



Publication Year	2020
Acceptance in OA	2022-01-21T16:10:34Z
Title	HST Grism-derived Forecasts for Future Galaxy Redshift Surveys
Authors	Bagley, MB, Scarlata, C, Mehta, V, Teplitz, H, BARONCHELLI, IVANO, Eisenstein, DJ, POZZETTI, Lucia, Cimatti, A, Rutkowski, M, Wang, Y, Merson, A
Publisher's version (DOI)	10.3847/1538-4357/ab9828
Handle	http://hdl.handle.net/20.500.12386/31345
Journal	THE ASTROPHYSICAL JOURNAL
Volume	897

HST Grism-derived Forecasts for Future Galaxy Redshift Surveys

MICAELA B. BAGLEY,^{1,2} CLAUDIA SCARLATA,² VIHANG MEHTA,² HARRY TEPLITZ,³ IVANO BARONCHELLI,^{4,3}
DANIEL J. EISENSTEIN,⁵ LUCIA POZZETTI,⁶ ANDREA CIMATTI,^{7,8} MICHAEL RUTKOWSKI,⁹ YUN WANG,³ AND
ALEXANDER MERSON^{10,3}

¹University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712-1205, USA

²Minnesota Institute for Astrophysics, University of Minnesota, Minneapolis, MN 55455, USA

³Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125, USA

⁴Dipartimento di Fisica e Astronomia “G. Galilei”, Università degli Studi di Padova, Vicolo dell’Osservatorio 3, I-35122, Italy

⁵Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

⁶INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Bologna, I-40129, Italy

⁷University of Bologna, Department of Physics and Astronomy, Via Gobetti 93/2, I-40129, Bologna, Italy

⁸INAF – Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Firenze, Italy

⁹Department of Physics and Astronomy, Minnesota State University, Mankato, MN 56001, USA

¹⁰Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

(Accepted May 30, 2020)

Submitted to ApJ

ABSTRACT

The mutually complementary Euclid and *Roman* galaxy redshift surveys will use H α - and [O III]-selected emission line galaxies as tracers of the large scale structure at $0.9 \lesssim z \lesssim 1.9$ (H α) and $1.5 \lesssim z \lesssim 2.7$ ([O III]). It is essential to have a reliable and sufficiently precise knowledge of the expected numbers of H α -emitting galaxies in the survey volume in order to optimize these redshift surveys for the study of dark energy. Additionally, these future samples of emission-line galaxies will, like all slitless spectroscopy surveys, be affected by a complex selection function that depends on galaxy size and luminosity, line equivalent width, and redshift errors arising from the misidentification of single emission-line galaxies. Focusing on the specifics of the Euclid survey, we combine two slitless spectroscopic WFC3-IR datasets – 3D-HST+AGHAST and the WISP survey – to construct a Euclid-like sample that covers an area of 0.56 deg² and includes 1277 emission line galaxies. We detect 1091 (~ 3270 deg⁻²) H α + [N II]-emitting galaxies in the range $0.9 \leq z \leq 1.6$ and 162 (~ 440 deg⁻²) [O III] $\lambda 5007$ -emitters over $1.5 \leq z \leq 2.3$ with line fluxes $\geq 2 \times 10^{-16}$ erg s⁻¹ cm⁻². The median of the H α + [N II] equivalent width distribution is ~ 250 Å, and the effective radii of the continuum and H α + [N II] emission are correlated with a median of $\sim 0''.38$ and significant scatter ($\sigma \sim 0''.2 - 0''.35$). Finally, we explore the prevalence of redshift mis-identification in future Euclid samples, finding potential contamination rates of ~ 14 -20% and $\sim 6\%$ down to 2×10^{-16} and 6×10^{-17} erg s⁻¹ cm⁻², respectively, though with increased wavelength coverage these percentages drop to nearly zero.

Keywords: Emission line galaxies (459); Redshift surveys (1378); Spectroscopy (1558)

1. INTRODUCTION

The nature of dark energy, the explanation of the observed cosmic acceleration (Riess et al. 1998; Perlmutter et al. 1999), is one of the most important unsolved

problems in cosmology today. A galaxy redshift survey enables us to measure the cosmic expansion history via the measurement of baryon acoustic oscillations (BAO), as well as the growth history of large scale structure via the measurement of large scale redshift-space distortions. The combination of these two measurements allows us to differentiate between an unknown energy component and the modification of general relativity as

the cause of the observed cosmic acceleration (Guzzo et al. 2008; Wang 2008).

Two future space missions, ESA’s Euclid (Laureijs et al. 2011, 2012) and NASA’s *Nancy Grace Roman Space Telescope* (*Roman*, formerly WFIRST; Green et al. 2012; Spergel et al. 2015), will carry out mutually complementary galaxy redshift surveys to probe dark energy. Both Euclid and *Roman* will use $H\alpha$ and [O III]-selected emission line galaxies as tracers of the large scale structure at $0.9 \lesssim z \lesssim 1.9$ ($H\alpha$) and $1.5 \lesssim z \lesssim 2.7$ ([O III]). The uncertainties in the cosmological parameters derived from a BAO survey are inversely proportional to the number of galaxies used in the survey. To optimize these redshift surveys for the study of dark energy, it is therefore critical to have a reliable and sufficiently precise knowledge of the expected numbers of $H\alpha$ and [O III] galaxies in the survey volume.

In the redshift range of interest for the galaxy redshift surveys ($0.9 < z < 2.7$), existing $H\alpha$ and [O III] luminosity function measurements show large uncertainties and are often inconsistent with one another. In the relevant redshift range, $H\alpha$ and [O III]-emitting galaxies are identified with two main techniques. Ground-based narrowband surveys (e.g., Geach et al. 2008; Sobral et al. 2009) cover large areas, but are limited by very thin redshift slices ($\Delta(z) \sim 0.03$). Slitless space-based spectroscopic surveys, with NICMOS first (e.g., Hopkins et al. 2000; Shim et al. 2009) and WFC3 more recently (Colbert et al. 2013; Mehta et al. 2015; Pirzkal et al. 2017), simultaneously probe a large redshift range ($\Delta(z) \sim 0.7$), albeit over much smaller areas. Despite the enormous effort, the uncertainties on the luminosity functions remain substantial. For example, the characteristic luminosities, L^* , measured from a variety of surveys across this redshift range span almost an order of magnitude (e.g., Hopkins et al. 2000; Geach et al. 2008; Hayes et al. 2010; Colbert et al. 2013; Sobral et al. 2013; Mehta et al. 2015; Matthee et al. 2017). These uncertainties lead to less certain number count predictions for galaxy redshift surveys such as those of Euclid and *Roman*, measurements necessary to constrain dark energy.

In addition to accurate number counts, simulations are also an important component of the preparation required for surveys such as these. Cosmological N-body simulations, hydrodynamical codes, semi-analytic models, and the mock catalogs generated from them are valuable tools in preparing to physically interpret the wealth of measurements that are expected. Additionally, such models and catalogs can be used to test reduction, sample selection, and source characterization software be-

ing developed to process and analyze the survey data. In both cases, it is crucial that these simulations reproduce the observed joint distributions of emission line fluxes and galaxy size, luminosity, and mass, and correctly assign line fluxes as a function of these properties. The proper assignment of galaxy properties is necessary to correctly account for observational selection effects, which depend on galaxy size and luminosity as well as emission line signal-to-noise (S/N) and equivalent width (EW).

There have been significant recent efforts to prepare for future galaxy redshift surveys. For example, Pozzetti et al. (2016) and Merson et al. (2018) use physically-motivated models to predict the expected number of $H\alpha$ -emitting galaxies that will be detectable down to a range of survey flux limits. Valentino et al. (2017) similarly predict emission line number counts using large, spectroscopically-calibrated photometric samples. Others have addressed the important challenges of automatically identifying emission lines in slitless data (e.g., Maseda et al. 2018) and of quantifying the quality of spectroscopic redshifts (e.g., Jamal et al. 2018). Yet much of this work either makes use of slit-based spectroscopy that has a distinct selection function from that of slitless data, or requires auxiliary datasets such as multi-wavelength photometry. In this paper, we add to these works by leveraging the similarities of future slitless grisms with those of the *Hubble Space Telescope* (*HST*) WFC3 G102 and G141 infrared grisms to create a selection function that closely approximates that of the upcoming galaxy redshift surveys. We expand on the work presented in Colbert et al. (2013) and Mehta et al. (2015), which has previously been compared with models by Pozzetti et al. (2016) and Merson et al. (2018), by combining multiple *HST* grism programs to cover a $>10\times$ greater area. As our results do not depend on photometrically-determined redshifts, our work is complementary to that of Maseda et al. (2018). The large survey footprints planned for future galaxy redshift surveys will not be fully covered by the same wealth of multi-wavelength imaging observations that is available for CANDELS fields, where photometric redshifts are based on 8 (UDS; Williams et al. 2009) to 35 (COSMOS; Whitaker et al. 2011) photometric measurements. Our results are therefore an important representation of the expectations for grism surveys, even for fields that will lack the coverage in additional auxiliary imaging datasets to obtain sufficiently accurate and precise photometric redshifts.

