations have emerged for this phenomenon: morphological effects [?, ?, ?], transition in dark matter halo accretion modes [?, ?, ?], and differences in SFG selection methods [?, ?, ?].

Some studies attribute massive-end flattening to increasing bulge fractions in SFGs. Since bulge stars are generally old and contribute little to star formation, this reduces the specific SFR (sSFR). Abramson et al. [?] performed bulge-disk decomposition on SDSS data and obtained disk sSFR ($\text{SFR}/M_{\text{disk}}$). Fitting galaxies with $M_* > 10^{10} M_\odot$ and bulge-to-total ratios $B/T > 0.6$, they found this treatment increased sSFR for massive galaxies and could alleviate the flattening. Schreiber et al. [?] concurred with this interpretation. Whitaker et al. [?] in 2015 used Sersic indices n as an indirect proxy for bulge fraction to investigate

morphological effects on sSFR. They found galaxies with $n > 2$ (indicating larger bulge fractions) have lower sSFR than the main sequence. The slope dependence on n was weaker at $z \simeq 2$ but strong at $z < 1$, suggesting rapid bulge growth at $z \simeq 2$ when central stars remain young, while at $z < 1$ bulge stars are older, causing steeper slope reduction at the massive end.

However, other studies argue bulge growth is not the primary cause of slope flattening. Schreiber et al. [?] in 2016 used high-resolution HST near-infrared imaging in the CANDELS fields to perform careful bulge-disk decomposition for distant galaxies, obtaining the $\log \text{SFR} - \log M_{\text{disk}}$ relation at $z = 1$. They found the massive-end slope still flattened (see Figure 8 in their paper), concluding that bulge growth is not the main driver at $z = 1$. They also studied the star formation efficiency ($\eta_{\text{SFE}} = \text{SFR}/M_{\text{gas}}$, where M_{gas} is the star-forming gas mass) and found its dependence on M_* could explain the slope change: massive galaxies have not experienced significant M_{gas} reduction, so their lower SFRs result primarily from decreased η_{SFE} .

Popesso et al. [?] in 2019 proposed that massive-end bending results from two processes: bulge growth (driven primarily by frequent mergers, though insufficient alone to explain flattening) and reduced disk SFR caused by hot halo environments leading to cold gas depletion. Since the transition mass where the slope changes ($M_* \simeq 10^{10.5} M_{\odot}$) corresponds to halo masses ($M_h \simeq 10^{12-12.5} M_{\odot}$) near the critical threshold between cold and hot accretion modes, they suggested the slope change might relate to this accretion mode transition. Recent work has supported this hypothesis. Daddi et al. [?] fitted two different observational results [?, ?] using equation (2) to obtain redshift-dependent transition mass M_0 : $M_0 \simeq 10^{10} M_{\odot}$ for $0 < z < 1$, increasing to $\sim 10^{11} M_{\odot}$ at $z = 2$, with slow growth or stabilization at higher redshifts. Converting M_0 to halo mass via the stellar mass-halo mass relation (SHMR) revealed behavior consistent with theoretical predictions for the cold/hot accretion mode transition (Daddi et al. [?] recently found observational evidence for this transition). They concluded that massive-end flattening results from reduced cold accretion and subsequent cold gas supply. Their work also examined morphological effects (bulge fraction B/T), finding most galaxies above M_0 on the main sequence remain disk-dominated ($B/T < 0.4$). Popesso et al. [?] in 2022 similarly found that converting their M_0 to halo mass produced evolution consistent with theoretical cold/hot accretion mode transition predictions (see Figure 2 [Figure 2: see original paper]), concluding that slope flattening occurs because gas entering halos via hot accretion reduces cold gas content, lowering SFRs in massive galaxies and creating the “bending” effect.

Some studies find the massive-end shape depends on SFG selection methods. Donnari et al. [?] in 2019 used IllustrisTNG hydrodynamical simulations ($M_* > 10^9 M_{\odot}$, $0 \leq z \leq 2$) and found that using UVJ color-color diagram boundaries to separate SFGs and QGs produced downward bending at the massive end, indicating lower SFRs compared to other selection methods. Leja et al. [?] in 2021 used recent observations (COSMOS-2015 and 3D-HST) and found different

SFG selection methods produced varying massive-end slopes, demonstrating that selection criteria affect the main sequence shape. Popesso et al. [?] also noted that SFG selection methods influence the massive-end slope.

3.2.2 Scatter of the Main Sequence

The intrinsic scatter of the main sequence reflects diversity in star formation histories among galaxies with similar stellar masses, providing insights into galaxy formation and evolution. However, different studies yield conflicting results, particularly regarding the mass dependence of scatter, $\sigma_{\text{SFR}} - M_*$.

Some studies find constant scatter across stellar mass. For example, Rodighiero et al. [?] and Schreiber et al. [?] using UV-based SFRs found $\sigma_{\text{SFR}} \approx 0.3$ dex (independent of M_*) for $z \simeq 2$ SFGs with $10^9 \sim 10^{10} M_\odot$. Other studies find increased scatter at higher masses: Guo et al. [?] using 12,641 SFGs from COSMOS ($> 10^{9.5} M_\odot$; $0.6 < z < 0.8$) found larger scatter for $M_* > 10^{10.5} M_\odot$. Conversely, some find larger scatter at lower masses, as in Santini et al. [?] and Boogaard et al. [?].

