The Next Generation Deep Extragalactic Exploratory Public (NGDEEP) Survey

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Abstract

We present the Next Generation Deep Extragalactic Exploratory Public (NGDEEP) Survey, a deep slitless spectroscopic and imaging Cycle 1 JWST treasury survey designed to constrain feedback mechanisms in low-mass galaxies across cosmic time. NGDEEP targets the Hubble Ultra Deep Field (HUDF) with NIRISS slitless spectroscopy ($f_{lim, line,5\mu m} \approx 1.2 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2}$) to measure metallicities and star formation rates (SFRs) for low-mass galaxies through the peak of the cosmic SFR density ($0.5 < z < 4$). In parallel, NGDEEP targets the HUDF-Par2 parallel field with NIRCam ($m_{lim,5\mu m} = 30.6 - 30.9$) to discover galaxies to $z > 12$, constraining the slope of the faint end of the rest-ultraviolet luminosity function. NGDEEP overlaps with the deepest HST Advanced Camera for Surveys optical imaging in the sky, F435W in the HUDF ($m_{lim,F435W} = 29.6$) and F814W in HUDF-Par2 ($m_{lim,F814W} = 30$), making this a premier HST+JWST deep field. As a survey team, NGDEEP data...
are public immediately, and we will rapidly release data products and catalogs in the spirit of previous deep-field initiatives. In this paper we present the NGDEEP survey design, summarize the science goals, and detail plans for the public release of NGDEEP reduced data products.

**Unified Astronomy Thesaurus concepts:** Early universe (435); Galaxy formation (595); Galaxy evolution (594); Galaxy chemical evolution (580)

### 1. Introduction

Deep-field observations push astronomical source detection to the faintest accessible limits. They are often motivated by the wish to discover, count, and study the most distant objects. Deep fields also survey the faintest objects detectable at intermediate distances, constraining luminosity functions and other statistical properties of the evolving galaxy population.

Although the Hubble Space Telescope (HST) Hubble Deep Field (HDF) may be the most iconic early deep field, it was not the first such observation. Astronomers took deep images of “blank” high-latitude fields using photographic plates (e.g., Kron 1978; Koo 1981) and CCDs (e.g., Tyson & Jarvis 1979) and at radio wavelengths (e.g., Windhorst et al. 1985). Measuring and analyzing faint galaxy number counts was a popular pastime, motivated in part by cosmological goals, but also providing evidence for the evolution of galaxies with cosmic time and distance. Observations through two or more filters led to the recognition of the abundant population of “faint blue galaxies” as further evidence for an evolving galaxy population (Koo & Kron 1992; Ellis 1997), and measurements with three or more filters were used to estimate galaxy redshifts (Koo 1985) and to identify very distant galaxy candidates via distinctive color signatures caused by the redshifted Lyman break (Guhathakurta et al. 1990; Steidel & Hamilton 1992).

The first HDF (Williams et al. 1996) was conceived as a public survey with nonproprietary data products available to any researcher. The HDF data were indeed widely used by the community and catalyzed extensive follow-up imaging and spectroscopy from ground- and space-based observatories, which further enriched the resources of widely available data to study galaxy evolution. The HDF was later observed with HST’s near-infrared (NIR) camera NICMOS (Thompson et al. 1998, 1999; Dickinson et al. 2000), detecting redshifted optical rest-frame light from galaxies out to \( z \approx 3 \) and extending the wavelength baseline for photometric redshift and spectral energy distribution (SED) analysis. The installation of a more sensitive Advanced Camera for Surveys (ACS; Clampin et al. 2000) during the second Hubble servicing mission motivated a Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006), with subsequent infrared follow-up with NICMOS (Thompson et al. 2005), the HUDF parallel program (Oesch et al. 2007), and later with the more sensitive WFC3 (Kimble et al. 2008) infrared channel (Oesch et al. 2010; Ellis et al. 2013; Illingworth et al. 2013; Koekemoer et al. 2013). The deep infrared data were used to identify and study galaxies with photometric redshifts as high as \( z \approx 12 \) (e.g., Bouwens et al. 2011a; Ellis et al. 2013; Oesch et al. 2013; Bouwens et al. 2016).

Space observatories (e.g., Chandra, ISO, Spitzer, and Herschel) conducted their own deep-field programs at X-ray and mid- to far-infrared wavelengths, typically in fields already surveyed by Hubble and ground-based facilities, including the HDF and the HUDF. HST itself revisited its deep fields many times, including deep observations using slitless spectroscopy with ACS and WFC3 to measure redshifts and other spectral properties for faint objects without spectroscopic preselection, including GRAPES and FIGS (PIDs 9793, 13779; PI S. Malhotra; Pirzkal et al. 2004; Malhotra et al. 2005; Rhoads et al. 2009; Pirzkal et al. 2017).

The potential of JWST (Gardner et al. 2023) deep fields was evident immediately in Cycle 1 with the Early Release Observation of the galaxy cluster and gravitational lens SMACS 0723.3–7327 (PID 2736; PI: K. Pontoppidan; Pontoppidan et al. 2022). The GLASS-JWST Early Release Science Program (PID 1324; PI: T. Treu; Treu et al. 2022) observed the A2744 lensing galaxy cluster, obtaining spectroscopy on the cluster with deep parallel imaging that reaches a 5σ point-source depth of \( \sim 30.2 \) mag in \( \sim 15.7 \) hr (Paris et al. 2023). The JADES (PID 1180, PI: D. Eisenstein, Eisenstein et al. 2017; PID 1210, 1286, 1287, PI: N. Luetzgendorf, Ferruit & Rieke 2017; Ferruit et al. 2017; Ferruit et al. 2017) and MIRI Deep Imaging Survey (MIDIS; PID 1283; PI: H. U. Nørgaard-Nielsen and G. Östlin; Nørgaard-Nielsen & Perez-Gonzalez 2017) GTO Programs are continuing the legacy of deep imaging and spectroscopy in and around the HUDF. Together the imaging portions of these early programs have easily detected galaxy candidates out to \( z \approx 16 \) (e.g., Robertson et al. 2023b; Adams et al. 2023; Castellano et al. 2022; Donnan et al. 2023; Harikane et al. 2023; Naidu et al. 2022; Atek et al. 2023; Pérez-González et al. 2023), while the spectroscopic portions of the programs are confirming galaxies from \( z \sim 7 \) to 13 (e.g., Curtis-Lake et al. 2023; Roberts-Borsani et al. 2022; Schaerer et al. 2022). These and other Cycle 1 surveys represent only the beginning of the deep-field science made possible by JWST’s great leap in sensitivity and exquisite angular resolution.

Here we present the Next Generation Deep Extragalactic Exploratory Public (NGDEEP; PID 2079; PIs: S. Finkelstein, C. Papovich, N. Pirzkal) Survey, which follows in the footsteps of previous treasury deep fields, probing a well-studied blank region of the sky, and providing data to the community with no proprietary period. NGDEEP leverages JWST’s parallel observation capabilities to obtain two deep fields for the price of one. NGDEEP primary observations are composed of deep NIRISS wide-field slitless spectroscopy (WFSS; Doyon et al. 2012; Willett et al. 2022; Doyon et al. 2023) covering the HUDF proper (Beckwith et al. 2006). At the same time, NGDEEP obtained deep NIRCam imaging (Rieke et al. 2003, 2005, 2023) in parallel covering the HUDF05-02 parallel field. We refer to these two observations as NGDEEP-NIS and NGDEEP-NRC, respectively.

NGDEEP is designed to illuminate the processes regulating galaxy evolution across cosmic time. Galaxy evolution is the result of a complex interplay between gas accretion from the cosmic web, the cooling and conversion of dense gas into stars, pollution of the interstellar medium (ISM) with heavy elements, and stellar- and black-hole-driven feedback processes that can disperse heavy elements into the circumgalactic medium (CGM) and intergalactic medium (IGM). Feedback

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35 This program was originally named WDEEP in our Cycle 1 proposal.
from massive stars and supernovae is a crucial element in regulating galaxy formation and shaping observable properties of galaxies, including their stellar mass, star formation history, gas fraction, metallicity, and morphological structure (Somerville & Davé 2015, and references therein). Yet the physical details of feedback remain highly uncertain.

Current cosmological simulations cannot calculate the feedback processes directly; thus, they make assumptions that differ significantly from one simulation to another (e.g., Somerville & Davé 2015). Gaining insights into how feedback works requires constraining the observables that are the most sensitive to these divergent assumptions. This task includes testing the inflows and outflows of heavy elements through observations of the mass–metallicity relation, measuring the amplitude and timescales of star formation, and constraining star formation efficiency in galaxies.

