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Extragalctic Star Formation and Dust Attenuation with Near-IR Hydrogen Emission-Lines

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ABSTRACT

We review recent and future studies of extragalactic star formation rates, star formation histories, and dust attenuation estimates using the near-infrared Paschen and Brackett recombination lines of hydrogen. Paschen and Brackett lines offer "gold standard" star formation measurements, as they are as insensitive to nuisance conditions in the interstellar medium as their Balmer and UV counterparts, yet suffer significantly less from dust attenuation. We also discuss future studies of Paschen and Brackett star formation with the *James Webb Space Telescope* which will offer attenuation-insensitive star formation measurements across cosmic time.

1. INTRODUCTION

Star formation is perhaps the most important mechanism in the behavior and evolution of a galaxy. As such, studies of star formation, on all scales, are at the forefront of modern astrophysics. Recent decades have drastically improved observational means of detecting star formation, though no method is without drawbacks.

The most direct method of measuring a star formation rate (SFR) of a given galaxy or stellar population is by directly counting young, massive stars. We are very limited in the scope of this method given modern instrumentation, and this can only be done beyond the Milky Way for local group objects like the Magellanic Clouds and Andromeda.

There exist several ways of measuring extragalactic SFRs beyond the local group, which require cross-calibration to match with direct star counting. The most common tracers of extragalactic SFR are continuum luminosities in the ultraviolet (UV) or infrared (IR), and UV/optical emission-lines like the Balmer lines of hydrogen.

UV continuum luminosities measure the formation of massive, hot, young ($\lesssim$ 100 Myr) stars, and as such measures recent star formation of a galaxy (Kennicutt & Evans 2012). The IR continuum luminosities trace reprocessed dust emission, usually measured using the emission at 24 μm. Each of these continuum SFR tracers have biases; the UV continuum suffers severely from dust attenuation, and IR emission is difficult to measure and is usually only well measured in more massive galaxies ($M_* > 10^8\ M_\odot$). UV dust attenuation can be, in principle, corrected using the slope of the UV continuum (β), but different attenuation laws and the unknown intrinsic slope make this extremely complicated (Salim & Narayanan 2020). The (partly) attenuation-corrected UV continuum SFR is calculated from Kennicutt (1998) as:

$$SFR_{UV}^{corr}\ [M_\odot yr^{-1}] = (1.09{\times}10^{-10})(10^{0.4A_{280}})\left(3.3\frac{L_{280}}{L_\odot}\right) \quad (1)$$

These issues of dust attenuation and uncertainty in the UV slope are (only partly) remedied further by using a combined UV + IR 'ladder' SFR indicator, which is calculated from Wuyts et al. (2011) as:

$$\mathrm{SFR}_{UV+IR}\ [M_\odot yr^{-1}] = 1.09 \times 10^{-10}(L_{IR} + L_{2800})L_\odot \quad (2)$$

The other primary mode of measuring extragalactic star formation is through emission-line luminosities. The most common of these emission-line SFRs are the Balmer lines of hydrogen, which are in the optical and near-UV. Balmer-line SFRs measure near-instantaneous (< 10 Myr) SFR from the hottest OB stars. The SFR from Hα (λ = 656.3 nm) is calculated from Kennicutt (1998) as:

$$\log(\mathrm{SFR}_{\mathrm{H}\alpha})\ [M_\odot/\mathrm{yr}] = \log(L_{\mathrm{H}\alpha}) - 41.27 \quad (3)$$

Balmer recombination lines have the benefits of being insensitive to conditions in the interstellar medium (ISM) such as metallicity, temperature, and density (Osterbrock 1989). Balmer lines like Hα and Hβ are often bright and easily identifiable, which makes them a valuable tracer of spectral features and SFRs in other galaxies.

Unfortunately, UV/optical emission-line SFR tracers suffer when measuring star formation in moderate to

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highly dusty galaxies. A common method of correcting for this dust attenuation issue with Balmer lines is to use the Balmer decrement, Hα/Hβ, which has a known intrinsic ratio from atomic physics (Hα/H$\beta = 2.86$) (Osterbrock 1989). When dust is present, the near-UV Hβ (λ = 486.1 nm) is attenuated more severely than the optical Hα, causing the measured Balmer decrement to exceed the intrinsic ratio. This measurement can then be used to correct SFRs for dust attenuation using an attenuation law like Calzetti et al. (2000).