Recent work suggests $\sigma_{\text{SFR}} - M_*$ may follow a U-shaped curve, with increased scatter at both low- and high-mass ends. Willett et al. [?] in 2015 used Galaxy Zoo data ($z < 0.085$) and found scatter increasing from 0.45 dex at $10^8 M_\odot$ to 0.35 dex at $10^{10} M_\odot$, then to ~ 0.5 dex at $10^{11.5} M_\odot$. Davies et al. [?] in 2022 used DEVILS survey data and found U-shaped $\sigma_{\text{SFR}} - M_*$ for $0.1 < z < 0.7$ intermediate-mass galaxies, suggesting the mass of minimum scatter may relate to the transition mass M_0 where the main sequence slope flattens.

Diverse results for scatter are understandable given different redshift ranges and methodological choices in SFR and M_* determination, SFG selection, IMF, and stellar population synthesis models. Despite ongoing controversy about mass and redshift dependence, astronomers have investigated scatter origins [?].

From a theoretical perspective, Katsianis et al. [?] in 2019 used EAGLE simulations and found a U-shaped $\sigma_{\text{SFR}} - M_*$ curve with minimum scatter at $\sim 10^{9.5} M_\odot$, attributing increased scatter at low masses to supernova feedback and at high masses to AGN feedback. Matthee and Schaye [?] in 2019 also used EAGLE simulations to study main sequence scatter origins, finding at $z = 0$ that scatter decreases slightly with increasing M_* . They concluded that scatter arises from both short-timescale fluctuations ($0.2 \sim 2$ Gyr) related to self-regulation of gas cooling, star formation, and outflows, and long-timescale variations (~ 10 Gyr) related to different halo formation times, with short-timescale fluctuations being more important for low-mass galaxies.

Observationally, Saintonge et al. [?] in 2017 used xCOLD GASS data to study galaxy gas content, finding that galaxies above the main sequence have higher gas fractions and shorter gas depletion timescales, suggesting that SFR variations among galaxies of similar mass may result from different gas contents or depletion timescales.

Rodriguez-Puebla et al. [?] approached scatter from another angle, noting that main sequence scatter (~ 0.3 dex) matches the scatter in accretion rates onto halos of the same mass. They combined SHMR and halo accretion rates to predict the distribution of galaxy samples in the $\log \text{SFR} - \log M_*$ plane, seeking consistency with the observed main sequence.

3.2.3 Comparison Between Observations and Theoretical Models

Theoretical models of galaxy formation and evolution can also produce main sequence relations, but many studies find that at intermediate and high redshifts ($0.5 < z < 3$), theoretical main sequences are systematically lower than observations by $0.2 \sim 0.5$ dex [?, ?, ?]. Sparre et al. [?] in 2015 found that for the Illustris simulation, the main sequence matched observations at $z = 0$ and $z = 4$, but fell significantly below at intermediate redshifts ($z = 1$ and $z = 2$). Similar results appear in IllustrisTNG: Donnari et al. [?] in 2019 calculated SFRs averaged over different timescales and spatial extents, finding that at $z = 0$, various SFR calculations were bracketed by observations, indicating good agreement. However, at $z = 0.75$ and $z = 1.75$, all SFR calculations were $\sim 0.2 \sim 0.5$ dex below observations, falling outside the observational range. At higher redshift ($z = 2$), the gap narrowed, with some agreement (see Figure 3 [Figure 3: see original paper]). Furlong et al. [?] in 2015 found EAGLE simulations similarly underpredicted sSFR by $0.2 \sim 0.5$ dex at $z = 1$ and $z = 2$, though the overall evolutionary trend matched observations, just less strongly. Tomczak et al. [?] in 2016 compared observations with Illustris [?] and the semi-analytic model L-Galaxies [?], finding that for $M_* \leq 10^{10.5} M_\odot$ SFGs at $0.5 < z < 2$, observations were ~ 0.4 dex higher than both models, with the gap narrowing to ~ 0.2 dex at higher redshifts. Mitchell et al. [?] in 2014 found the semi-analytic model GALFORM similarly underpredicted the main sequence at $0.6 < z < 3$.

Current research suggests two primary explanations for these systematic differences. First, theoretical models may have deficiencies. Furlong et al. [?] argued that the underprediction of the main sequence at $z \simeq 2$ and the overprediction of the galaxy stellar mass function (GSMF) at similar redshifts stem from similar physical mechanisms, indicating that current models require stronger feedback at $z > 2$. Recent JWST data from Labbe et al. [?] showing unexpectedly massive galaxies at $z > 7$ challenge current theory, demonstrating our incomplete understanding of star formation processes. Second, systematic uncertainties in observational data processing may contribute. Recent studies suggest that applying identical analysis methods to both theoretical and observational data might resolve this long-standing issue [?]. Leja et al. [?] in 2021 used SED-fitting to derive SFRs and a normalization flow method to generate the main sequence, obtaining results $0.2 \sim 0.5$ dex lower than previous work and consistent with theoretical models.