Together, both the primary NGDEEP-NIS and parallel NGDEEP-NRC observations will constrain the mechanisms regulating feedback in low-mass galaxies. At $z \sim 1–3$, NGDEEP-NIS has obtained spectroscopy of the diagnostic emission lines in these $m_{AB} \sim 28$ mag galaxies, leveraging the multiplexing of NIRISS WFSS to measure signal-to-noise ratio ($S/N > 3$) emission lines of over 2000 (1500) galaxies (see Section 2.3). These observations will enable (1) measurements of multiline metallicities for >350 galaxies at $z \sim 0.5$–4 down to log$(M_*/M_\odot) \sim 7$, testing predictions for the low-mass slope of the mass–metallicity relation (MZR) where models currently diverge (e.g., Ma et al. 2016); and (2) measurements of Hα-based star formation rates (SFRs) for $\sim 1000$ low-mass galaxies at $0.7 \lesssim z \lesssim 2.3$ to $\sim 0.1 M_\odot$ yr$^{-1}$, matching the UV SFR limit from the ultradeep HDF F435W image. This will quantify the level of and constrain the effects of the stochasticity of SFRs in galaxies $100 \times$ lower in mass than the best NIR spectroscopic surveys (Kriek et al. 2015; Shivaei et al. 2015).

At $z > 9$ low-mass galaxies are predicted to be $\sim 30$ mag and are only accessible by deep NIRCam imaging; thus, NGDEEP-NRC will probe the population of faint galaxies ($M_{UV} = -17.5, 10\sigma$) out to the highest redshifts ($z \sim 10$–15), constraining the faint (low-mass) end of the rest-UV luminosity (stellar mass) function via the discovery of $\sim 100$ galaxies at $z > 10$ and up to 10 galaxies at $z \gtrsim 14$. This unique combination of NIRISS prime spectroscopy and NIRCam parallel imaging will provide in-depth insight into galaxy evolution across cosmic time.

In this paper we present the NGDEEP survey, including its design, scientific motivation, and presurvey predictions. In Section 2 we present the survey design, field orientation, and observing timeline, describing the NGDEEP NIRISS (NGDEEP-NIS) and NIRCam (NGDEEP-NRC) observations in Sections 2.3 and 2.4, respectively. As part of the survey design and verification process, we performed end-to-end simulations for both observations, which we present in Section 3. We discuss the leading science cases for NGDEEP-NIS in Section 4 and for NGDEEP-NRC in Section 5. Finally, we outline our timeline for the public release of NGDEEP data products in Section 6 and briefly summarize in Section 7. We express all magnitudes in the AB system (Oke & Gunn 1983) unless otherwise noted.

2. Survey Design

In this section, we describe the design of the NGDEEP survey and the capabilities of each set of observations.

2.1. Field Choice and Orientation

We center the NGDEEP-NIS observations on the HUDF to fully exploit the large investment of HST observations. Imaging with HST/ACS B band (F435W) reaches a limiting depth of $m_{AB,F435W} = 29.6$, sufficient to detect galaxies with UV-based SFRs to $\sim 0.1 M_\odot$ yr$^{-1}$ at $z \sim 2$, which matches the NIRISS Hα SFR limit of the NGDEEP-NIS observations. Extremely deep WFC3/IR imaging in the same region provides critical constraints on the stellar masses of the star-forming galaxies (to log$(M_*/M_\odot) \sim 7.3$ at $z = 2$). These data in the HUDF are the deepest available. The separation between NIRISS and NIRCam on the JWST field of view is similar to that of WFC3 and ACS, placing our coordinated parallels on the HUDF05-02 parallel field (HUDF-Par2; Oesch et al. 2009; Bouwens et al. 2011b). This field has been observed repeatedly with ACS, while NICMOS and WFC3 observed the HUDF (Stiavelli 2005; Illingworth 2009), building the deepest F814W imaging on the sky ($m_{AB,F814W} = 30.0$). While NIRCam alone can select $z > 9$ galaxies, these candidates will be strengthened by nondetections in this ultradeep optical image, which covers $\gtrsim 50\%$ of our deepest NIRCam data, and the deep F814W data also allow dropout selection to $z \sim 7$–9.

In addition to the HST imaging mentioned above, the HUDF has been covered by extensive observations from both ground- and space-based observatories. Spitzer/IRAC imaging at 3.6, 4.5, 5.8, and 8.0 μm covers GOODS-S to average 5σ depths of $\sim 27.0, 26.6, 23.9$, and 23.9, respectively (Dickinson et al. 2003; Ashby et al. 2013; Labbé et al. 2013; Ashby et al. 2015; Labbé et al. 2015; Stefanon et al. 2021).

The region is covered by observations with the Atacama Large Millimeter Array (ALMA; Walter et al. 2016; Dunlop et al. 2017; Hatsukade et al. 2018), the Very Large Array (VLA; Kellermann et al. 2008; Rujopakarn et al. 2016), Chandra (Xue et al. 2011; Luo et al. 2017), and XMM-Newton (Comastri et al. 2011), as well as integral field spectroscopy with MUSE on the Very Large Telescope (Bacon et al. 2017, 2023). GOODS-S has also already been observed several times with JWST/NIRCam broadband and medium-band imaging, including JADES, JADES Origins (PID 3215; PIs: D. Eisenstein, R. Maiolino; Eisenstein et al. 2023), MIDIS, the Systematic Mid-infrared Instrument Legacy Extragalactic Survey program (SMILES; PID 1207; PI: G. Rieke), and the JWST Extragalactic Medium-band Survey (JEMS; PID 1963; PIs: C. Williams, M. Maseda, S. Tacchella; Williams et al. 2023), as well as NIRSpec multijobject and NIRCam wide-field slitless spectroscopy (e.g., JADES; the First Reionization Epoch Spectroscopic Complete Survey (FRESCO); PID 1895; PI: P. Oesch; Oesch et al. 2023). The majority of these deep observations are focused on the HUDF, but many also cover the HUDF-Par2 field. This is far from an exhaustive list of the programs that have observed in GOODS-S, but just a few examples of the abundance of multiwavelength data available to support the NGDEEP science goals.

Centering the NIRISS primary data on the HUDF and placing NIRCam on HUDF-Par2 results in an observatory V3 position angle $V_{3,PA} = \sim 70°$. We obtain the NIRISS WFSS with both the row (R) and column (C) grisms to provide two-orient observations. However, based on our trade studies, simulated spectroscopy, and previous work in the literature (Pirzkal et al. 2004; Ryan et al. 2018), an additional position angle separated by $\sim 3°$ will significantly improve the contamination modeling, emission-line identification, and map reconstruction without
sacrificing the spatial coverage of the HUDF. However, splitting the observations across two position angles results in less area covered at total depth for NIRCam. We therefore limit the difference in position angle to $\Delta (V3\_PA) = 3^\circ$, the minimum acceptable for NIRISS without sacrificing full-depth coverage for NIRCam. Therefore, each source in the HUDF is observed in four distinct position angles ($V3\_PA = 67^\circ, 70^\circ, R$ and C grism).

In Figure 1, we present a visualization of the NGDEEP-NIS and NGDEEP-NRC field centroids and orientations. The figure also provides a summary of some of the existing HST data sets overlapping the NGDEEP observations.

**2.2. NGDEEP Epochs 1 and 2**

The strict position angle requirements for NGDEEP result in a limited window of $\sim 10$–16 days during which the program can be scheduled. Unfortunately, on 2023 January 20, NIRISS experienced an unexpected software timeout. All primary and coordinated parallel NIRISS observations were temporarily suspended while the observatory and instrument teams diagnosed the problem. When NIRISS observations resumed 10 days later, there was not enough time to observe the entire program before the NGDEEP observing window closed on February 6. Instead, all observations from a single position angle ($V3\_PA = 70^\circ$) were obtained in the remaining time (2023 January 31–February 3). This Epoch 1 of NGDEEP includes all grisms and filters but half of the total integration time for both instruments. Epoch 2 ($V3\_PA = 67^\circ$) was observed 2024 January 23–24 and January 30–February 1, during which the other half of the imaging and grism data were obtained. In Sections 2.3 and 2.4, we present the sensitivity and limiting magnitude estimates that correspond to the total program time.

**2.3. NGDEEP-NIS Observations**

The NGDEEP observations obtained in the HUDF with NIRISS (NGDEEP-NIS) provide deep $R \sim 150$ spectroscopy over 1–2.2$\mu$m. The spectra will detect emission lines from $>1000$ galaxies, many with multiple lines, down to a limiting emission-line flux of $(1.2–1.5) \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ ($5\sigma$). This not only is much deeper than previous HST grism surveys (e.g., Momcheva et al. 2016; Pirzkal et al. 2017) but also extends the...
upper end of the wavelength range covered from 1.7 to 2.2 μm (Figure 3).