This almost solves the problems of dust attenuation in measurements of extragalactic SFRs. The catch comes in moderate to highly dusty galaxies where these corrections like the Balmer decrement become biased due to significant attenuation in both Hα and Hβ. For example, Hα flux is halved at a modest attenuation of $A_V = 1$, and reduced by a factor of $\sim$10 in a dusty galaxy with $A_V = 3$, assuming a Calzetti et al. (2000) attenuation law. The Balmer decrement can fail completely in regions where the ISM is optically thick to Hβ emission.

These problems can be remedied by introducing the 'gold standard' of SFR indicators, the Paschen and Brackett recombination lines of hydrogen (Kennicutt & Evans 2012). These lines of hydrogen are well-deserving of such high praise, since they offer the same benefits of being insensitive to ISM conditions like UV/optical lines, but suffer significantly less from dust attenuation than the UV continuum or UV/optical emission-lines. The Paschen series ($n_f = 3$) and the Brackett series ($n_f = 4$) are both in the near-IR, which means they can trace star formation in regions optically thick to UV and optical indicators.

Figure 1 shows continuum A_V measurements against stellar mass for galaxies in the 3D-HST and CLEAR surveys of *HST* (Skelton et al. 2014; Momcheva et al. 2016; Cleri et al. 2020). This visualization details what kinds of galaxies suffer from use of only UV/optical emission-lines and UV and IR continuum SFR indicators. Dusty galaxies suffer serious issues from attenuation of UV/optical tracers and experience highly biased and uncertain conventional attenuation estimates. Low-mass galaxies suffer from lack of IR detections, so the Wuyts et al. (2011) UV + IR "ladder" SFR cannot be used to correct for the attenuation biases of the UV continuum. The gray region represents these dusty or small galaxies which will be insufficiently measured using only UV/optical SFR tracers, but can be well-measured by near-IR emission.

Paschen and Brackett lines can also be used to estimate dust attenuation, much like the Balmer decrement. For example, taking the ratio of Paα/Hα can offer an emission-line attenuation measure which is less susceptible than the Balmer decrement to biases in moderate to extremely dusty galaxies, due to the use of the longer-wavelength Paschen lines.

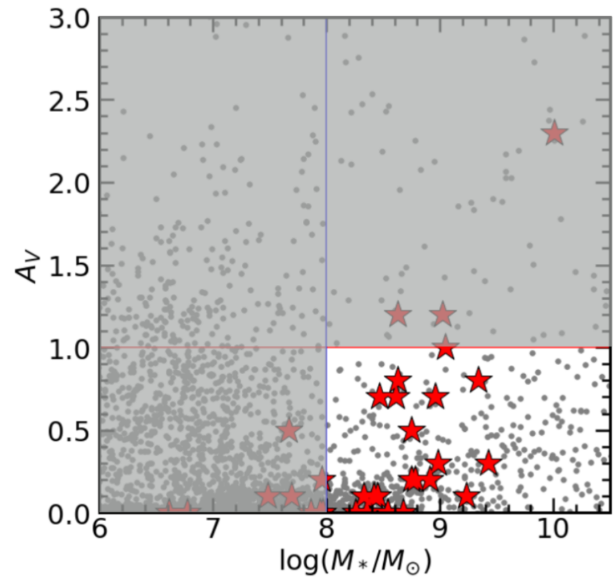

Figure 1. Continuum A_V-stellar mass relation for objects in 3D-HST galaxies (gray points) and Paβ -detected CLEAR galaxies (red stars). The grayed-out region represents galaxies which are either too dusty to be well detected by UV/optical tracers or too low-mass to have well-detected IR luminosities. Using Paschen and Brackett SFRs allows us to probe star formation in regions hidden to other tracers.

In this work, we will review studies of extragalactic star formation with near-IR Paschen and Brackett recombination lines. These studies have become increasingly more prevalent in the era of near-IR spectroscopy in space-based telescopes such as the *Hubble Space Telescope* (*HST*), and will grow by orders of magnitude with the next generation of spectroscopy with the *James Webb Space Telescope* (*JWST*).