While the details of the *Roman* survey are still under development, the Euclid Consortium is in the process of finalizing the observing strategy for the Euclid mis-

sion. In this paper, we therefore focus on the projected characteristics for Euclid and use available slitless spectroscopic data from *HST* grism surveys to make predictions for this survey. In what follows we calculate the number densities of $H\alpha$ and $[O\ III]$ -emitting galaxies, measure the size and EW distributions for $H\alpha$ -emitters, and quantify the expected number of contaminating redshifts from misidentified single emission lines as a function of survey depth and redshift. We estimate the number density of $H\alpha$ -emitters accessible to galaxy redshift surveys by applying selection criteria matching those of the Euclid Wide Survey. The Wide Survey will use the Near Infrared Spectrograph and Photometer (NISP) to detect emission line galaxies (ELGs) in a $15000\ \text{deg}^2$ survey area down to a 3.5σ flux limit of $2 \times 10^{-16}\ \text{erg s}^{-1}\ \text{cm}^{-2}$ for sources $0''.5$ in diameter (Racca et al. 2016; Vavrek et al. 2016). We note, however, that similar predictions can be tuned for *Roman* by adjusting the selection criteria appropriately.

This paper is organized as follows. In Section 2, we present the slitless grism survey characteristics and describe the creation of a Euclid-like Wide Sample using the Euclid selection function. In preparation for characterizing the emission size distributions of the sample, we describe the creation of an empirical PSF and our method for fitting models to emission maps in Section 3. We present our results in Section 4, including the number counts of emission line galaxies (Section 4.1), the continuum and emission line sizes (Section 4.2), the EW distribution for $H\alpha$ + $[N\ II]$ -emitters (Section 4.3), and a potential $[O\ III]$ selection bias based on the $[O\ III]$ line profiles in the grism data (Section 4.4). We present an empirical measurement of the redshift accuracy achievable with slitless grism data in Section 4.5 and discuss the effects of contamination from misidentified single emission lines in Section 4.6. Finally, we summarize the key results in Section 5. Throughout this paper we assume a Λ CDM cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70\ \text{km s}^{-1}\ \text{Mpc}^{-1}$. All magnitudes are expressed in the AB system (Oke & Gunn 1983).

2. THE EUCLID-LIKE SAMPLE

For this work, we use existing spectroscopic data from three *HST* grism programs: the WFC3 Infrared Spectroscopic Parallel survey (WISP, see Section 2.1; Atek et al. 2010), 3D-HST (Section 2.2; Brammer et al. 2012; Skelton et al. 2014; Momcheva et al. 2016), and A Grism H-Alpha SpecTroscopic survey (AGHAST, Section 2.2; Weiner 2009). All programs perform near-infrared slitless spectroscopic observations using one or both of the

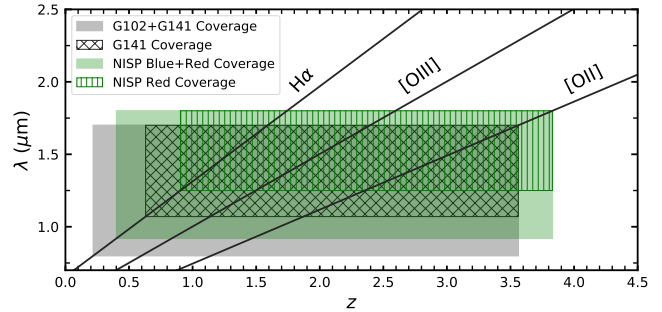


Figure 1. The redshift and wavelength coverage of the WFC3 grisms (gray) is compared with that of the Euclid NISP grisms (green). The wavelengths of $H\alpha$, $[O\ III]$, and $[O\ II]$ as a function of redshift are designated by black lines. The shaded and hatched regions indicate the redshift range in which at least one of these three emission lines is accessible to the given grism. The coverage of the WFC3 grisms is comparable to that planned for Euclid, making the HST grisms important tools for exploring the performance of the upcoming galaxy redshift survey.

WFC3¹ IR grisms: G102 ($0.8 - 1.1\ \mu\text{m}$, $R \sim 210$) and G141 ($1.07 - 1.7\ \mu\text{m}$, $R \sim 130$). The wavelength range of the G141 grism in particular covers a comparable redshift range as that planned by the Euclid galaxy redshift survey (see Figure 1). The IR channel of the WFC3 (Kimble et al. 2008) has a field of view of $123'' \times 134''$ and a native pixel scale of $0''.13/\text{pixel}$. The WFC3 observations compiled here from the WISP, 3D-HST, and AGHAST surveys cover a total area of $0.56\ \text{deg}^2$, which is approximately equal to the NISP field of view. The sources detected by these three surveys, while not necessarily representative of the full population of galaxies, are representative of the galaxies accessible to similar grism surveys.

2.1. The WISP Survey

The WISP Survey (PI: M. Malkan; Atek et al. 2010) is an *HST* pure parallel program, obtaining WFC3 observations of nearby fields while other *HST* instruments are in use. In particular, WISP observations are taken in parallel when either the Cosmic Origins Spectrograph (COS; Froning & Green 2009) or the Space Telescope Imager and Spectrograph (STIS; Kimble et al. 1998) are used as the primary instrument, as programs with these two instruments typically involve long integrations of a single pointing. The WISP parallel field is offset by $\sim 5'$ from the primary target. Since the selection of parallel opportunities depends on the integration time rather than the position of the primary target, WISP

¹ www.stsci.edu/hst/wfc3

fields are independent and uncorrelated. In this paper, we include emission line measurements from 419 WISP fields collectively covering ~ 1520 arcmin².

The WISP observing strategy depends on the details of each parallel opportunity, and therefore varies from field to field. In short opportunities consisting of one to three continuous orbits, the G141 grism is typically used along with one imaging filter (F140W or F160W) to aid in spectral extraction and to mark the zero point for wavelength calibration. The G102 grism and the F110W imaging filter are added to longer opportunities consisting of four or more continuous orbits. For these deeper fields, the integration times in the two grisms are tuned to achieve approximately uniform sensitivity for an emission line of a given flux across the full wavelength range. As the visit lengths depend on the specifics of the primary observations, we do not reach a uniform depth in all WISP fields. Additionally, the sky background in each field is affected to varying degrees by, for example, zodiacal light and Earth limb brightening. The median 5σ detection limit for emission lines in both grisms is $\sim 5 \times 10^{-17}$ erg s⁻¹ cm⁻², yet the detection limit in a given field can differ from this median by more than a factor of 2. As a consequence, while all WISP fields are deeper than the Euclid Wide Survey, only $\sim 75\%$ of fields reach the expected depth of the Euclid Deep Survey.

All WISP data are reduced with the WFC3 pipeline CALWF3 in combination with custom scripts that account for the specific challenges of un-dithered, pure-parallel observations. The foundation of the WISP reduction pipeline is described in Atek et al. (2010), and crucial updates implemented for the current version will be presented in Baronchelli et al. (*in prep*). We use the *AstroDrizzle* software (Gonzaga 2012) to combine the individual exposures, correcting for astrometric distortions and any potential alignment issues. The IR direct images are drizzled onto a $0''.08$ /pixel scale. Object detection in the IR direct images (F110W, F140W, and F160W) is performed with *Source Extractor* (version 2.5; Bertin & Arnouts 1996). For fields with imaging in two filters, we create a combined detection image and supplement the catalog with sources detected individually in only one of the filters. We use the *aXe* software package (Kümmel et al. 2009a) to extract and calibrate the spectra. The *aXe* software drizzles all extracted spectral stamps from individual exposures to a combined spectral image with a constant dispersion and cross-dispersion pixel scale, thus removing geometric distortions. The individual drizzled spectral stamps are on the $0''.13$ /pixel scale. For each source identified in the direct imaging, the spatial width of the extraction window is a factor of $4\times$ the projected size of the

source (either semi-major or semi-minor axis depending on the source orientation) onto the extraction direction². We then use *aXe*'s optimal weighting method with Gaussian weights (with widths based on the size of the sources in the direct image) to extract 1D spectra from the 2D spectral stamps. The emission line finding process described in the next section is performed on the 1D spectra.