Multiline diagnostics for metallicity and dust content require sampling [O II], [O III], Hβ, and Hα. NGDEEP-NIS obtained F115W, F150W, and F200W spectroscopy in order to examine the redshift evolution of these metrics (1.6 < z < 2.5). As mentioned above, we obtain spectroscopy in both the R and C grisms, as well as at two PAs separated by 3° (V3_PA = 67°, 70°). The grism exposures were obtained with the NIS readout pattern, 20 groups per integration and six integrations per exposure (eight integrations for F150W). We used a three-point dither pattern optimized for NIRISS-NIRCam coordinated parallel observing. We summarize the observation setup in Table 1.

Table 1: NGDEEP Observation Sequences

<table>
<thead>
<tr>
<th>Filter/Grism</th>
<th>Specification</th>
<th>Exptime (s)</th>
<th>NGDEEP-NRC</th>
<th>Specification</th>
<th>Exptime (s)</th>
<th>Dithers</th>
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<tr>
<td>F115W Imaging</td>
<td>NIS/5/1</td>
<td>225</td>
<td>F115W/F356W</td>
<td>SHALLOW4/4/1</td>
<td>204</td>
<td>1</td>
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<td>F115W/GRISMR</td>
<td>NIS/20/6</td>
<td>15654</td>
<td>F115W/F444W</td>
<td>MEDIUM8/7/7</td>
<td>15525</td>
<td>3</td>
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<tr>
<td>F115W Imaging</td>
<td>NIS/5/1</td>
<td>902</td>
<td>F115W/F356W</td>
<td>SHALLOW4/4/1</td>
<td>816</td>
<td>4</td>
</tr>
<tr>
<td>F115W Imaging</td>
<td>NIS/5/1</td>
<td>15654</td>
<td>F115W/F444W</td>
<td>MEDIUM8/7/7</td>
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<td>3</td>
</tr>
<tr>
<td>F115W Imaging</td>
<td>NIS/5/1</td>
<td>676</td>
<td>F115W/F356W</td>
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<tr>
<td>F150W Imaging</td>
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<tr>
<td>F150W/GRISMR</td>
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<td>20872</td>
<td>F150W/F277W</td>
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<td>F150W/F356W</td>
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Notes. Observation sequences for Epoch 2 NGDEEP-NIS and NGDEEP-NRC, including the NIRISS imaging filter or WFSS filter/grism pair, the NIRCam short wavelength channel (SWC) and long wavelength channel (LWC) filters, the specification for each instrument (listed as readout pattern/groups per integration/integrations per exposure), the number of dithers, and the exposure time including dithers. The F115W sequence is observed three times.

* The NIRISS observing sequence consists of one direct image, three dithers with the R grism, four direct images, three dithers with the C grism, followed by another three direct images. The second and third sets of direct images include the extra dithers with offsets designed to maximize coverage of objects with spectra.

* The NIRCam observing specification listed is that of Epoch 2. The deep NGDEEP-NRC observations from Epoch 1 have the same exposure times but use DEEP8 with four groups and seven integrations (F115W/F444W, F200W/F356W) or five groups and seven integrations (F150W/F277W).

The total exposure times for the F115W, F150W, and F200W spectroscopy are 190, 86, and 63 ks, respectively. Based on 1D outputs from the JWST Exposure Time Calculator (ETC, v2.0) and optimal extractions of our simulated NGDEEP-NIS observations (see Section 3.1), NGDEEP-NIS will reach (1.2–1.5) × 10−18 erg s−1 cm−2 (5σ). Pirzkal et al. (2023) demonstrate that the Epoch 1 NIRISS WFSS observations (NGDEEP-NISS1, or the NGDEEP NIRISS Infrared Slitless Survey1) have achieved this targeted sensitivity for the first epoch of data. This sensitivity limit allows us to measure metallicities at ~0.2 dex precision down to log(M/M⊙) = 7 at z = 2 (see Section 4). We present the NGDEEP-NIS total exposure times and line sensitivities in Table 2. These observations include direct imaging in the F115W, F150W, and F200W filters with total exposure times of 10.8, 3.6, and 3.6 ks, reaching MAB = 29.5, 29.0, and 29.1 (3σ), respectively, deep enough to identify the faint continuum of contaminating sources. We use two extra dithered direct images to maximize the number of sources with first-order spectra and imaging coverage at full depth. Our NGDEEP-NIS simulations (Section 5) demonstrate we will detect emission lines (≥3σ) in >1000 galaxies (see Table 3 and Pirzkal et al. 2023). The NIRSpec GTO team targets this field with NIRSpec (PI: N Luetzgendorf; PID 1210), and examination of their prelaunch APT file finds that ~80 objects in the HUDF will receive slits with t = 8 ks. Early results from these GTO observations are already revealing the exquisite sensitivity of JWST spectroscopy, with spectroscopic confirmations of four galaxies at z > 10 (Robertson et al. 2023b; Curtis-Lake et al. 2023). NGDEEP will expand this legacy, with >1000 galaxies receiving 60–190 ks spectroscopic integrations.

Table 2: NGDEEP Line Sensitivities and Limiting Magnitudes

<table>
<thead>
<tr>
<th>Filter</th>
<th>Exposure Time (hr)</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGDEEP-NIS</td>
<td>(erg s⁻¹ cm⁻²)</td>
<td></td>
</tr>
<tr>
<td>F115W</td>
<td>52.2</td>
<td>1.2 × 10⁻¹⁸</td>
</tr>
<tr>
<td>F150W</td>
<td>34.8</td>
<td>1.3 × 10⁻¹⁸</td>
</tr>
<tr>
<td>F200W</td>
<td>17.4</td>
<td>1.5 × 10⁻¹⁸</td>
</tr>
<tr>
<td>NGDEEP-NRC</td>
<td>(AB mag)</td>
<td></td>
</tr>
<tr>
<td>F115W</td>
<td>53.9</td>
<td>31.2</td>
</tr>
<tr>
<td>F150W</td>
<td>23.0</td>
<td>30.9</td>
</tr>
<tr>
<td>F200W</td>
<td>18.0</td>
<td>30.9</td>
</tr>
<tr>
<td>F277W</td>
<td>22.3</td>
<td>30.9</td>
</tr>
<tr>
<td>F356W</td>
<td>20.8</td>
<td>30.8</td>
</tr>
<tr>
<td>F444W</td>
<td>51.8</td>
<td>30.7</td>
</tr>
</tbody>
</table>

Note. Estimates for NGDEEP-NIS 5σ integrated emission-line sensitivities and NGDEEP-NRC 5σ resolved-source limiting magnitudes are from v2.0 of the JWST ETC. These estimates are based on the full survey depth.

Table 3

Expected Emission-line Counts in NGDEEP-NIS

<table>
<thead>
<tr>
<th>Line or Index</th>
<th>Number (3σ)</th>
<th>Number (5σ)</th>
<th>Redshift Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any line</td>
<td>2266</td>
<td>1601</td>
<td>...</td>
</tr>
<tr>
<td>Lyα λ1216</td>
<td>6</td>
<td>1</td>
<td>7.22–17.09</td>
</tr>
<tr>
<td>Mg II λ2796, 2804</td>
<td>40</td>
<td>19</td>
<td>2.57–6.87</td>
</tr>
<tr>
<td>[O II] λ3727, 3730</td>
<td>464</td>
<td>307</td>
<td>1.68–4.90</td>
</tr>
<tr>
<td>[Ne III] λ3870</td>
<td>40</td>
<td>8</td>
<td>1.58–4.68</td>
</tr>
<tr>
<td>Hβ λ4863</td>
<td>289</td>
<td>162</td>
<td>1.06–3.52</td>
</tr>
<tr>
<td>[O III] λ5008</td>
<td>837</td>
<td>618</td>
<td>1.00–3.39</td>
</tr>
<tr>
<td>Hα λ6565</td>
<td>965</td>
<td>676</td>
<td>0.52–2.35</td>
</tr>
<tr>
<td>[S II] λ6718, 6732</td>
<td>156</td>
<td>96</td>
<td>0.49–2.27</td>
</tr>
</tbody>
</table>

Number of Galaxies with Δz < 0.2 dex

| z > 1 | 361 |
| z > 2 | 275 |
| z > 3 | 98  |

Note. Number of emission lines (or robust multiline metallicities) in our end-to-end NGDEEP-NIS simulations at 3σ and 5σ significance, using the JADES galaxy mock catalog as input (see Section 3.1). We note that the Lyα predictions depend on the assumed IGM attenuation and may be underestimated, as several Lyα detections at z > 7 have already been confirmed (e.g., Vanzella et al. 2011; Castellano et al. 2018; Jung et al. 2020; Tilvi et al. 2020; Jung et al. 2022; Larson et al. 2022). Note that wavelengths are in rest-frame vacuum. Doublets will be blended.