The remainder of this work is as follows. Section 2 reviews studies of Paschen-line star formation. Section 3 reviews studies of Brackett-line star formation. Section 4 discusses future studies of extragalactic star formation with Paschen and Brackett lines in the era of *JWST*. Finally, Section 5 will conclude with remarks on the state of extragalactic star formation measurements.

2. EXTRAGALACTIC PASCHEN-LINE STAR FORMATION

The Paschen series represents the $n_f = 3$ lines of the hydrogen spectrum, lying in the near-IR with the longest wavelength Paα (λ = 1875 nm) and the Paschen limit at (λ = 820.4 nm). In this section we will discuss several

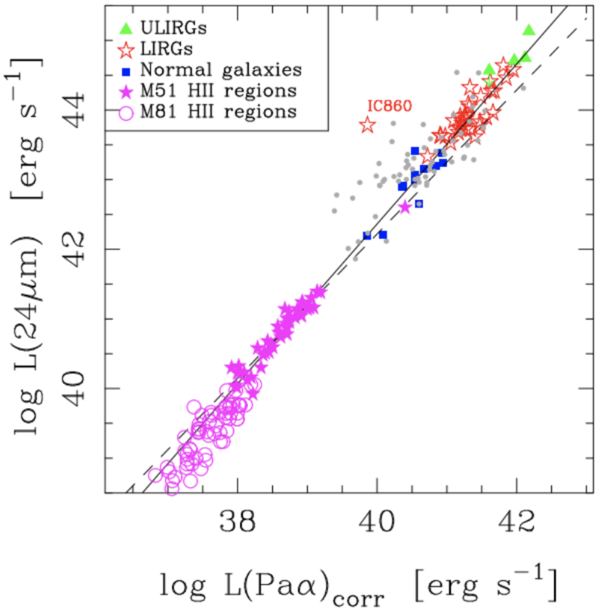

Figure 2. From Alonso-Herrero et al. (2006). The relation between 24 μm and attenuation corrected Paα luminosities for 30 local luminous IR galaxies. Paα is well-correlated with the IR emission, meaning that both are valuable tracers of attenuation-insensitive SFRs.

studies of Paschen-line star formation and dust attenuation.

With current instrumentation, detailed spectroscopy of Paschen-line star formation is limited to relatively low-redshift galaxies. *HST* G141 grism and NICMOS data have been used to study small samples of relatively local Paschen-emitting galaxies.

One such work, Alonso-Herrero et al. (2006), studies Paα emission in a representative sample of 30 local luminous infrared galaxies (LIRGs). As Figure 2 shows, the Paα emission in these LIRGs is consistent with well-correlated with the 24 μm IR luminosities, indicating that both IR luminosity and Paα are valid tracers of attenuation-insensitive SFRs.

Alonso-Herrero et al. (2006) also introduce attenuation-correction of SFRs by using the Paα/Hα ratio. This offers a distinct benefit over more traditionally used nebular attenuation indicators like the Balmer decrement, in that Paα can "see" star formation in regions optically thick to Balmer lines. This means that a near-IR to UV/optical attenuation indicator is better suited for measuring attenuation in moderate to extremely dusty galaxies, where measures like the Balmer decrement see significant optical depth to both Hα and Hβ .

Another work, Cleri et al. (2020), studies a 32 galaxy sample of Paβ -emitting galaxies in the CLEAR survey of *HST* (Estrada-Carpenter et al. 2019). From this study we see another valuable product of near-IR SFRs: when compared to longer-timescale SFR indicators such as the UV continuum, we can find attenuation-insensitive star formation histories (SFHs). The CLEAR data show burstier star formation at lower stellar mass, consistent with previous work Guo et al. (2016); Weisz et al. (2014); Broussard et al. (2019).