2.1.1. WISP Emission Line Catalog

We construct the WISP emission line catalog via the combination of an automatic detection algorithm that identifies emission line candidates and a visual inspection of each candidate performed by two reviewers. There are two versions of the WISP emission line detection algorithm. The first version, presented in Colbert et al. (2013) for ~ 30 WISP fields, identified emission lines as groups of contiguous pixels about the continuum. The resulting lists of line candidates identified by the detection algorithm were dominated by spurious sources and fake emission lines, and the inspection and cleaning of these lists required extensive time and effort from reviewers. We developed the new method to substantially reduce the time required for reviewers to inspect all 400+ WISP fields by improving the methods for automatic identification and vetting of emission line candidates. This second version of the detection algorithm improves on this method by including a continuous wavelet transform, which fits not only the amplitude, but also the shape, of emission line features in a spectrum. The new algorithm also includes additional quality checks aiming to remove most spurious sources before the inspection stage. The details of the new algorithm will be presented in an upcoming paper, Bagley et al. (*in prep*).

Following detection, each emission line candidate is visually inspected by two reviewers to reject artifacts such as cosmic rays and hot pixels, to remove lines that are heavily contaminated by overlapping spectra, and to identify the emission lines and fit the source redshift. The full spectrum is then fit with a single model consisting of a continuum and Gaussian emission lines at wavelengths determined by the redshift assigned to the source. Specifically, the reviewer provides an initial guess at the source redshift by identifying an emission feature. The best-fit redshift is determined using a least-squares minimization of the full emission model, including emission lines and the continuum. The red-

² See Figure 1.12 of the *aXe* User Manual (version 2.3), www.stsci.edu/institute/software_hardware/stsdas/axe/extract.calibrate/axe_manual

shift of the fit is constrained to be between $\Delta z \pm 0.02$ of the initial guess, which corresponds to $\sim 130 \text{ \AA}$, or $\sim \pm 3$ pixels at the dispersion of the G141 grism. The peak wavelength of each additional emission line in the spectrum is allowed to vary by the same amount to allow for any offsets from the systemic redshift and/or centering differences due to the low resolution of the spectra.

This method ensures that all emission lines are fit with profiles of the same full width at half maximum (FWHM)³, appropriate for slitless spectra where all emission lines are images of the same host source. Simultaneously fitting all emission lines also helps eliminate contamination from overlapping spectra, as the wavelengths of lines from other sources will not match the model for the given source redshift. As a consequence of this simultaneous fitting, fluxes or upper limits are measured for all lines in the wavelength range determined by the assigned redshift, whether or not the lines were identified by the detection algorithm. The WISP emission line catalog therefore contains both “primary” emission lines detected by the automatic peak finder and “secondary” lines that often have a lower S/N than the detection threshold. This distinction is relevant for the application of completeness corrections (see below) and can have important implications for sample selection. While sources in the emission line catalog can have multiple primary lines (usually $\text{H}\alpha$ and $[\text{O III}]$) secondary lines (often $[\text{S III}] \lambda\lambda 9069, 9532$ for example) are measured as a consequence of a primary line detection. Finally, we note that in the absence of multiple emission lines, single lines are assumed to be $\text{H}\alpha$ unless the clear asymmetry of the $[\text{O III}]+\text{H}\beta$ line profile is visible. We discuss this assumption further in Section 4.4.

The WISP emission line catalog was constructed after processing and inspecting the spectra from 419 WISP fields, covers $\sim 1520 \text{ arcmin}^2$, and includes ~ 8000 emission line objects. The improved emission line detection process and completeness analysis will be presented in Bagley et al. (*in prep*), and the resulting emission line catalog will be released at the time of publication. We use this catalog, in combination with that from 3D-HST+AGHAST discussed in Section 2.2, to construct a Euclid-like sample in Section 2.4.

2.2. The 3D-HST+AGHAST Survey

The 3D-HST Survey (PI: P. van Dokkum; Brammer et al. 2012; Skelton et al. 2014; Momcheva et al.

2016) and the AGHAST Survey (PI: B. Weiner; Weiner 2009) together obtained spectroscopic observations of the CANDELS (Grogin et al. 2011; Koekemoer et al. 2011) fields. In ~ 150 pointings, the 3D-HST+AGHAST Survey covered each field to a uniform two-orbit depth, including G141 observations and direct imaging in the F140W filter. We add the 3D-HST+AGHAST pointings from the AEGIS, COSMOS, GOODS-North (GOODS-N) and GOODS-South (GOODS-S) fields, $\sim 507 \text{ arcmin}^2$ in total, to the WISP fields. Including these fields in our analysis has several benefits in addition to the increase in area coverage. With the extensive multi-wavelength catalogs available for the well-studied CANDELS fields, we can identify regions in color space indicative of misidentified single emission lines (see Section 4.6).

The 3D-HST+AGHAST team has released a catalog with emission line measurements for all galaxies detected in imaging (Momcheva et al. 2016). Their method involves combining the CANDELS photometry with the grism spectroscopy to determine augmented photometric redshifts, which are then used as a prior for detecting and measuring emission lines in the grism data. The Euclid Wide survey observations will, at a minimum, include imaging in the Y , J , and H filters of the NISP instrument as well as the very broad VIS filter covering $\sim 5500 - 9000 \text{ \AA}$. While additional ground-based imaging in the g , r , i , and z bands will be obtained, the SEDs of sources will not be as fully sampled as in the CANDELS fields. The amount of information Euclid obtains for each source will be closer to the level obtained in WISP observations. We therefore reprocess all 3D-HST+AGHAST data in a consistent manner with the WISP fields (Rutkowski et al. 2016). We note, however, that time scales and effort required to run even the improved WISP emission line procedure on all $15,000 \text{ deg}^2$ of the Euclid Wide survey will be impossibly unrealistic. Alternative emission line detection algorithms will be needed, such as the citizen science pilot program described in Dickinson et al. (2018) or the integration of machine learning and human classification such as that of Beck et al. (2018).

Rutkowski et al. (2016) describe the reduction of the 3D-HST+AGHAST data using the WISP pipeline with minor modifications to account for the dithered observations as well as the creation of the 3D-HST+AGHAST emission line catalog. Emission line detection and measurement are performed using the first version of the WISP line finding procedure, which is presented in Colbert et al. (2013) and discussed in Appendix A.2. Briefly, emission line candidates are identified as groups of contiguous pixels above the continuum. In contrast to the WISP catalog (Section 2.1.1), we fit each

³ For each source, the best-fit FWHM is determined by the emission model fitting and the initial guess depends on the source size in the direct imaging as follows. The semi-major axis (a) is used as an approximate FWHM in pixels and multiplied by the grism dispersion ($\Delta\lambda$): $\text{FWHM}_{\text{init}} = 2.35a \text{ [pixel]} \Delta\lambda \text{ [\AA/pixel]}$.

Table 1. Euclid Sample Selection Criteria

	Euclid WS	Euclid DS
S/N	≥ 5	≥ 5
EW_{obs}	$\geq 40 \text{ \AA}$	$\geq 40 \text{ \AA}$
Flux	$\geq 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$	$\geq 6 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$
λ_{obs}	$\geq 12500 \text{ \AA}$	$\geq 9200 \text{ \AA}$
H α Coverage	$0.9 \leq z \leq 1.6$	$0.4 \leq z \leq 1.6$
[O III] Coverage	$1.5 \leq z \leq 2.4$	$0.8 \leq z \leq 2.4$
[O II] Coverage	$2.5 \leq z \leq 3.5$	$1.5 \leq z \leq 3.5$

NOTE—In this paper we focus on observational constraints relevant for the Euclid Wide Survey and create a Wide Sample (WS) with these criteria. The Euclid DS selection criteria are presented here for reference. In Section 4.6 we extend our analysis of the WISP+3D-HST catalog down to the expected flux and wavelength limits of the Deep Survey in order to explore sample contamination from redshift misidentification.

3D-HST+AGHAST emission line individually, therefore measuring the redshift, flux, FWHM, and EW separately for each line. Single, symmetric emission lines are again assumed to be H α . The 3D-HST+AGHAST catalog includes ~ 5700 emission line objects, and is combined with the WISP catalog in Section 2.4.

2.3. Emission line catalog completeness corrections

Grism surveys such as WISP, 3D-HST+AGHAST, and Euclid can suffer from incompleteness for a variety of reasons. Sources may be lost amidst the noise in images if their fluxes are close to the detection limit. Some sources may not be detected, or their emission lines missed in their spectra, because they overlap or are blended with nearby bright objects. The completeness of a survey depends on the specific selection function used to detect sources. In the case of the WISP and 3D-HST+AGHAST emission line catalogs, the selection function includes the detection of the sources in the direct images, the identification of emission line candidates via the detection algorithm, and the acceptance during visual inspection.

The completeness corrections applied to the WISP and 3D-HST+AGHAST emission line catalogs were derived in a manner consistent with each of the emission line detection procedures. These derivations are similar but not identical for the two catalogs, reflecting the differences in the line finding algorithms, visual inspection, and emission line fitting. Specifically, the completeness corrections from Colbert et al. (2013) are adopted for the 3D-HST+AGHAST catalog, while a new set of simulations is used to determine the completeness of the updated line finding procedure that created the WISP

catalog. Each method is described in more detail in Appendix A.