2.4. NGDEEP-NRC Observations

The NGDEEP observations obtained in the HUDF-Par2 field with NIRCam (NGDEEP-NRC) provide deep imaging from ~1–5 μm. Imaging in F115W+F150W+F200W samples below the Lyα break and the rest-UV continuum for galaxies at z > 9. We simultaneously observe with F277W+F356W+F444W to sample the SED at longer wavelengths (rest-UV and optical for z > 9) and to minimize sample contamination from lower-redshift galaxies based on the SED shape in the range 1–5 μm. The NIRCam observations will enable the discovery of ~30–100 galaxies at z ≥ 11 and constrain the faint end of the rest-UV luminosity function (UVLF), where stellar feedback model predictions differ the most. NGDEEP-NRC will also constrain black hole formation and probe the morphological transformation of galaxies. We discuss the main NGDEEP-NRC science goals in Section 5.

The NIRCam strategy is set by the primary NIRISS observations, though we distribute the integration time to achieve approximately uniform sensitivity (30.7–30.9 mag; 5σ) in all filters. We increase the time in F115W (and F444W simultaneously) to detect <0.3–0.4 mag Lyα breaks at our limit of m = 30.7–30.9. These data will allow for a robust selection of galaxies at 9 < z < 13 that are detected in >4 filters (>2 mag deeper than CEERS and up to 0.1–0.5 mag deeper than the JADES GTO Program). The individual planned exposure times were ~5.1 ks (F115W, F200W, F356W, and F444W) and ~6.7 ks (F150W, F277W) with the DEEP8 readout, four groups per integration (five for F150W, F277W), and seven integrations per exposure. Images taken in parallel to NIRISS direct imaging have t = 150 s using SHALLOW4 readout to allow for three groups. However, the Epoch 1 NGDEEP-NRC imaging is ~0.1–0.5 mag shallower than expected (see Leung et al. 2023, for details). At the time of this writing, while we are still investigating the cause of this issue, we suspect that images taken with the DEEP8 readout mode and several groups (four to five for NGDEEP-NRC) suffer from poor ramp fitting and jump detection, leading to increased pixel-to-pixel noise. We therefore updated our strategy for Epoch 2 to use MEDIUM8 with seven groups (nine for F150W, F277W), achieving the same exposure time while better sampling the ramps. The final exposure times are 60–84 ks (F150W, F200W, F277W, and F366W) and 170–180 ks (F115W and F444W). We estimate depths with the ETC, assuming expected resolved sizes (FWHM ∼ 0.07 at m = 30.6; Kawamata et al. 2018).

The combination of imaging at two position angles separated by 3° results in tiers of depth in the NGDEEP-NRC mosaic. We present the anticipated area as a function of depth in the left panel of Figure 2, where these depth tiers are evident as a set of step functions for the NGDEEP observations. All six bands are observed in the deepest tier to at least 30.7 mag. The filters F150W, F200W, and F277W will reach 30.9 mag, and F115W will achieve a depth of 31.2 mag. At an area of 5 arcmin², NGDEEP-NRC is expected to be comparable in depth to the deepest tier of JADES in F150W, F200W, F277W, and F356W. However, NGDEEP-NRC is ∼0.3 mag deeper than JADES36 in the important F115W ∼ 10 dropout filter (194 ks over our deepest 5 arcmin² compared with 143 ks for JADES), allowing robust candidate galaxy selection to the limiting magnitude in the redder filters. NGDEEP-NRC will also be ∼0.5 mag deeper in F444W (186 ks compared with 94 ks), a crucial filter for limiting contamination by low-redshift objects. JADES is shown as the dotted lines in Figure 2.

MIDIS, operated by the MIRI European Consortium Team, is also obtaining deep observations with MIRI on the HUDF. Their parallel NIRCam imaging includes 55 ks of integration for F115W, F150W, F277W, and F356W. We note that three of the four planned visits were observed in 2022 December, with the final visit observed in 2023 December. Additionally, one of the three visits was observed at a slightly different position angle. As a result, the current set of publicly available MIDIS NIRCam observations include 55 ks in F115W +F277W and 28 ks in F150W+F356W, reaching depths of m ∼ 30.0–30.2 in all filters and m ∼ 30.7 in F277W. There is an area of ∼8 arcmin² in common between the two filter sets, ∼3.7 arcmin² of which overlaps with the NGDEEP-NRC footprint. Early results from Pérez-González et al. (2023) have identified 45 new, faint z > 8 candidates, highlighting the potential offered by the increased depth and filter coverage that NGDEEP-NRC brings to this region. While each program is impressive on its own, the depth achieved in the areas of overlap will be unprecedented among HST and JWST Cycle 1 observations. Following the NGDEEP Epoch 2 observations and the public release of the MIDIS NIRCam imaging, we plan to create combined NGDEEP-NRC+MIDIS mosaics. These mosaics will cover a total area of ∼18.5 arcmin² to a depth of z ≥ 31.2 mag in the ∼2 arcmin² of deepest overlap.

Based on the predictions of a range of models, NGDEEP-NRC will discover ∼50–100+ galaxies at z ∼ 10 and up to 60, 25, 12, and 10 galaxies at z ∼ 11, 12, 13, and 14–15, respectively. As shown in Figure 8, the expected constraints

36 NGDEEP versus GTO Programs: We derived JADES and MIDIS exposure times and depths directly from their APT files, assuming 5σ resolved sources for comparison with NGDEEP-NRC depths. Our estimates of the depths differ in places from the summaries in Williams et al. (2018; JADES) and Pérez-González et al. (2023; MIDIS), which are calculated for point sources.
on the faint end of the UVLF are significantly tighter than the predicted abundances from models with varied stellar feedback mass-loading factors. We discuss these model predictions and the constraining power afforded by NGDEEP-NRC observations in Section 5. In Section 3.2, we also demonstrate that NGDEEP-NRC’s $\sim 2$ mag increase in depth compared to CEERS is essential to detect galaxies at $z = 10–13$.

3. NGDEEP Simulated Observations

We performed a careful evaluation of the feasibility of NGDEEP using a complete set of end-to-end simulations for both the primary and parallel observations. We used the Multi-Instrument Ramp Generator\textsuperscript{37} (MIRAGE) to generate mock NGDEEP observations for both JWST instruments. The simulations are based on the NGDEEP APT file and so reproduce the filters, grisms, exposure specifications, dither patterns, and position angles of the planned observations. These simulations include realistic noise, sky background structure, and all known instrument-dependent (e.g., bad pixels, cross talk, etc.) and scene-dependent (e.g., variation in dispersed background, object morphology, crowding) effects for the NIRISS WFSS and NIRCam imaging. We reduced and analyzed these data in exactly the same way we plan to do with using real data. We describe each set of simulations in the following subsections.

3.1. NGDEEP-NIS Simulations

As input to the NIRISS WFSS simulations we used the JADES catalog (Williams et al. 2018), which provides morphological and spectroscopic data. The resulting input catalogs and spectra were used in conjunction with an APT observing plan and the simulation software MIRAGE to produce individual uncalibrated NIRISS imaging and WFSS exposures. We therefore produced a set of rate files with dithers and readout mode that were the same as our proposed observations. Spectra from the WFSS rate files were then extracted using the Simulation Based Extraction (SBE) method, following closely the methodology described in Pirzkal et al. (2018). Combined GRISMR and GIRSMC 1D spectra, wavelength and flux calibrated, were produced and served to check our expected $S/N$, and we stress that our simulations include as detailed as possible treatment of all the known instrumental effects and of the observing strategy. We show an example of our simulated WFSS observations in Figure 3. This figure also shows the extracted spectra for a source as seen by the GRISMR and GRISMC grisms.

3.2. NGDEEP-NRC Simulations

For the mock NIRCam observation inputs, we used a modified version of the ultradeep simulated light cone presented by Yung et al. (2022). The galaxies therein are simulated using the Santa Cruz semianalytic model (SAM; Somerville et al. 2015; Yung et al. 2019a, 2019b; Somerville et al. 2021), with dark matter halos extracted from the IllustrisTNG-100 dark-matter-only simulation (Nelson et al. 2019) and Monte Carlo merger trees constructed based on the extended Press–Schechter formalism (e.g., Somerville & Kolatt 1999; Somerville et al. 2008). The SAM incorporates the evolution of a variety of physical processes, such as cosmological accretion, cooling, star formation, chemical enrichment, and stellar and active galactic nucleus (AGN) feedback. See Yung et al. (2022) for a concise summary of the internal workflow of the SAM and light-cone construction. The free parameters in the SAM are calibrated to a subset of observed constraints at $z \sim 0$, and the model performance at high redshift has been tested extensively and shown to well reproduce a wide variety of observed constraints (Yung et al. 2019a, 2020a, 2021).