Several other small sample studies of star formation with the Paschen lines have been conducted in the literature. Studies have used the Paα emission line to calibrate mid-IR SFR indicators in nearby starburst galaxies (Calzetti et al. 2007) and in rare lensed galaxies at higher redshift (Papovich et al. 2009; Finkelstein et al. 2011; Shipley et al. 2016). Paβ and Hα SFRs and attenuation have also been studied in a 2 galaxy sample in Kessler et al. (2020).

3. EXTRAGALACTIC BRACKETT-LINE STAR FORMATION

The Brackett series represents the $n_f = 4$ lines of the hydrogen spectrum, lying in the near-IR with the longest wavelength Brα ($\lambda = 4051$ nm) and the Brackett limit at ($\lambda = 1458$ nm). In this section we will discuss several studies of Brackett-line star formation and dust attenuation.

In a similar manner to the Paschen-line SFR studies discussed in Section 2, several studies of Brackett-line star formation have shown that the near-IR Brackett recombination lines are valuable attenuation-insensitive SFR tracers. One such work, Pasha et al. (2020), studies a sample of 21 Brγ ($\lambda = 2.16$ μm)-detected galaxies from the TripleSpec instrument on the Palomar 200-inch telescope to show Brγ as yet another direct tracer of recent star formation which has the added benefit of being considerably less attenuated that its UV/optical counterparts.

As shown in Figure 4, the Brγ luminosities of these 21 galaxies correspond directly with the UV-derived 30 Myr SFRs, showing that Brγ directly traces recent star formation, all while retaining insensitivity to dust attenuation.

Other Brackett-line star formation studies have shown similarly these results. One such work, Ho et al. (1989), studies four galaxies with spatially-resolved Brα and Brγ measurements from the NASA Infrared Telescope Facility on Mauna Kea. These detections show bursty star formation in the nuclei of these galaxies, which demonstrates another use of near-IR emission-line SFRs, and the nuclei of galaxies are often far too attenuated to be well measured by UV/optical tracers.