Finally, in the sample selection presented in the following section, we have adopted additional selection criteria: line $EW_{\text{obs}} > 40 \text{ \AA}$ and $S/N > 5$. We discuss the motivation behind these two additional criteria in Appendix A. We note, however, that while these two criteria are applicable to the emission line detection processes used for both the WISP and 3D-HST+AGHAST datasets in this paper, they will not necessarily be appropriate for Euclid or other future grism surveys.

2.4. Sample Selection

The Euclid Mission will be composed of two surveys. The Wide Survey aims to obtain redshift measurements for ~ 25 million galaxies over 15000 deg^2 (e.g., Vavrek et al. 2016), using the Euclid Red grism ($1.25 - 1.85 \mu\text{m}$, $R \sim 380$) and achieving a 3.5σ line flux sensitivity of $2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ for a source with a diameter⁴ of $0''.5$. The Deep Survey will cover 40 deg^2 in three separate pointings, reaching a depth of $6 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. In addition to the Red grism, the Deep Survey may make use of a Blue grism ($0.92 - 1.3 \mu\text{m}$, with a tentative $R \sim 250$). In this paper, we focus on obser-

⁴ As emission line fluxes obtained through slitless spectroscopy depend on source size, a single flux limit is not fully representative of what the Wide Survey will detect. More compact sources may be detectable down to fainter fluxes, and the distribution of sources increases rapidly toward fainter emission line fluxes. However, following the example of Laureijs et al. (2011), we adopt here a single flux limit for all sources, noting that our analysis therefore represents a conservative estimate of the number density of sources available to Euclid.

vational constraints relevant for the Wide Survey but note that *HST* grism observations are valuable for Deep Survey predictions as well.

From the full WISP+3D-HST catalog, we create a “Wide Sample” (WS) of ELGs selected to match the planned Euclid Wide Survey. We leave the construction of a “Deep Sample” (DS) for future work, but capitalize on the depth of the WISP+3D-HST catalog to discuss contamination and redshift misidentification in Section 4.6. We begin by considering only sources with secure redshifts, where either both reviewers agree on the assigned redshift or multiple, high-S/N lines are detected in the source’s spectrum. Next we impose a selection in emission line S/N and observed EW to match the completeness limits of the full WISP+3D-HST catalog: $S/N > 5$ and $EW_{\text{obs}} \geq 40 \text{ \AA}$ (see Appendix A as well as Colbert et al. 2013). For galaxies at $z \sim 1 - 1.5$, $EW_{\text{obs}} > 40 \text{ \AA}$ corresponds to a rest EW of $\sim 16 - 20 \text{ \AA}$. The remaining selection criteria depend on emission line flux and observed wavelength. For the WS, we select sources with at least one emission line with flux $f \geq 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ and $\lambda_{\text{obs}} \geq 1.25 \mu\text{m}$. The DS will include additional sources down to $f \geq 6 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ and, in fields observed with the Blue grism, $\lambda_{\text{obs}} \geq 0.92 \mu\text{m}$. Given the drop in the sensitivity of the G141 grism at wavelengths longer than $\sim 1.7 \mu\text{m}$, this wavelength selection results in $H\alpha$ ([O III]) coverage from $0.9 \leq z \leq 1.6$ ($1.5 \leq z \leq 2.4$) for the WS and $0.4 \leq z \leq 1.6$ ($0.8 \leq z \leq 2.4$) for the DS, respectively. See Table 1 for a summary of the selection criteria.

We note that given the spectral resolution of the planned missions, $H\alpha + [\text{N II}]$ will be blended for most sources in Euclid (and some sources in *Roman*) spectra. These two emission lines are also blended in observations obtained with the WFC3 grisms. For the purpose of predicting the number, size and EW distributions of the $H\alpha$ -emitters that will be detected by the galaxy redshift surveys, we do not correct the observed $H\alpha$ fluxes for the contribution by [N II]. All measurements presented here of $H\alpha$ flux, EW, and size refer to $H\alpha + [\text{N II}]$.

Similarly, the [O III] $\lambda\lambda 4959, 5007$ doublet is partially blended at the resolution of the WFC3 grisms. The [O III] fluxes are obtained by fitting two blended Gaussians of the same FWHM to the doublet line profile using amplitudes fixed in a 1 : 3 ratio, following the theoretical calculations of Storey & Zeppen (2000). Since the [O III] doublet will be resolved by Euclid and *Roman*, we correct the observed [O III] $\lambda 5007$ flux for the contribution from the $4959 \text{ \AA}$ line using the same flux ratio. All measurements presented here of [O III] flux therefore refer to [O III] $\lambda 5007$ only.

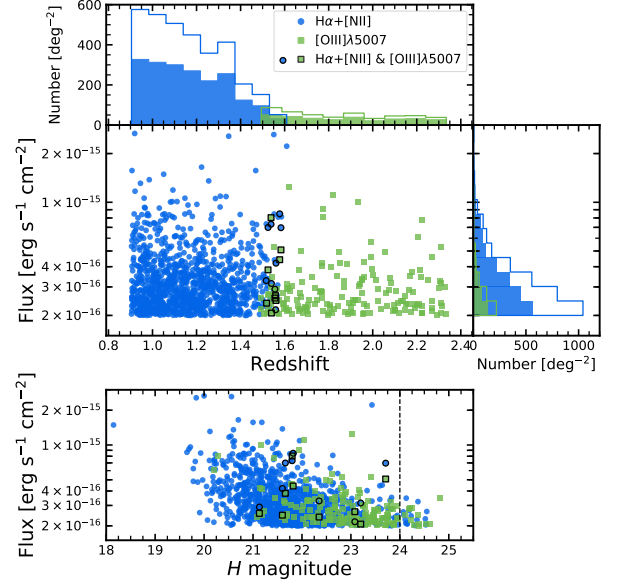


Figure 2. The $H\alpha + [\text{N II}]$ and [O III] $\lambda 5007$ line fluxes of sources in the Wide Sample (WS) as a function of redshift (top panel) and H magnitude (bottom panel). The handful of sources with both lines detected at the redshift and depth of the Euclid Wide Survey are outlined in black. The majority of sources in the WS are $H\alpha + [\text{N II}]$ -emitters at $z \lesssim 1.5$. The observed and completeness-corrected distributions of source redshift (top) and line flux (right) are shown as filled and empty histograms, respectively. In the bottom panel, the sources fainter than $H = 24$ (black dashed line) will be missed if Euclid spectral extraction is only performed for sources with $H < 24$. This subset amounts to $\sim 50 \text{ ELGs deg}^{-2}$, or $\sim 2\%$ of the WS.

The WS consists of 1277 ELGs (2270 deg^{-2}), the majority of which are $H\alpha + [\text{N II}]$ -emitters below redshift $z \lesssim 1.5$ (85%, see Figure 2). There are 73 galaxies in the redshift range $1.5 \lesssim z \lesssim 1.6$, where both $H\alpha$ and [O III] are accessible to the Euclid Red grism. Of these, only 9 (16 deg^{-2}) have both $H\alpha + [\text{N II}]$ and [O III] $\lambda 5007$ bright enough for the Euclid WS selection. The median $H\alpha + [\text{N II}] / [\text{O III}] \lambda 5007$ of these 9 galaxies is 1.45 ± 0.30 , though the strength of this ratio increases with $H\alpha + [\text{N II}]$ line flux, as can be seen in Colbert et al. (2013) and Mehta et al. (2015). The Euclid NISP instrument will reach a 5σ sensitivity of 24th magnitude in all three of its imaging filters. Fainter sources will be in the photometric catalogs, but the current observing strategy calls for spectral extraction only for sources brighter than this 5σ limit. We note that the 28 real ELGs (50 deg^{-2} , $\sim 2\%$ of the WS) with $H > 24$ in the bottom panel of Figure 2, all with emission lines brighter than the Euclid flux limit, would be missed by this extraction strategy. Extracting spectra for sources detected at lower S/N (e.g., $3 - 3.5\sigma$) or down to fainter magni-

tudes ($H < 24.5$) would allow for the recovery of these high-EW sources. Yet this strategy would also result in significantly more spectra to process and search for emission lines. For example, 10% of sources in the full WISP+3D-HST catalog have continuum magnitudes in the range $24 < H < 24.5$, amounting to ~ 2500 more extracted spectra per square degree.

3. EMISSION SIZE MEASUREMENTS

We aim to use *HST* grism observations to predict the distribution of emission sizes that Euclid will detect as well as the effect source size will have on the Euclid selection function. Observations of a source, and therefore any resulting measurements of the source size and shape, are the result of the convolution of the intrinsic source shape and the point spread function (PSF) of the telescope and instrument. Before analyzing the size distributions, we must first deconvolve the observations with the PSF in order to recover the intrinsic sizes of the sources in the WISP and 3D-HST+AGHAST catalogs. In Section 3.1 we describe the construction of an empirical PSF for each imaging filter and as a function of wavelength for the grisms. We then present the methods for measuring the emission sizes in Section 3.2.