The predicted star formation and chemical enrichment histories of each mock galaxy are coupled with synthetic stellar SEDs from Bruzual & Charlot (2003) and are forward-modeled into rest-frame and observed-frame photometry in the NIRCam filters, accounting for ISM dust (Calzetti et al. 2000) and IGM extinction (Madau et al. 1996). Each synthetic SED

\textsuperscript{37} mirage-data-simulator.readthedocs.io

Figure 2. Left: the area covered in each NGDEEP-NRC filter as a function of $5\sigma$ depth measured for resolved sources. The solid lines denote the full survey (Epochs 1 and 2 covering both position angles), and the dashed line shows the depth and area coverage achieved in Epoch 1 ($V_3, PA = 70^\circ$) for F277W as an example. The dotted lines show the depths that will be achieved by the JADES deep-field observations in the HUDF once the survey is completed. While JADES covers a larger area, NGDEEP-NRC will go $\sim 0.5$ mag deeper in F444W and $\sim 0.3$ mag deeper in F115W, allowing for the detection of $z > 9.5$ Ly$\alpha$ breaks in galaxies at the detection limit in F150W, F200W, and F277W. As a treasury program, NGDEEP will also be public immediately, providing the community the opportunity to explore a JWST deep field right away in Cycle 1. Right: exposure time maps in $10^3$ s for each of the six NGDEEP-NRC filters. The overlapping position angles, NIRISS filter FWHM-dependent direct imaging dithers, and short-wavelength detector gaps result in the multiple depth tiers that are present in the left panel.
also includes nebular emission lines simulated based on the predicted contributions of young stars, AGN, and post-asymptotic giant branch (AGB) stellar populations (Hirschmann et al. 2017, 2019, 2023, Yung, Hirschmann, Somerville et al. 2024, in preparation). The mock catalog contains galaxies out to $z \sim 12$ and is complete to $m_{F200W} \sim 34$. The SAM mock galaxies also provide simulated Sérsic profiles (Sérsic 1963; Sérsic 1968), with Sérsic indices and effective radii determined as described in Brennan et al. (2015).

We supplemented this galaxy mock catalog with three additions. First, we injected $\sim 20$ galaxies at redshifts 11–15, with NIRCam filter magnitudes pulled from the SAM extended Press–Schechter catalogs, providing us with realistic photometry for these high-redshift galaxies. We placed these additional sources randomly in the NGDEEP-NRC footprint with the goal of evaluating the expected recovery rate of galaxies with $m < 30$ and $z > 12$, should they exist in the real field. Next, we included postage stamps of extended sources with realistic morphologies derived from both the VELA (Simons et al. 2019) and SIMBA (Davé et al. 2019) simulations. The VELA simulated sources were included to test the recovery of faint, extended structures such as streams and tidal features, and the SIMBA simulated sources provided tests of morphological measurements of substructures such as spheroids, disks, and clumps.

The full NGDEEP-NRC simulation includes 1400 simulated images (140 exposures each with 10 NIRCam detectors). We created raw images with MIRAGE and reduced them using the JWST Calibration Pipeline (Bushouse et al. 2023). We show an example of our simulated NIRCam observations in Figure 4, which highlight the ability of these data to identify very high redshift galaxies fainter than 30th magnitude.

4. NGDEEP-NIS Science Cases: Star Formation, Enrichment, and Feedback at $z = 0.5$–4

4.1. Constraining Feedback via the Low-mass End of the Mass–Metallicity Relation

A fundamental probe of galaxy evolution is the stellar mass versus gas-phase metallicity relation (MZR; e.g., Tremonti et al. 2004; Maiolino et al. 2008). The MZR is thought to result from the general growth of galaxies over time, where they increase both their stellar mass and the abundance of metals produced but are also sensitive to competing feedback processes. Figure 5 shows the expected tight, positive MZR for NGDEEP-NIS. The MZR slope, normalization, and intrinsic scatter are shaped by galaxy feedback processes, where metals are created by star formation, ejected by outflows, and diluted by gas infall (Tremonti et al. 2004; Zahid et al. 2014). Further, the MZR is observed to exist out to at least

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38 https://archive.stsci.edu/prepds/vela/

39 jwst-pipeline.readthedocs.io
Figure 4. Full simulated NGDEEP-NRC F277W 22.3 hr mosaic, displaying the footprint of the proposed observations, including all instrumental effects and sensitivities. The main input for this simulation is the ultradeep Santa Cruz SAM light cone (Yang et al. 2022). The central inset zooms in on a 10″2 region, demonstrating the increase in depth compared with CEERS. On the upper left we show composite NGDEEP-NRC images of $z = 1.5$ and $z = 3$ galaxies from the VELA simulation (Simons et al. 2019), with faint tidal features (indicated by white dashed lines) clearly detected in the planned exposure times. By resolving low-mass galaxies at early times, NGDEEP will probe a new frontier in galaxy assembly. On the lower left we show 2 galaxies, again compared with CEERS imaging, highlighting the power of NGDEEP-NRC imaging to detect extended emission and complicated morphologies are evident in all generated from the SIMBA simulation covering an observed range of $1.0 < z < 3.4$.

Simulations predict the MZR in detail (e.g., Davé et al. 2011; Torrey et al. 2014) but show significant tension. As depicted in the right panel of Figure 5, different state-of-the-art models predict staggeringly different redshift evolution of the MZR slope at low masses; predictions vary by more than 0.3 dex in $d \log Z / d \log M_\odot$. Progress requires robust metallicity measurements in low-mass galaxies across a range of redshifts.

NGDEEP-NIS will obtain NIRISS slitless spectroscopy covering an observed range of 1.0–2.2 μm with the sensitivity to detect emission lines as faint as $\sim 10^{-18}$ erg s$^{-1}$ cm$^{-2}$. This will enable the measurement of galaxy gas-phase metallicities using well-calibrated rest-frame optical emission-line diagnostics from $R_{23} \equiv ([\text{O II}] \lambda 3727 + [\text{O III}] \lambda 5008)/\text{H}\beta$ at $1.7 < z < 3.4$ and $\text{Ne}\text{III} \equiv [\text{Ne III}] \lambda 3868/\lambda 3727$ to $z < 5$ (e.g., Maiolino & Mannucci 2019). While most MZR studies only probe the most massive galaxies in targeted surveys, NGDEEP-NIS will measure metallicities for an unbiased galaxy sample (i.e., no preselection) with stellar masses of $\log M_\odot / M_\odot \gtrsim 7$ at these redshifts. Recently, Li et al. (2023) used stacks of JWST observations of 55 $z \sim 2–3$ galaxies to reveal our first glimpse of the evolution of the MZR out to cosmic noon. This work hints at a shallower slope for low-mass galaxies ($M_\odot < 10^9 M_\odot$), possibly due to the dominance of different feedback processes in the low-mass regime. NGDEEP-NIS will significantly increase the sample size of low-mass galaxies on the MZR at cosmic noon, allowing us to discern any turnover resulting from varying feedback sources.

Figure 5 shows the MZR (slope, normalization, and scatter) from our NGDEEP-NIS simulations using $R_{23}$, showing constraints to $\lesssim 0.2$ dex across our mass range. Comparing to simulation predictions, the NGDEEP-NIS MZR will place stringent empirical constraints on the appropriate feedback prescriptions that should be incorporated into models. Joint constraints on the low-mass end of the stellar mass function and the MZR can constrain the mass-loading factors of stellar- and AGN-driven winds and test whether feedback is ejective or preventative, thereby constraining the energy content of winds. NGDEEP-NIS measurements of the MZR will thus provide critical benchmarks for the next generation of galaxy formation simulations in and after the JWST era.

4.2. Constraints on Bursty Star Formation from Rest-UV and Hα Measurements

A powerful capability of NGDEEP-NIS is that it combines NIRISS measurements of the Hα recombination line for galaxies at $0.7 < z < 2.3$ with rest-UV measurements from HUDF ACS F435W (the deepest B-band imaging anywhere on the sky, $m_{54}=29.6$; Illingworth et al. 2013). Figure 6 shows that the NIRISS Hα line flux limit is well matched to the ACS
Figure 5. Understanding the details of the MZR is fundamental for theories of galaxy evolution. Left: arrows show that (1) metal abundance increases with the nucleosynthetic yields of star formation, (2) accretion of metal-poor gas both dilutes metals and can trigger star formation, and (3) outflows remove enriched gas with an efficiency that is inversely proportional to the galaxy gravitational well. The purple line and swath show the MZR and its scatter measured from synthetic NIRISS spectra, derived from our simulations: NGDEEP will significantly extend the MZR mass coverage by ~2 dex. Right: the diversity in the evolution of the MZR slope predicted by simulations with different assumptions about feedback (with color scheme as in the left panel); NGDEEP will measure this slope and scatter and thereby constrain the physics of feedback.

rest-UV limit: both will detect SFRs from galaxies down to 0.22 (0.04) $M_{\odot}$ yr$^{-1}$ at $z = 2$ ($z = 1$). With NGDEEP-NIS we will make a first measurement of the stellar mass–SFR relation down to $\log M_*/M_\odot = 7$ at $z = 1–2$.