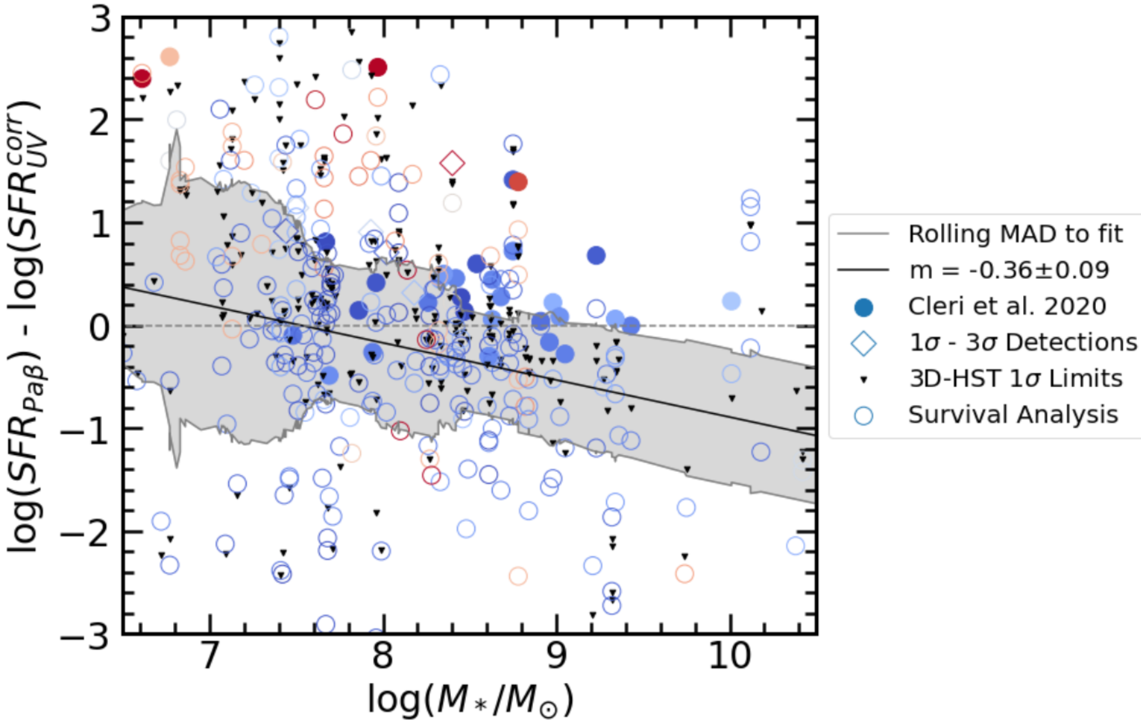

Figure 3. From Cleri et al. (2020). A survival analysis of the relation of the log ratio of Paβ SFRs to UV continuum SFRs to mass for Paβ detections and non detections in the CLEAR survey of *HST*. We can use the scatter of the ratios of Paschen-line SFRs and continuum SFRs (gray envelope) to measure star formation histories which are insensitive to attenuation, a major issue for SFH estimates according to prior work Guo et al. (2016); Weisz et al. (2014); Broussard et al. (2019).

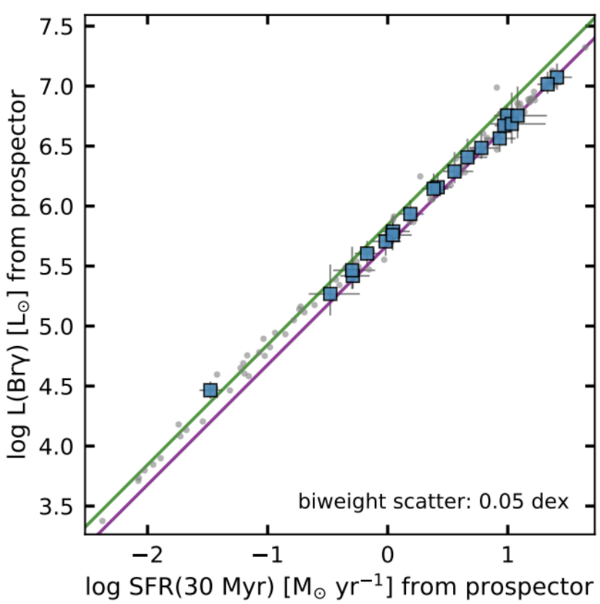

Figure 4. From Pasha et al. (2020). The relation between Brγ luminosities and UV-derived 30 Myr SFRs for 21 local galaxies observed using the TripleSpec instrument on the Palomar 200-inch telescope. The Brγ luminosities correlate tightly with the 30 Myr SFRs, showing that Brγ can be used as another attenuation-insensitive recent SFR tracer.

4. FUTURE STUDIES OF NEAR-IR STAR FORMATION

These discussions of Paschen and Brackett star formation have shown great usefulness, but are severely limited by current instrumentation. The largest samples of these types are of order $\sim$30 galaxies, not large enough to make decisive changes to the ways we measure star formation as a whole. With new IR sensitivity from next-generation instruments, we will have access to samples of orders of magnitude larger than these.

The *James Webb Space Telescope* (*JWST*) will be a veritable gold mine for these "gold standard" SFR indicators Kennicutt & Evans (2012). The near to mid-IR sensitivity of *JWST* are carried by three primary instruments NIRCam, giving slitless grism spectroscopy as a blind census to all galaxies in a pointing, with 3-4 μm coverage. NIRSpec, a more traditional micro-shutter array (MSA) spectrograph, giving detailed slit-like spectroscopy to galaxies which fall on an open shutter, with 1-5 μm coverage. MIRI, which will give lower-resolution spectroscopy in a wide range of wavelengths (4-28 μm). The combination of these three instruments will drastically increase the sensitivity to Paschen and Brackett emission in a much greater redshift range.

The first data products of *JWST* will come in mid 2022 from the Early Release Science (ERS) programs. One already approved ERS program is the Cosmic Evolution Early Release Science (CEERS) Survey, which overlaps with the already well-studied CANDELS EGS field.

A prospective sample of Paα and Paβ detected galaxies using NIRCam grism and NIRSpec measurements is shown in Figure 5. The combined sample of NIRCam and NIRSpec detections is of order ∼500 galaxies, representing better than an order of magnitude increase over the largest Paschen-line star formation studies with *HST* (Cleri et al. 2020; Alonso-Herrero et al. 2006). This sample also covers a much greater redshift range (0 ¡ z ¡ 2.9) than previous studies which were limited to very low redshift (z ¡ 0.3) galaxies.