3.1. Constructing an empirical PSF

We construct an empirical PSF using the imaging and spectral stamps of ~ 3000 stars in the WISP fields included in the WS. The stars are selected by H band magnitude and half-light radius as described in Bruton et al. (*in prep*). We consider stars in the magnitude range $22 \geq H \geq 18.3$, where the faint limit is imposed to avoid selecting compact galaxies, and the upper limit conservatively removes stars that may be saturated or approaching the non-linearity regime of the detector where the *Source Extractor* centroids are unreliable. We do not explicitly select isolated sources, which are ideal for minimizing imaging and spectral overlap with nearby sources, but instead depend on the median profile to provide an accurate representation of the observed PSF.

We begin by describing the creation of the imaging PSF. For each star in the *Source Extractor* imaging catalog, we create $10'' \times 10''$ stamps in all available IR filters. We then construct a radial profile of each star by calculating the azimuthally averaged flux in circular annuli of increasing radii. The median radial profile for F160W is shown in Figure 3 as an example. The half width at half maximum (HWHM) is indicated by the circle and dashed lines and corresponds to a FWHM = $0''.18$, larger than the FWHM reported in the WFC3 Instru-

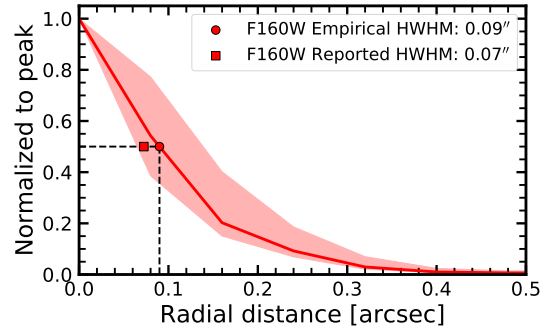


Figure 3. The empirical *HST* WFC3 F160W PSF measured using ~ 1720 stars. The median azimuthally averaged radial profile is shown as the red curve, and the shaded band includes $\pm 1\sigma$ of all measured profiles. The half width at half maximum is indicated by the circle and dashed lines. The measured HWHM is larger than that reported in the WFC3 Handbook (square).

ment Handbook⁵ for Cycle 26: $0''.145$ for F160W. As we have measured the radial profile of each star individually, rather than from a stacked image, we conclude that the discrepancy is not caused by problems centering the stars in the imaging stamps. There are not enough stars in all fields containing ELGs to measure a field-dependent PSF. Additionally, the *HST* PSF is undersampled. The FWHM of an undersampled PSF is typically measured by sampling the PSF with multiple stars and therefore multiple sub-pixel centroid positions. We therefore take the median profile as the effective PSF and adopt this FWHM for all ELGs, including those in 3D-HST+AGHAST fields. We note that the values reported in the handbook are listed before pixelation and are therefore expected to be smaller than the measurements of the pixelated PSF we perform here, though slight variations in the telescope focus during these observations can also contribute to the discrepancy. Here we aim to deconvolve the PSF from galaxy emission size measurements, and so adopt the larger, empirically-measured FWHMs to ensure the galaxy emission and PSF are measured consistently from the same data.

The grism PSFs are measured on median-combined spectral stamps in order to achieve a high S/N. As aXe drizzles together the individual exposures using the positions of the sources in the corresponding individual imaging exposures, the spatial centroid and the wavelength solution are consistent enough in each spectral stamp to allow stacking. The combined stellar spectrum in G141 is displayed in the top panel of Figure 4. We measure the FWHM of the combined spectrum along the

⁵ www.stsci.edu/hst/wfc3/documents/handbooks/currentIHB

Table 2. Empirical WFC3 PSFs

Filter	N_{stars}	Measured FWHM	Reported FWHM
		[arcsec]	[arcsec]
F110W	1408	0.207	0.130
F140W	916	0.180	0.141
F160W	1720	0.180	0.145
G102	1523	0.164	0.128
G141	2749	0.178	0.141

NOTE—The reported FWHM are taken from the WFC3 Handbook and represent the measurement of the PSF pre-pixelation and at the wavelengths that most closely match the pivot wavelengths of the filters. The grism FWHMs are those for the approximate midpoint wavelengths: 10000 Å for G102 and 14000 Å for G141.

spatial axis (vertically in Figure 4) by fitting a Gaussian to the flux profile at each wavelength in a moving average window 5 pixels wide. The FWHM measured in this manner is plotted as a function of wavelength in the bottom panel of Figure 4 (black curve). We smooth the wavelength-dependent FWHM using a Savitzky-Golay filter (Savitzky & Golay 1964) with a window 11 pixels wide (red curve). Finally, we calculate the integrated FWHM over the passband of each imaging filter and confirm that the FWHMs measured in the grisms are consistent with those measured in imaging. This comparison is also displayed in Figure 4 for G141, F140W, and F160W. Table 2 provides the measured FWHM in each filter as well as the number of stars that were included in the measurement.

3.2. Modeling Continuum and Line Emission

We measure the sizes of each ELG in both the continuum and the $\text{H}\alpha + [\text{N II}]$ emission. The continuum sizes are measured on $9'' \times 9''$ stamps created from the H band direct images in either the F140W or F160W filters. The emission line sizes are measured on stamps created from the two-dimensional spectra extracted from the full grism images (see Section 2.1 for a description of this spectral extraction). We create stamps for each emission line from the 2D spectra as follows. The stamps extend 35 pixels in the wavelength direction (~ 850 Å in G102, ~ 1600 Å in G141) on either side of the center of the emission line. We fit the continuum row by row in the stamp by fitting a line to the fluxes in the pixels on either side of the line excluding 8 pixels (370 Å) centered at the wavelength of the emission line. We subtract each linear fit from the corresponding full row and are left with a continuum-subtracted map of each galaxy

in the given emission line. An example of an $\text{H}\alpha + [\text{N II}]$ emission line map is shown in the bottom left panel of Figure 5.

Next, we model the shapes of the continuum and $\text{H}\alpha + [\text{N II}]$ emission for the Euclid WS sources using Sérsic profiles. The Sérsic profile describes the intensity of the source as a function of radius (Sérsic 1963, 1968). The functional form is given by:

$$I(R) = I_e \exp \left\{ -b_n \left[\left(\frac{r}{r_e} \right)^{1/n} - 1 \right] \right\}, \quad (1)$$

where r_e is an effective or scale radius and I_e is the profile intensity at r_e . The Sérsic index, n , determines the shape of the light profile, with larger values corresponding to more centrally concentrated sources. A value of $n = 1$ results in an exponential profile that is a good approximation of disk galaxies, while $n = 4$ gives the de Vaucouleurs (1948) profile approximating elliptical galaxies. The constant b_n is coupled to n such that r_e is the half-light radius — or the radius that encircles half of the light emitted by the source — and is therefore not a free parameter.

For each image stamp and emission line map, we determine the best-fit Sérsic models using the two-dimensional image fitting software GALFIT⁶ (v3.0; Peng et al. 2010). In fitting, GALFIT convolves the Sérsic profiles with a Gaussian kernel to emulate the PSF, such that the best-fit model parameters will be those of the PSF-corrected emission shapes and sizes. For the continuum emission measured in the imaging stamps, the FWHM of either the F140W or F160W filter is used. The FWHM for each emission line map is taken from the smoothed function described in Section 3.1 at the wavelength of the line. We use relatively large stamp sizes ($9''$ in the continuum) so that a sufficient number of sky pixels are available for the GALFIT fitting algorithm. However, we ensure that close neighboring sources do not interfere with the fitting of the target source by constraining all models to have centroids within ± 3 pixels of the stamp centers. The stamps, models, and residuals for one of the WISP sources are shown in Figure 5 as an example of the model fitting.