These NGDEEP-NIS SFR observations will provide diagnostics on the stochasticity of star formation, another strong probe of feedback. The amplitude and characteristic timescale of star formation variability are a test of state-of-the-art cosmological hydro simulations that implement star formation and feedback differently (Iyer et al. 2020), where increased star formation efficiency and stronger feedback produce more stochastic star formation (Hopkins et al. 2018). The H$\alpha$ emission and UV emission are sensitive to different star formation timescales: the UV continuum is emitted by massive (OB) stars and probes star formation variations on $\sim 100$ Myr timescales; H$\alpha$ emission requires ionization from the most massive (O) stars and probes 5–10 Myr timescales (Kennicutt & Evans 2012). Observations of H$\alpha$ and UV SFRs are therefore sensitive to stochasticity and bursts, the effects of which are strongest in lower-mass galaxies (Weisz et al. 2012; Broussard et al. 2019).

With NGDEEP-NIS we will combine the H$\alpha$ emission from NIRISS and rest-UV from ACS to study star formation variability in low-mass galaxies ($\log M_*/M_\odot \approx 7$) at 0.7 $< z < 2.3$. NGDEEP-NIS enables the measurement of the scatter in these SFRs for galaxies above a fixed SFR and stellar mass, achieving results for galaxies 10× fainter than previous work (MOSDEF; see Figure 7; Shivaei et al. 2015), where theory predicts that the SFR scatter is more pronounced (Sparre et al. 2017; Iyer et al. 2020). The right panel of Figure 6 shows that we are able to recover the intrinsic SFR scatter $\sigma = 0.45$ for H$\alpha$ and 0.3–0.35 for the UV for our simulated data set. If the real difference between the H$\alpha$ and UV SFR scatter is larger than predicted by models, then it would imply that stronger ejective feedback is needed to regulate star formation in low-mass systems. However, to measure this accurately will require simulations using the NGDEEP-NIS data to determine accurate emission-line flux limits as a function of redshift and surface brightness, which we will execute in a dedicated study of the SFR variability. Regardless, NGDEEP-NIS is the only survey sensitive enough to measure SFRs to these limits in both H recombination lines and UV continua for galaxies at $z \approx 1–2$.

We note that several factors will affect the H$\alpha$-derived SFRs. This includes [N II] contamination to the H$\alpha$ emission, dust extinction, and possible presence of AGN. First, the H$\alpha$ and [N II] lines are blended at the resolution of the NIRISS WFSS spectra ($R \sim 150$), and so we will use the relation between [N II]/H$\alpha$ flux and stellar mass presented by Faisst et al. (2018) to derive intrinsic H$\alpha$ fluxes. This relation is calibrated up to $z = 2.5$, fully encompassing the redshift range probed by NGDEEP-NIS observations. However, the [N II] contamination does increase the uncertainties on the H$\alpha$ fluxes.

Second, we will explore both the UV spectral slope ($\beta$) and the Balmer line ratios to correct the H$\alpha$ fluxes for extinction. Early results of Balmer line ratios from the NGDEEP NIRISS spectra are presented in Pirzkal et al. (2023), and Matharu et al. (2023) present similar measurements of NIRISS spectra from the CAnadian NIRISS Unbiased Cluster Survey (CANUCS; PID 1208; PI: C. Willott). We refer the reader to these works for a full discussion of the subtleties involved in this analysis.

Third, studies using NGDEEP may identify AGN either through multiwavelength catalogs (e.g., X-ray, radio) or through the analysis of emission-line ratios. For example, using the NGDEEP data set, Shen et al. (2024) identified star-forming galaxies at 0.5 $< z < 3$ that are flagged as AGN candidates by Lyu et al. (2022) using the X-ray, mid-/far-IR, and radio data available in the field. Similarly, Pirzkal et al. (2023) identified AGN at these redshifts using a “mass-excitation” (MEx) diagram, which identifies AGN candidates based on their [O III]/H$\beta$ ratio as a function of their stellar mass. The MEx method has been tested and validated at the redshifts targeted by NGDEEP-NISS (see Juneau et al. 2011, 2014; Coil et al. 2015; Backhaus et al. 2022). These
methods provide a means to identify AGN in star-forming galaxy samples.

### 4.3. Physical Conditions of Galaxies in the HUDF

The unbiased nature of the NIRISS slitless spectroscopy means that the data probe every galaxy in the HUDF. This will enable additional science for galaxies beyond that articulated here. This includes galaxies with additional diagnostic lines (see Table 3), such as rest-UV spectra of faint galaxies at $z > 4$. For example, the rest-frame UV hosts a number of high-ionization emission lines (e.g., N IV $\lambda\lambda$1483, 1487, He II $\lambda$1640, O III $\lambda\lambda$1661, 1666, N III $\lambda$1750, C III $\lambda\lambda$1907, 1909) that can help characterize the radiation field hardness of reionization-era galaxies. Further, detections of any combination of these C, N, and O lines will place important constraints on their relative abundances, varying nucleosynthetic production via core-collapse supernovae and AGB stars and, subsequently, their star formation histories (e.g., Jones et al. 2023). Additionally, similarly to Ly$\alpha$, the Mg II $\lambda\lambda$2796, 2804 lines are resonant transitions originating from low ionization energies (7.6–15.0 eV) that sensitively probe the amount of neutral gas along the line of sight. Any Mg II detections would thus indicate low neutral column densities favorable to the escape of ionizing radiation (e.g., Henry et al. 2018; Chisholm et al. 2020). Therefore, the data set here has a legacy value with which to study galaxies in this JWST+HST deep field.

### 5. NGDEEP-NRC Science Cases: A Public and Parallel Deep Survey toward First Light

NGDEEP parallel NIRCam imaging aims to achieve $m_{AB,5\mu m} = 30.7 \pm 0.4$ from 1 to 5 arcmin over 5 (11) arcmin$^2$, on the deepest F814W imaging in the sky ($m_{AB,5\mu m} = 30.0$). These data will allow some of the first robust constraints on galaxy formation at $z > 10$. Public NGDEEP-NRC data will enable immediate community-led deep-field legacy science up to magnitudes comparable to or deeper than proprietary GTO NIRCam surveys, all coming in parallel at essentially no added observational cost.

### 5.1. Physical Processes Regulating the Emergence of the First Galaxies

Over the first 500 Myr of cosmic time ($z > 10$) galaxies began to coalesce, enriching and ionizing their environments, altering subsequent gas accretion and star formation. HST has only scratched the surface with just a handful of $z \sim 9$–11 (mostly) tenuous candidates (McLeod et al. 2015; Oesch et al. 2018; Bouwens et al. 2019; Bagley et al. 2024; Finkelstein et al. 2022a). Prior to JWST, the number of faint galaxies ($M_{UV} < -17$) found by different surveys was in tension, and there is evidence for both smooth and accelerated decline in the observable cosmic SFR (CSFR) density (Bouwens et al. 2015; Finkelstein et al. 2015; McLeod et al. 2015; Finkelstein et al. 2016; Oesch et al. 2018; Bouwens et al. 2019). This leaves theoretical models highly unconstrained, where differences in star formation and feedback prescriptions result in a wide range of predictions (Figure 8; Mason et al. 2015a, 2015b; Behroozi & Silk 2015; Gnedin 2016; Dayal et al. 2017; Wilkins et al. 2017; Yung et al. 2019a; Davé et al. 2019; Behroozi et al. 2020; Wilkins et al. 2022). This leads to uncertainties on the details of the history of reionization of the IGM (Robertson et al. 2015; Finkelstein et al. 2019; Yung et al. 2020a, 2020b).

NGDEEP-NRC will provide the first observational constraints on faint $z > 10$ galaxies from public data sets. These observations will enable the measurement of the shape of the UVLF, which constrains the relative strength of processes governing gas conversion into stars (and these depend on gas density, metallicity, magnetic field strength, turbulence, and feedback mechanism). Different theoretical predictions for the UVLF at $z > 10$ vary by orders of magnitude in galaxy number density (e.g., Mason et al. 2015b; Behroozi & Silk 2015; Dayal et al. 2017; Wilkins et al. 2022), because of differences in adopted subgrid physics. Two physical processes are most important for the shape and normalization of the UVLF at high redshift: the star formation law (i.e., the star formation efficiency as a function of cold gas surface density), and the prescription for stellar feedback.
Using an SAM, Yung et al. (2019a) explored how modifications to these relationships alter the UVLF, shown in the right panel of Figure 7. Altering the star formation efficiency primarily changes the bright end of the UVLF, which will be constrained by medium-depth, wider-field JWST programs (such as CEERS, Finkelstein et al. 2022; and COSMOS-Web, Casey et al. 2023). However, stellar feedback dominates the UVLF of faint galaxies (as feedback regulates star formation in lower-mass halos). In particular, this feedback depends on the mass-loading factor of ejected gas, and changing this within the currently allowable parameter space changes the number density of the lowest-luminosity galaxies ($M_{UV} \lesssim -18$) by up to 1 dex. NGDEEP-NRC provides the missing constraint: Figure 8 shows that adding NGDEEP-NRC observations reduces the uncertainty on the number density of faint galaxies by $\sim 4-5$× compared with the range currently spanned by models (this includes both counting and a 30% fractional cosmic variance uncertainty; Bhowmick et al. 2020).