This new era of *JWST* will bring with it many answers to the mysterious questions about the farthest reaches of the universe. High-redshift star formation has always served problematic to measure, and the IR capabilities of *JWST* will soon give much more reliable spectroscopy in these earliest galaxies.

Incredibly, the NIRCam and NIRSpec observations will already give attenuation-insensitive star formation measurements all the way to $z \sim 3$ with Paα and Paβ . When considering the mid-IR capabilities of MIRI, *JWST* will have the sensitivity to detect Brackett-lines to a ridiculous $z \sim 6$, within 1 Gyr of the Big Bang.

The combination of these measurements will give deep insight to the history of cosmic star formation, detailed in Figure 6. NIRCam and NIRSpec will give Paschen line SFRs at the peak of cosmic star formation at $z \sim 2$, while MIRI will give Brackett line SFRs to much earlier times, where the cosmic star formation history is still highly uncertain (Finkelstein 2016).

5. CONCLUSION

We have discussed various studies of extragalactic star formation using the near-IR Paschen and Brackett lines of hydrogen. These "gold standard" SFR indicators are insensitive to ISM parameters, like their Balmer counterparts, but do not suffer significantly from interstellar dust attenuation. The major results of this review are as follows:

- More commonly used SFR indicators, namely the Balmer lines and UV and IR continuum luminosities, suffer several issues. Balmer/UV emission is highly sensitive to attenuation, and IR emission is well-detectable only in high-mass galaxies. Using near-IR hydrogen recombination lines gives reliable star formation measurements in these galaxies which otherwise cannot be well measured by more common SFR tracers.

- Paschen and Brackett lines offer near-instantaneous (¡10 Myr) SFRs while maintaining insensitivity to attenuation. This allows us to compare Paschen or Brackett SFRs to longer timescale SFR tracers, such as the UV continuum, to measure attenuation-insensitive star formation histories.

- We can use ratios of near-IR lines to optical lines as a dust attenuation indicator which is more accurate than the Balmer decrement at measuring attenuation in moderate to highly dusty galaxies. The Balmer decrement loses efficacy at high optical depth to Hα and Hβ emission.

- Future studies of Paschen and Brackett emission with *JWST* will give attenuation-insensitive SFRs across most of cosmic time. Paschen-line SFRs will be well detectable at cosmic noon, in samples an order of magnitude larger than the largest Paschen-line studies to date. Brackett lines will be detectible with MIRI at very high redshifts ($z \sim 6$), offering attenuation-insensitive insight into the earliest galaxies.

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This work made use of the following software:

Software: linmix (Kelly 2007), `grizli` (Brammer et al. 2008) Astropy (Astropy Collaboration et al. 2013), Matplotlib (Hunter 2007)