We perform the same size measurement on the simulated data discussed in Section 2.3 and Appendix A.1. Recall that the simulated sources are the same size and shape in both the continuum and emission lines. The effective radii should therefore be tightly correlated, and we can use the scatter as an estimate of the statistical

⁶ <https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html>

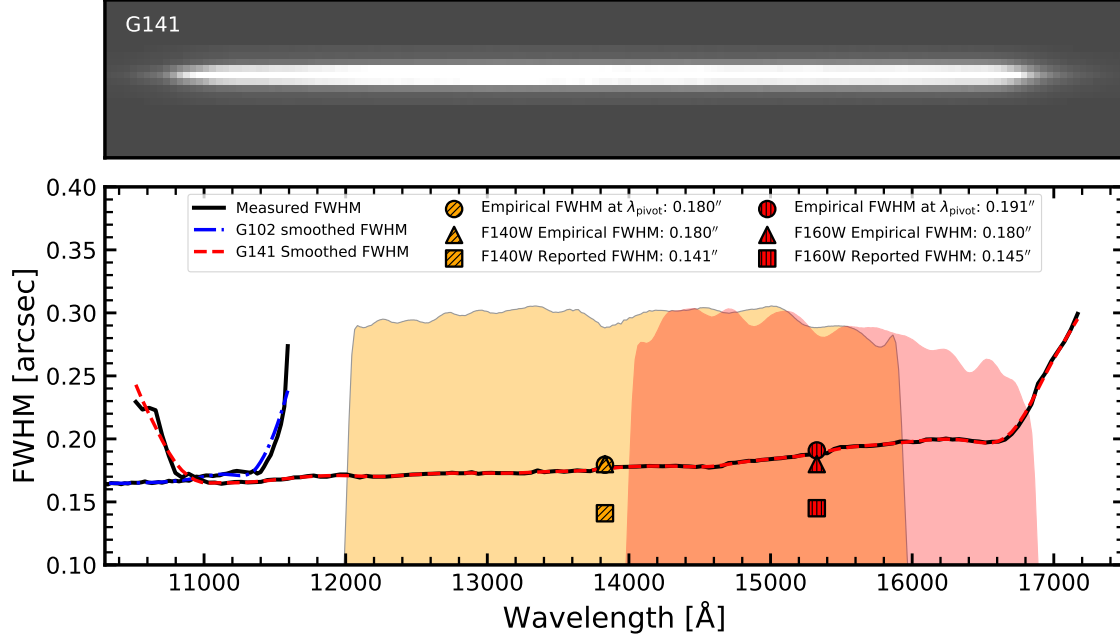


Figure 4. The empirical G141 PSF, measured from the stacked spectra of ~ 2700 stars. The stacked spectrum is shown in the top panel. The measured FWHM as a function of wavelength is shown in black for both grisms. The smoothed wavelength-dependent FWHM is shown in red (blue) for G141 (G102). The FWHMs integrated over the F140W and F160W filter profiles are plotted as orange and red circles, respectively, at the filter pivot wavelengths. These values are consistent with the FWHMs we measure for each filter in the imaging stamps (triangles), while the FWHM reported in the WFC3 Handbook for Cycle 26 (squares) are both lower by a factor of ~ 0.2 – 0.3 . We focus here on the filters used in the analysis of the Euclid WS: F140W, F160W, and G141. The PSF FWHMs for all filters, including F110W and G102, are listed in Table 2.

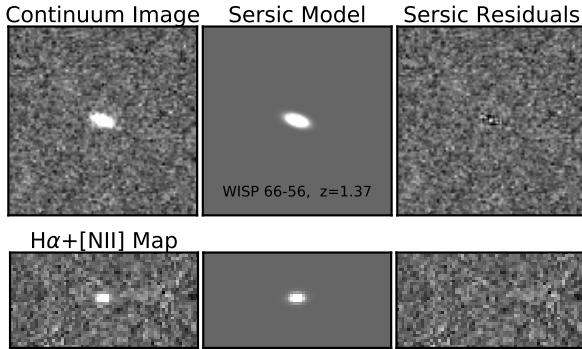


Figure 5. The best-fit Sérsic models for the continuum image (top row) and $H\alpha$ emission line map (bottom row) for an example source. The columns from left to right show the input image stamps, the Sérsic model, and the residuals.

error of our model fitting. As the synthetic sources were simulated as two-dimensional Gaussians, we similarly fit the simulated data with elliptical Gaussian models rather than the Sérsic profiles used for the real sources.

The R_{eff} for the simulated data are shown in Figure 6, where here R_{eff} refers to a circularized radius constructed from the standard deviation of the Gaussian model along each axis, $R_{\text{eff}} = \sqrt{\sigma_x \sigma_y}$. The median $H\alpha$ +[N II] R_{eff} in bins of continuum R_{eff} are plotted

as squares with 1σ error bars. The standard deviation of the relation between the continuum and emission line R_{eff} is $\sim 0''.05 - 0''.15$. The continuum and $H\alpha$ +[N II] emission sizes are correlated down to small radii, $R_{\text{eff}} \sim 0''.07$, below which the R_{eff} are smaller than one pixel in the grism spectra and therefore unreliable. We present the relationship between continuum and $H\alpha$ +[N II] R_{eff} for the observed WS sources in Section 4.2.2.

4. RESULTS AND DISCUSSION

4.1. Emission Line Number Counts

We begin by considering the number of ELGs that meet the selection criteria for the Euclid WS. Galaxies emitting $H\alpha$ +[N II] are the main target for the dark energy science, as they will be used to trace the large scale structure at $z \sim 1 - 2$. There are 1939 ± 21 $H\alpha$ +[N II]-emitters deg^{-2} in the WS from $0.9 \leq z \leq 1.6$ and an additional 288 ± 9 [O III] $\lambda 5007$ -emitters deg^{-2} up to $z \sim 2.3$. Correcting these observed counts for the incompleteness of the WFC3 grism data, there are 3266 ($H\alpha$ +[N II]) and 445 ([O III] $\lambda 5007$) deg^{-2} , respectively. In addition to the WS sources with $H\alpha$ +[N II] and [O III] $\lambda 5007$ emission, there are a handful of sources at lower redshift ($z \sim 0.4$) that were selected due to the

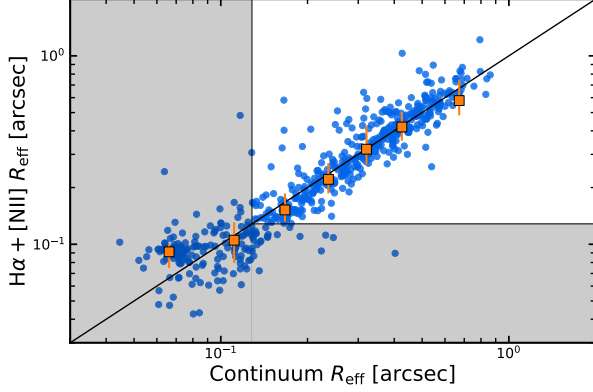


Figure 6. The effective radii of simulated sources measured in both the continuum and $H\alpha + [N II]$ emission. The orange squares show the median values and 1σ scatter in bins of equal number of sources. Simulated sources are both created by and fit with elliptical Gaussian models. Since **axSIM** creates sources that are the same size in both the continuum and line emission, we take the $\sim 0''.05 - 0''.15$ scatter in this relationship as an estimate of the statistical error of our model fitting. The shaded area indicates the size of one pixel in the WISP images, where the pixel scale is $0''.13/\text{pixel}$.

strength of the $[S III]$ and He I emission. The number counts with and without completeness corrections of all selected emission lines are presented in Table 3.

We obtained the errors presented on the number counts in Table 3 through a Monte Carlo process by creating 200 realizations of the full WISP+3D-HST emission line catalog, re-running the WS sample selection, and measuring the resulting distribution of number counts. For the observed number counts (N_{obs}), each catalog realization is generated with redshifts and emission line fluxes (and therefore EWs) pulled randomly from Gaussian distributions centered at the measured values and with standard deviations equal to the uncertainties on these measurements in the catalog. The number of sources recovered by the selection criteria varies from realization to realization. For the completeness-corrected number counts (N_{corr}), we leave the line fluxes and redshifts untouched and pull the completeness corrections from Gaussian distributions with standard deviations equal to the uncertainties on the completeness corrections. In this case, the number of recovered sources stays the same, while the completeness-corrected number varies. In both cases, we report the 16th and 84th percentiles as the lower and upper errors in Table 3, respectively.

The cumulative number counts of both $H\alpha + [N II]$ -emitters and $[O III] \lambda 5007$ -emitters are shown in Figure 7. The observed counts are shown as fainter points with Poisson uncertainties determined by the number of sources in each bin. The completeness-corrected counts

Table 3. WS number counts for lines with $1.25 \leq \lambda_{\text{obs}} \lesssim 1.7 \mu\text{m}$