To make this measurement as accurate as possible requires deep surveys of blank fields. This is complementary to surveys of regions that are strongly lensed by clusters of galaxies. Those observations can reach fainter intrinsic luminosities over small

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**Figure 7.** Redshift vs. Hβ flux for galaxies in simulated NGDEEP-NIS data. The small gray points represent all sources in the simulation. The red squares are simulated objects with NIRISS-detected Hβ emission (S/N >3σ). NGDEEP will measure faint Hβ emission from >900 sources from 0.7 < z < 2.3 (see Table 3). The open circles are sources that would have been targeted by MOSDEF, a dedicated survey using the 10 m Keck telescope. Surveys like MOSDEF must preselect objects and are subject to slit crowding: MOSDEF only targeted galaxies with $H_{160} < 25$ AB mag and had a flux limit of $F \approx 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (3σ). MOSDEF would be sensitive to fewer than 70 of the NGDEEP-NIS sources (at higher stellar masses).

**Figure 8.** Left: predicted cumulative number of high-redshift galaxies detected across the NGDEEP NIRCam imaging mosaic. Simulations (solid lines; Mason et al. 2015b; Behroozi & Silk 2015; Dayal et al. 2017; Wilkins et al. 2022, Yung et al. 2023) span a wide range, reflecting the lack of observational constraints prior to JWST. Across the full NGDEEP NIRCam mosaic (to the F277W 5σ limit) NGDEEP should cover ~50–1100 galaxies at z ~ 10, 3–25 galaxies at z ~ 13, and up to 10 galaxies at z ~ 13.5–15, distinguishing between these models. We note that early results from CEERS (Finkelstein et al. 2023) are consistent with the most optimistic of these models (Behroozi & Silk 2015). Right: model uncertainties highlight our state of knowledge of important physical processes. Purple shading shows the plausible range of the dependence of SFR on gas surface density, which primarily affects the bright end, which is constrained by wider-area programs like CEERS and COSMOS-Web (Casey et al. 2023). Red shading denotes the plausible range in stellar feedback mass-loading factors, which primarily affect the faint end (Yung et al. 2019a). The symbols show the precision achievable by CEERS and NGDEEP+JADES (assuming the fiducial Yung et al. 2019a UVLF; dotted line). At $M_{UV} = -17.5$ (NGDEEP-NRC 10σ limit), NGDEEP-NRC alone will significantly constrain these models (~4.5σ, including cosmic variance, improving to ~5.5σ with the eventual combination with JADES), placing the first definitive constraints on feedback processes in early galaxies.
volumes, albeit with uncertainties associated with the magnification. By directly identifying galaxies to $m > 30.5$ mag. NGDEEP-NRC will measure the evolution of the UVLF and SFR density to $z > 10–15$ and provide unique constraints on stellar feedback physics at $z > 10$. In Figure 8 we also list predicted numbers of high-redshift galaxies to be discovered by NGDEEP-NRC based on a range of recent models. As early JWST results are finding observed yields at the high end of predictions, these numbers may be lower limits (e.g., Finkelstein et al. 2023, 2022; Adams et al. 2023; Castellano et al. 2022; Donnan et al. 2023; Harikane et al. 2023; Naidu et al. 2022; Atek et al. 2023; Pérez-González et al. 2023).

As an example, in Leung et al. (2023) we used data from the first half of NGDEEP-NRC observations to identify a robust sample of 38 galaxy candidates at $z > 9$, including two “Little Red Dots.” Our deep imaging allowed us to probe $\sim 1.5$ mag fainter than previous public JWST surveys such as CEERS (Finkelstein et al. 2023, 2023). We present a new measurement of the faint end of the UVLF at $z \sim 9$ and 11, finding no significant evolution in the faint-end slope and number density from $z = 9$ to 11. The observed number density of galaxies at $z \sim 11$ at the faint end is consistent with some theoretical predictions, but all the physics-based models we compared to underpredict the abundance of bright galaxies, highlighting the importance of deep surveys such as NGDEEP in measuring the properties of galaxies through a wide range of luminosities.

5.2. The Onset of Chemical Enrichment

As we explore higher redshifts, we will eventually witness the periods during which galaxies have formed no more than a few generations of stars, characterized by extremely low metallicities. It is critical to quantify how low the early metallicities are. If all dense gas in the Universe is rapidly enriched beyond the critical metallicity ($\sim 10^{-4} Z_{\odot}$), both the stellar initial mass function and stellar photospheric temperatures will likely not be dramatically different than those seen in low-metallicity environments. If the opposite is true, and fairly massive metal-free stars can form down to even $z \sim 10$, we expect markedly harder stellar spectra, with consequences for the ability of stellar light to reionize the IGM.

Work using HST data found that the colors of the most distant galaxies are consistent with low (but nonzero) metallicities, without much dust obscuration in the lowest-mass galaxies (Finkelstein et al. 2012; Dunlop et al. 2013; Bouwens et al. 2014; Wilkins et al. 2016). NGDEEP-NRC imaging will push this analysis to $z > 10$, allowing us to measure the UV spectral slope $\beta$, where $f_\lambda \propto \lambda^\beta$ (Calzetti et al. 1994), with four (three) rest-UV colors for galaxies at $z \sim 10$ (12). Simulations at our proposed depths show that we can recover $\beta$ with minimal bias and $\sigma_{\beta} = 0.2$ to $z > 13$. NGDEEP-NRC will also improve measures of $\beta$ in galaxies at $z = 6–8$ (currently restricted to just one or two colors), measuring $\beta$ with five colors. As an example of the results achieved with the first epoch of NGDEEP-NRC, Morales et al. (2023) analyzed the redshift evolution of $\beta$ and its correlation with galaxy properties using the sample of $z \sim 9–16$ galaxies from Leung et al. (2023). We measured $\beta$ using both SED fitting with Bagpipes (Carnall et al. 2021) and photometric power-law fitting to the observed photometry. Our sample averages $\beta_{\text{SED}} = -2.46^{+0.24}_{-0.19}$ and $\beta_{\text{PL}} = -2.65^{+0.57}_{-1.51}$, indicating predominantly low-metallicity galaxies without evidence of exotic stellar populations (i.e., $\beta \lesssim -3$). We observed moderately positive correlations between the UV spectral slope and dust attenuation, age, stellar mass, and SFR from Bagpipes but weak to no correlations with UV magnitude and redshift. Comparisons with simulations at these redshifts and stellar masses show no evidence of ultrablue UV slopes ($\beta < -3$).

5.3. The Sites of Early Black Hole Formation

Massive black hole seeds forming at $z > 12$ via direct collapse, with masses $\sim 10^{7–8} M_\odot$, are expected to form in the satellite halos of early star-forming galaxies, which will eventually merge and acquire a stellar component (Agarwal et al. 2016). In these galaxies with overly massive black holes (referred to as overmassive black hole galaxies, or OBGs), the accretion luminosity outshines the stellar component (Natarajan et al. 2017), offering a unique way to discriminate between light and massive initial black hole seeds. Computing the multiwavelength energy output of OBGs, they should stand out from typical galaxies via their steep 1–3 $\mu$m SED, identified via NGDEEP-NRC colors, with candidates cross-correlated with the very deep Chandra X-ray data in this field. The boosted infrared luminosity of OBGs (predicted $m_{AB} < 25$) makes them detectable in the NGDEEP-NRC survey. Recent results have already identified two $z > 10$ OBGs in the lensing cluster A2744 (UHZ1 and GHZ9; Goulding et al. 2023; Natarajan et al. 2024, private communication), promising results for the search in NGDEEP-NRC. Recent models predict roughly two to five OBG candidates between $z \sim 9$ and 12 in the NGDEEP-NRC field, revealing the sites of early black hole formation and enabling discrimination between early black hole seeding models (Ricarte & Natarajan 2018).