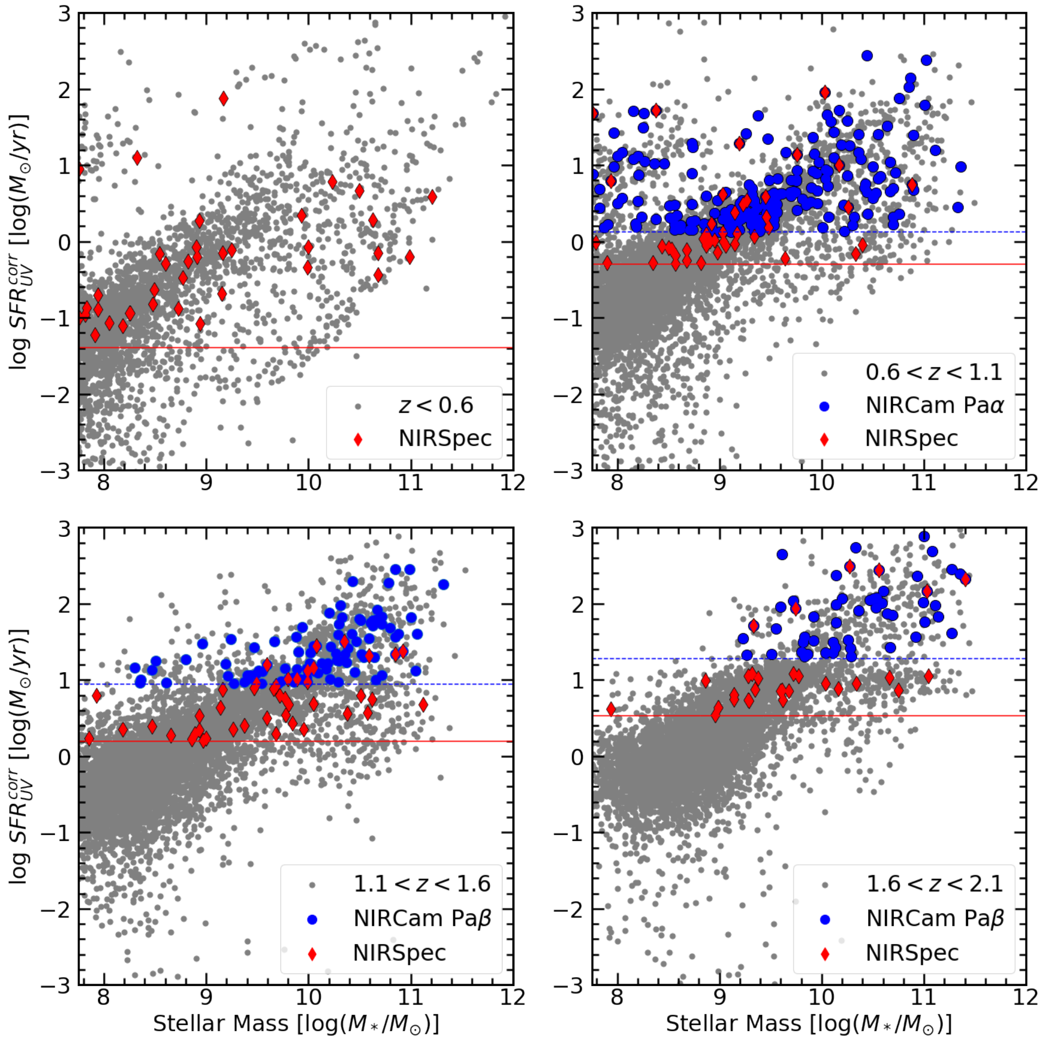

Figure 5. Star-formation mass relation of CANDELS EGS galaxies, with colored points indicating the projected sample of Paschen-line galaxies detected by CEERS spectroscopy. We anticipate ∼400 NIRCam grism detections and ∼150 NIRSpec detections based on the CEERS spectroscopic limits and field of view. The red and blue lines represent the SFR detection limits for NIRSpec and NIRCam grism detections respectively.

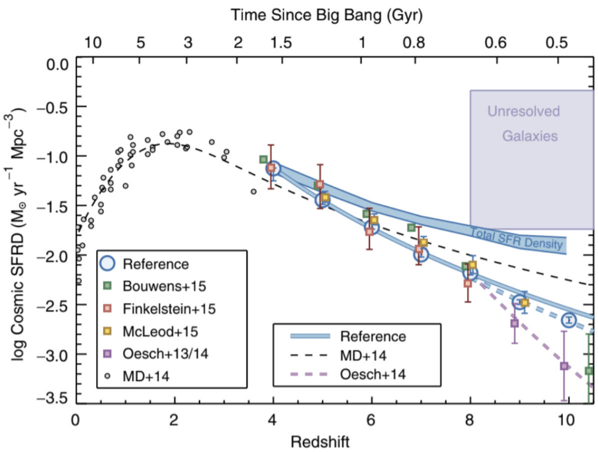

Figure 6. From Finkelstein (2016). The evolution of the cosmic star formation rate density. The peak of cosmic star formation occurs at $z \sim 2$, with declining SFR density to higher redshifts, where the behavior of the power-law relation becomes more uncertain. The advent of *JWST* data will give Paschen and Brackett line SFRs at a wide range of redshifts, all the way to $z \sim 6$, within 1 Gyr of the Big Bang. These new data will serve to answer many questions about the earliest galaxies.

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