	Flux	N_{obs}	$N_{\text{obs}}/\text{deg}^2$	$N_{\text{corr}}/\text{deg}^2$
$H\alpha + [N II]$ ($0.9 \leq z \lesssim 1.6$)	≥ 4	$269^{+6.2}_{-7.0}$	$478.1^{+10.9}_{-12.4}$	$704.5^{+19.7}_{-18.0}$
	≥ 3	516 ± 10.0	917.2 ± 17.8	$1421.0^{+42.0}_{-35.0}$
	≥ 2	1091 ± 12.0	1939.2 ± 21.3	$3266.0^{+157.7}_{-174.8}$
	≥ 1	$2378^{+17.8}_{-19.7}$	$4226.7^{+31.7}_{-34.9}$	$7887.3^{+148.5}_{-166.0}$
$[O III] \lambda 5007$ ($1.5 \leq z \lesssim 2.4$)	≥ 4	$20^{+1.0}_{-2.0}$	$35.5^{+1.8}_{-3.6}$	$46.0^{+2.2}_{-2.0}$
	≥ 3	$46^{+2.0}_{-2.2}$	$81.8^{+3.6}_{-3.8}$	$112.2^{+3.8}_{-2.5}$
	≥ 2	162 ± 5.0	287.9 ± 8.9	$444.6^{+15.5}_{-10.6}$
	≥ 1	$517^{+8.3}_{-9.0}$	$918.9^{+14.8}_{-16.0}$	$1608.5^{+14.6}_{-11.9}$
$[S III] \lambda 9069$ ($0.38 \leq z \lesssim 0.87$)	≥ 4	6 ± 1.0	10.7 ± 1.8	14.6 ± 1.3
	≥ 3	6 ± 1.0	10.7 ± 1.8	14.6 ± 1.3
	≥ 2	$6^{+1.0}_{-2.0}$	$10.7^{+1.8}_{-3.6}$	14.6 ± 1.3
	≥ 1	6 ± 2.0	10.7 ± 3.6	14.6 ± 1.3
$[S III] \lambda 9532$ ($0.31 \leq z \lesssim 0.78$)	≥ 4	4 ± 1.0	7.1 ± 1.8	$11.2^{+1.6}_{-1.2}$
	≥ 3	$6^{+1.0}_{-2.0}$	$10.7^{+1.8}_{-3.6}$	$15.7^{+1.5}_{-1.4}$
	≥ 2	$10^{+3.0}_{-2.0}$	$17.8^{+5.3}_{-3.6}$	$25.1^{+1.9}_{-1.3}$
	≥ 1	20 ± 3.0	35.5 ± 5.3	$52.6^{+1.7}_{-1.5}$
He I $\lambda 10830$ ($0.15 \leq z \lesssim 0.57$)	≥ 4	3 ± 1.0	5.3 ± 1.8	$7.9^{+1.8}_{-1.4}$
	≥ 3	$6^{+2.0}_{-1.0}$	$10.7^{+3.6}_{-1.8}$	$18.8^{+3.9}_{-2.3}$
	≥ 2	$8^{+2.0}_{-1.2}$	$14.2^{+3.6}_{-2.1}$	$28.9^{+7.2}_{-4.0}$
	≥ 1	10 ± 2.0	17.8 ± 3.6	$35.6^{+5.1}_{-6.4}$

NOTE—Observed (N_{obs}) and completeness-corrected (N_{corr}) cumulative number counts. Numbers presented here are for unique sources, i.e., ELGs with both $H\alpha + [N II]$ and $[O III] \lambda 5007$ are counted only for $H\alpha + [N II]$. The redshift ranges associated with each emission line are given for observed wavelengths $12500 \leq \lambda_{\text{obs}} \lesssim 17000 \text{ \AA}$, where the approximate upper limit is set by the decreasing sensitivity of the *HST* G141 grism. The line fluxes indicated in the first column are $\times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$.

are calculated as

$$N_{\text{corr}} = \sum_i \frac{1}{C_i}, \quad (2)$$

where C_i is the completeness for each source in the bin. The error bars are obtained by varying the completeness corrections maximally within the uncertainties, i.e. $C_i + \sigma_{C_i}$ and $C_i - \sigma_{C_i}$. These error bars therefore represent the range of possible number densities given the uncertainties on the completeness corrections. The number counts are separated into two redshift bins in the left column to highlight the evolution in the number density with redshift due to the increasing luminosity limit. There is a factor of more than 1.5 times more $H\alpha + [N II]$ -emitters at $0.9 \leq z < 1.2$

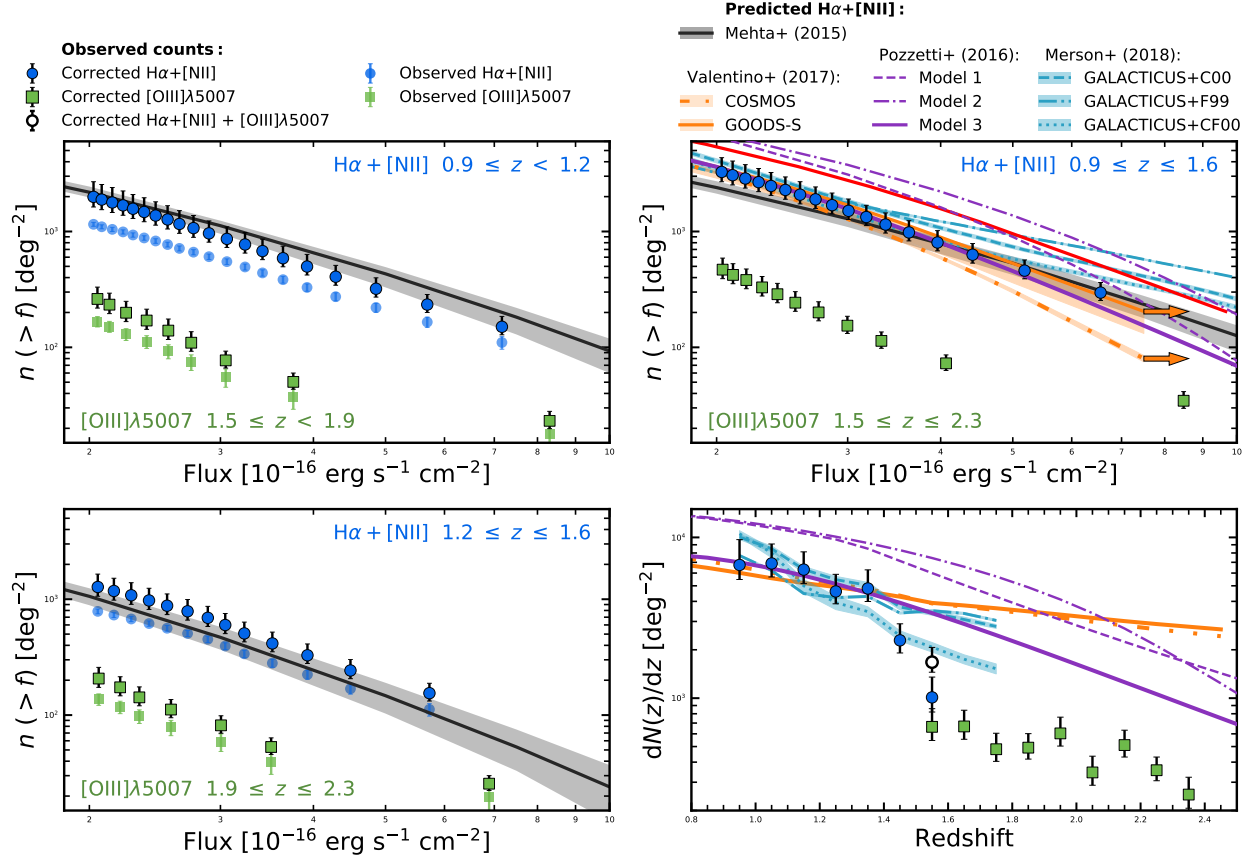


Figure 7. The cumulative number counts (left column and top right panel) and redshift distribution (bottom right) of $H\alpha + [N II]$ and $[O III] \lambda 5007$ -emitters in the WS. In the left column we have separated the cumulative number counts into two redshift bins to demonstrate the evolution in the number counts of each line with redshift. The number counts of $H\alpha + [N II]$ and $[O III] \lambda 5007$ -emitters are shown as blue circles and green squares, respectively. The fainter points are the observed number counts and the larger, solid symbols indicate those that have been corrected for survey incompleteness. The black curve indicates the $H\alpha + [N II]$ predictions from Mehta et al. (2015) in each redshift bin. In the top right panel, we compare the observed, completeness-corrected $H\alpha + [N II]$ number counts across the full redshift range to those predicted by Mehta et al. (2015) (black curve); the models from Pozzetti et al. (2016) (purple curves); Valentino et al. (2017) for galaxies in the COSMOS (dot-dashed orange) and GOODS-S (solid orange) fields; and Merson et al. (2018) for dust models from Calzetti et al. (2000) (C00; dashed blue), Ferrara et al. (1999) (F99; dot-dashed blue), and Charlot & Fall (2000) (CF00; dotted blue). The arrows indicate the level of uncertainty in number counts associated with the choice of $[N II]$ correction (see the text for details). The redshift distributions (dN/dz) of the WS ELGs are shown in the bottom right panel, again compared with the models from Pozzetti et al. (2016), Valentino et al. (2017), and Merson et al. (2018). In the redshift bin where both $H\alpha + [N II]$ and $[O III] \lambda 5007$ are both accessible to the WFC3 grism, the total ($H\alpha + [N II]$) + ($[O III] \lambda 5007$) counts are indicated by an empty circle.

than at $1.2 \leq z \leq 1.6$. The observed number counts are in good agreement with the predictions from Mehta et al. (2015), calculated using a subset of WISP fields from the earlier data reduction and original line finding procedure. The top right panel includes the cumulative number counts for the full redshift ranges available to the *HST* grism: $0.9 \leq z_{H\alpha + [NII]} \lesssim 1.6$ and $1.9 \leq z_{[OIII]\lambda 5007} \lesssim 2.3$. Finally, the redshift distributions of $H\alpha + [N II]$ and $[O III] \lambda 5007$ -emitting galaxies (dN/dz) in bins of $\Delta z = 0.1$ are shown in the bottom right panel.