3.2.4 Unification of Measurement Results

As discussed above, different observational studies yield varying main sequence results in slope, scatter, normalization, and their redshift evolution. These differences arise from the many methods and models employed, preventing direct comparison and integration across redshift ranges. S14 pioneered efforts to homogenize scales (see Section 3.1).

Building on S14, Popesso et al. [?] in 2022 (hereafter P22) applied similar methods to an expanded sample covering $10^{8.5} \sim 10^{11.5} M_{\odot}$ and $0 < z < 6$. They extended S14' s dataset to include 78 main sequence results from 20 post-2014 observational papers, collecting approximately 700 uniformly calibrated data points to determine the main sequence and its evolution. Unlike S14, which struggled to fit the local universe and excluded those data, P22 incorporated local universe data based on Popesso et al. [?] (2019), which found similar scatter at low and high redshifts. P22 homogenized IMF, SFR indicators, and cosmological parameters, but not SFG selection methods.

P22 employed two fitting approaches. The first, similar to S14, sought the optimal functional form:

$$\log \text{SFR}(t; \log M_*) = (a_1 t + b_1) \log M_* + b_2 \log^2 M_* + (b_0 + a_0 t)$$

where $a_0 = 0.26 \pm 0.03$, $a_1 = -0.04 \pm 0.01$, $b_0 = -27.58 \pm 0.05$, $b_1 = 4.95 \pm 0.02$, and $b_2 = -0.20 \pm 0.02$. The quadratic term $b_2 \log^2 M_*$, independent of time, differs from S14' s best fit and drives the massive-end flattening together with the linear term $(a_1 t + b_1) \log M_*$. The fitted scatter is 0.06 dex, with amplitude evolution $\propto (1+z)^3$.

The second method used equation (2), fitting in different time intervals to find that both $\log \text{SFR}_{\text{max}}$ and $\log M_0$ depend linearly on time: $\log \text{SFR}_{\text{max}}(t) = a_0 + a_1 t$ and $\log M_0(t) = a_2 + a_3 t$. The final relation (see Figure 4 [Figure 4: see original paper]) is:

$$\log \text{SFR}(M_*; t) = a_0 + a_1 t - \log[1 + (M_*/10^{a_2+a_3 t})^{-a_4}]$$

with $a_0 = 2.62 \pm 0.05$, $a_1 = -0.17 \pm 0.05$, $a_2 = 10.66 \pm 0.01$, $a_3 = -0.042 \pm 0.02$, and $a_4 = 0.98 \pm 0.01$. The best-fit scatter is 0.07 dex, demonstrating this form also provides an excellent description. Since $\beta \approx 1$, they also provided fits with $\beta = 1$ fixed.

4. Summary and Outlook

Over the past decade, advances in observational facilities, data processing techniques, and theoretical simulations have yielded significant progress in understanding the star-forming main sequence.

Controversy about the massive-end shape has largely been resolved: while early work suggested a constant slope, most recent studies favor flattening at the massive end, with the transition mass M_0 increasing with redshift. Explanations have evolved from attributing this to bulge growth within SFGs to the current consensus that transition between cold and hot accretion modes reduces cold gas supply. Methodological differences in main sequence determination also contribute.

Due to varying procedures and definitions, studying main sequence scatter remains challenging, though observations generally find $0.2 \sim 0.4$ dex scatter. Recent work reveals a U-shaped mass dependence, with supernova feedback likely driving increased scatter at low masses and AGN feedback at high masses. Theoretical simulations suggest scatter arises from both short-timescale ($0.2 \sim 2$ Gyr) fluctuations related to gas cooling, star formation, and outflows, and long-timescale (~ 10 Gyr) variations related to halo formation times. Observationally, scatter may connect to molecular gas content and depletion timescales, with galaxies above the main sequence showing higher gas fractions and shorter depletion times.

The long-standing problem of theoretical main sequences being $0.2 \sim 0.5$ dex lower than observations at intermediate and high redshifts ($0.5 < z < 3$) persists across both hydrodynamical and semi-analytic models. Some studies suggest homogenizing analysis methods may resolve this discrepancy, while others indicate model improvements are needed, such as enhanced feedback at higher redshifts to increase gas content and SFR at intermediate redshifts. Future work must also consider gas observations at these redshifts to constrain models and compare with GSMF evolution.

To address methodological differences, S14 and P22 homogenized observational data to reduce systematic errors, though precise quantification of some factors' effects on SFR and M_* determination remains challenging.

Despite substantial progress, further research is needed, particularly observationally. JWST's successful deployment and initial data will revolutionize high-redshift galaxy studies. As observational capabilities improve, SFR and M_* measurements will become more precise. Uniform methods across studies will enable direct comparison and better characterization of the main sequence, providing stronger constraints on theoretical models. Additionally, observations of gas content and the cold/hot accretion mode transition at intermediate redshifts will provide crucial indirect constraints on the main sequence.

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