5.4. Galaxy Morphologies

Ultra-deep subkiloparsec imaging across the NIR is needed to understand how galaxies assembled. The suppression of runaway star formation by feedback is encoded in galaxies’ structural and mass assembly histories. Additionally, models predict various pathways for emergence of galaxy structure at early times (e.g., Wellons et al. 2016), and the role of galaxy mergers in the mass assembly of galaxies over the age of the Universe remains uncertain. This is especially true for galaxies at $z \gg 2$, at $M_\star < 10^{10} M_\odot$, and for minor mergers (Kaviraj 2014; Martin et al. 2017; Mantha et al. 2018; Duncan et al. 2019). By characterizing structures in and around low-mass galaxies, we can constrain the link between feedback physics and galaxy structure over cosmic time (e.g., Moody et al. 2014; Oklopič et al. 2017; Zhang et al. 2019). Early morphological studies with JWST have demonstrated its power to probe the detailed morphologies of galaxies out to very high redshift, to reveal low surface brightness features in galaxies that were previously undetected with HST, and to identify complex structures even at $z > 7$ (e.g., Finkelstein et al. 2023; Robertson et al. 2023a; Bowler et al. 2022; Ferreira et al. 2023; Kartaltepe et al. 2023; Nelson et al. 2023; Chen et al. 2023; Treu et al. 2023).

NGDEEP-NRC will push morphological analyses into new frontiers. The observations will enable the measurement of rest-frame optical morphologies and sizes of both galaxies with low mass and galaxies at very high redshift, including the structure of spheroids, disks, and clumps. We will explore morphological classifications visually, as well as through parametric
(e.g., Sérsic profile fits with Galfit: Peng et al. 2002, 2010) and nonparametric (e.g., measurements of concentration, asymmetry, the Gini coefficient, $M_{20}$, etc., with packages such as Statmorph; Rodriguez-Gomez et al. 2019) approaches (e.g., Kartaltepe et al. 2023). While the sample size will be small overall, we will take advantage of machine-learning strategies in Cycle 3 and beyond. With NGDEEP and GTO programs (such as JADES) as building blocks, we envision programs executed by multiple teams to ultimately push several fields to ambitious depths early in the mission and get data to the community rapidly. NGDEEP offers a very efficient first step toward this goal.

To that end, we will deliver high-quality data products to enable broad community science from NGDEEP. While a comprehensive treatment of the NGDEEP data reduction is beyond the scope of this paper, we provide here a brief summary of our process for each instrument. A full discussion of our reduction of Epoch 1 data is presented in Pirzkal et al. (2023) and Leung et al. (2023) for NGDEEP-NIS and NGDEEP-NRC, respectively, and we will present our Epoch 2 reduction along with updates and improvements to our Epoch 1 reductions in subsequent papers.

We reduce the data from each instrument using a combination of the JWST Calibration Pipeline (Bushouse et al. 2023) and custom procedures. The NGDEEP-NIS observations are processed through Stages 1 and 2 of the JWST Calibration Pipeline. Significant care is required to properly handle the astrometric alignment, the location and geometry of the spectral traces, and the wavelength calibration of the NIRISS slitless spectra. We refer the reader to Pirzkal et al. (2023) for a detailed discussion of our NIRISS reduction and treatment of these issues. We extract the spectra using the SBE method (Pirzkal et al. 2017), which involves creating a simulated spectrum for every object in the field that is then used to quantify contamination from overlapping spectra.

We reduce the NGDEEP-NRC observations with the Pipeline and custom additions and modifications we have identified through our work with CEERS imaging (Bagley et al. 2023). These modifications include the removal of low-level features such as wisps and 1/f correlated noise, a careful astrometric alignment, and a global background subtraction, steps that are necessary to achieve the expected NGDEEP-NRC imaging depths. The Epoch 1 NGDEEP-NRC data reduction is presented in detail by Leung et al. (2023). As mentioned in Section 2.4, the Epoch 1 NIRCam imaging is ~0.1–0.5 mag shallower than expected from the ETC. It is also approximately the same depth as the MIDIS NIRCam imaging in F115W, F150W, and F356W despite having 35%–70% more exposure time in these filters. We are still exploring the cause of this sensitivity loss in the NGDEEP-NRC images, though we suspect that a large contributing factor is the use of the DEEP8 readout mode with too few groups. As mentioned in Section 2.4, these preliminary findings motivated our change to MEDIUM8 for the Epoch 2 exposures. We are also exploring alternate reduction methods to recover some of the depth in the Epoch 1 images. We will present any updates to our Epoch 1 reduction and the resulting imaging depths in a future paper.

Our data management plan is built on successful Hubble Treasury programs, where speed is valued over perfection for the first v0.5 releases, with limitations noted in the accompanying documentation. Our first reductions will therefore represent a best effort based on the current state of the instrument calibrations, especially that of the NIRISS WFSS
mode. Later v1 releases will include more extensive testing and refinement and be accompanied by well-tested catalogs. The NGDEEP-NIS release will include 2D and 1D calibrated spectra of each source detected in the field with an accurate correction for spectral contamination as demonstrated by Pirzkal et al. (2017). We will also provide an emission-line catalog including spectroscopic redshifts. The NGDEEP-NRC release will include 30 mas mosaics pixel-aligned across all NIRCam filters and the deep ACS F814W imaging in the field. We will provide separate mosaics for Epochs 1 and 2, as well as single mosaics combining all imaging. We will also release photometric and morphological catalogs incorporating the NIRCam and HST imaging.

Our released catalogs will be accompanied by Python Jupyter notebooks to train users to interact with data products. All products will be shared with STScI and hosted on our own team website. With the completion of the NGDEEP observations in 2024 February, we anticipate announcing our first data release (v0.5) at the beginning of 2024 May. Table 4 shows the planned NGDEEP data release schedule.

### 7. Summary

We present the NGDEEP Survey, which is obtaining deep NIRISS WFSS of the HUDF and deep NIRCam imaging in the HUDF-Par2 parallel field. The NGDEEP observations are split across two position angles, with V3_PA = 70° observed in 2023 February (Epoch 1) and V3_PA = 67° observed in 2024 January (Epoch 2). The position angles are chosen to improve the NIRISS emission-line identification and contamination modeling while maximizing the overlap between the two NIRCam imaging sets.

The NGDEEP NIRISS observations (NGDEEP-NIS) obtained spectroscopy from 1 to 2.2 µm with the GRISMR and GRISMC grisms dispersed through the F115W, F150W, and F200W filters. The integration times are distributed to achieve approximately uniform emission-line sensitivities at all wavelengths, with expected 5σ integrated line sensitivities of (1.2, 1.3, 1.5) × 10⁻¹⁸ ergs s⁻¹ cm⁻² for F115W, F150W, and F200W, respectively. The NGDEEP-NIS observations will detect emission lines from >1000 galaxies, many of which have multiple lines. The unbiased nature of the NGDEEP-NIS slitless spectroscopy will result in NIR spectroscopic measurements for every source in the HUDF, complemented by the deep ACS F435W imaging in the field.

The NGDEEP NIRCam observations (NGDEEP-NRC) obtained imaging from 1 to 5 µm with the F115W, F150W, F200W, F277W, F356W, and F444W filters. The NIRCam imaging will reach comparable depths in all filters (m = 30.7–30.9, 5σ resolved source) and m = 31.2 in F115W. The NGDEEP-NRC observations are defined by the NIRISS observing strategy, including the exposure times, dither patterns, and NIRISS direct imaging. There are therefore multiple tiers of depth in the NIRCam imaging, with ~5 arcmin² of the deepest imaging where the two position angles overlap. This imaging will enable the discovery of ~30–100 galaxies at z ≥ 11, probing the faint end of the UVLF 2 mag fainter than that possible with CEERS. NGDEEP-NRC is supplemented by deep ACS F814W imaging covering the NIRCam footprint, with 50% of the footprint covered by the deepest F814W imaging on the sky (m₅ₐ ≈ 30).

Together, these coordinated parallel observations are designed to explore the dominant feedback mechanisms in low-mass galaxies across cosmic time. NGDEEP will constrain

1. the redshift evolution and scatter in the MZR slope from \( z \sim 1 \) to 5;
2. the stochasticity, burstiness, and variability of star formation at \( z = 0.7–2.3 \);
3. the physical processes (stellar feedback and star formation efficiencies) regulating the emergence of the first galaxies;
4. the evolution of chemical enrichment starting as early as \( z \gtrsim 12 \);
5. the sites and mechanisms of early black hole formation; and
6. the link between feedback and morphological structures in and around low-mass galaxies.

As a program continuing the legacy of HST ultra–deep-field astronomy, NGDEEP will enable many additional community-led explorations into the study of galaxies from cosmic noon (\( z \sim 1–2 \)) to the early epochs of galaxy formation (\( z > 10 \)).

NGDEEP provides the deepest publicly available spectroscopy and imaging obtained in Cycle 1, making it one of the first JWST deep fields. When combined with NGDEEP Epoch 2, as well as the JADES and MIRI GTO programs, these legacy observations will transform deep-field science and dramatically enhance our understanding of the Universe.

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