In the right column of Figure 7, we compare the observed $H\alpha + [N II]$ number counts with the empirical models of Pozzetti et al. (2016) in purple. The three models represent different parameterizations of the $H\alpha$ luminosity function and its redshift evolution. For the purposes of comparison, we have converted the $H\alpha$ counts of all three models to $H\alpha + [N II]$ counts using a fixed $[N II]/H\alpha$ line ratio: $H\alpha = 0.71 (H\alpha + [N II])$, the same conversion used in Section 5 of Pozzetti et al. (2016) while comparing the model counts to observations. The observed $H\alpha + [N II]$ number counts in the top right panel of Figure 7 agree most closely with

Model 3, which is the result of a fit to observations presented by Sobral et al. (2013, HiZELS), Colbert et al. (2013, WISP), Yan et al. (1999), and Shim et al. (2009). Model 3 is also one of the models against which the Euclid Flagship mock catalog has been calibrated. While the cumulative counts agree with Model 3 at almost all fluxes across the full redshift range, the distribution of $H\alpha$ +[N II]-emitters with redshift falls off at $z \sim 1.5$. For $H\alpha$ +[N II], this redshift corresponds approximately to the wavelengths at which the sensitivity in the G141 grism begins to decrease.

We also show the predictions from Valentino et al. (2017) in orange in the right panels of Figure 7. Valentino et al. (2017) use the large photometric samples in the COSMOS and GOODS-S fields to predict the number counts of ELGs that will be accessible to future galaxy redshift surveys. They derive $H\alpha$ fluxes from the star formation rates obtained via spectral energy distribution fitting and use $H\alpha$ -emitters at $z = 1.55$ observed with the FMOS-COSMOS survey (Silverman et al. 2015) to calibrate the star formation rate to $H\alpha$ conversion. The $H\alpha$ + [N II] predictions for galaxies on the star-forming main sequence in the range $0.9 \leq z \leq 1.6$ are shown in orange in Figure 7. The counts have been corrected for the Eddington bias, which is a bias introduced by measurement uncertainties that can enhance the observed number of bright galaxies compared to fainter galaxies (Eddington 1913). The orange shaded bands indicate the 68% Poissonian confidence intervals, where the authors report the maximum of the upper and lower Poisson uncertainties. The uncertainties due to the Eddington bias correction are not included here, but are available in Table 3 of Valentino et al. (2017). The cumulative flux counts, particularly in the GOODS-S field, are consistent with the *HST* grism measurements at all fluxes, and are in good agreement with the predictions of Mehta et al. (2015) and Pozzetti et al. (2016). The redshift distributions of galaxies in both fields are consistent up to $z \sim 1.5$, where the differential counts from Valentino et al. (2017) follow a shallower evolution than those from the other predictive works.

We note that the different [N II] corrections adopted by each team can introduce some systematic uncertainties and contribute to this disagreement in the blended counts. Specifically, while we have used a single correction for all number counts from Pozzetti et al. (2016), Valentino et al. (2017) employ a complex correction as a function of mass that is smaller on average than that used for the models from Pozzetti et al. (2016). As a result, the $H\alpha$ -only counts (i.e. not including the [N II] correction) from Valentino et al. (2017) lie between Models 1 and 3 of Pozzetti et al. (2016), yet their

$H\alpha$ + [N II] counts are generally lower and agree most closely with Model 3 (see Fig. 12 from Valentino et al. 2017 compared with the upper right panel of Figure 7). The median $\log_{10}([N II]/H\alpha)$ of the sample in Valentino et al. (2017) is ~ -0.45 for galaxies with an $H\alpha$ flux of $2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ (see their Fig. 9), while the correction applied here to Models 1, 2, and 3 corresponds to $\log_{10}([N II]/H\alpha) = -0.39$. The arrows in the upper right panel of Figure 7 indicate the extent to which the number counts of Valentino et al. (2017) would change if the $H\alpha$ + [N II] fluxes were boosted by an additional factor (corresponding to $\Delta \log_{10}([N II]/H\alpha) = 0.06$) to match the [N II]/ $H\alpha$ ratio adopted by Pozzetti et al. (2016). These arrows can be interpreted as the approximate uncertainty in number counts due to the [N II] correction. As the [N II]/ $H\alpha$ line ratio remains uncertain at these redshifts and observations at the resolution of the *HST* grism cannot provide adequate constraints, these uncertainties are an important consideration when comparing $H\alpha$ and $H\alpha$ + [N II] number counts from different models and observations.

We finally compare the observations with predictions from Merson et al. (2018), who use the GALACTICUS galaxy formation model (Benson 2012) and the dust attenuation methods from Ferrara et al. (1999), Calzetti et al. (2000), and Charlot & Fall (2000) to predict $H\alpha$ + [N II] number counts in the redshift range $0.9 \leq z \leq 1.55$, matching that available to the *HST* grism. Merson et al. (2018) use $H\alpha$ + [N II] blended fluxes where the [N II]/ $H\alpha$ ratios are determined by cross-matching the stellar mass and specific star formation rate of each GALACTICUS galaxy to the SDSS sample from Masters et al. (2016). For each dust model, the red curve and shaded region in Figure 7 is the mean and standard deviation of 1000 Monte Carlo realizations sampling the model's optical depth parameters. The likelihoods for the sampling were constructed as $\mathcal{L} \propto \exp(-\chi^2/2)$, where the χ^2 values were obtained by stepping through the dust parameter space and comparing GALACTICUS counts to the WISP counts from Mehta et al. (2015) for $0.7 \leq z \leq 1.5$ (see Merson et al. 2018, for more information). While the *HST* grism $H\alpha$ + [N II] number counts presented in this paper (blue circles in Figure 7) are lower than all three predictions from Merson et al. (2018) for the brightest galaxies, the predictions and observations are consistent at the depth of the Euclid Wide Survey.

The number of galaxies observed by WISP+3D-HST are a lower limit to those that will be observed by Euclid. We remind the reader that the upper wavelength of the Euclid Red grism is $\sim 18500 \text{ \AA}$, $1500 \text{ \AA}$ redder than the WFC3 G141 grism. The Euclid $H\alpha$ + [N II]

and [O III] $\lambda 5007$ observations will therefore extend out to $z \sim 1.8$ and $z \sim 2.7$, respectively. Euclid will detect more sources per square degree than those reported here. However, as can be seen in Figure 2, at the depth of the Euclid Wide Survey, the number of detected ELGs drops quickly with redshift. The majority of the ELGs that Euclid detects will be $H\alpha + [N II]$ at $z \lesssim 1.5$, a population that is fully sampled by the *HST* grism observations presented here.

With these *HST* grism observations, we show that Euclid will meet the goal of measuring redshifts for ~ 25 million galaxy redshifts over 15000 deg^2 . Extrapolating the completeness-corrected number densities to the full Euclid Wide Survey area provides a rough estimate of ~ 48 million $H\alpha + [N II]$ -emitters and ~ 6 million [O III] $\lambda 5007$ -emitters down to $f \geq 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$. Even the observed, uncorrected counts, which provide an estimate in the case the Euclid galaxy redshift survey and these *HST* grism observations suffer from the same level of incompleteness⁷, are larger than the planned number of galaxy redshifts. These *HST* observations therefore contribute a valuable resource to the effort to calibrate and verify the performance of the planned Euclid survey. Finally, we note that at the resolution of the Red grism, Euclid will be able to resolve the $H\alpha$ and [N II] $\lambda\lambda 6548, 6584$ doublet for compact galaxies. However, the contribution from [N II] for compact, low-mass ($< 10^{10} M_{\odot}$) galaxies is $\lesssim 10\%$ (e.g., Erb et al. 2006; Masters et al. 2016; Faisst et al. 2018). Therefore, even for the galaxies for which Euclid will resolve the two lines, we do not expect a [N II] correction to the $H\alpha + [N II]$ fluxes to significantly affect our results.

4.2. Emission and Continuum Sizes

The location and size of the window used for spectral extraction from grism images depend on the detection of the galaxy in a direct image. This process relies on a few assumptions, including (1) that the full extent of the source has been detected in the direct image, and (2) that the emission line size is correlated with the source size in the direct image. We briefly explore both assumptions below.

4.2.1. Flux Loss from Spectral Extraction

The first case is analogous to slit or fiber losses in spectroscopic observations obtained with apertures smaller than the source. In this case, flux loss depends par-

⁷ However, with multiple roll angles planned for the Euclid grism observations, the incompleteness due to spectral confusion and emission lines lost to nearby bright neighbors will be lower than it is for the *HST* grism data, particularly that of the WISP parallel data.

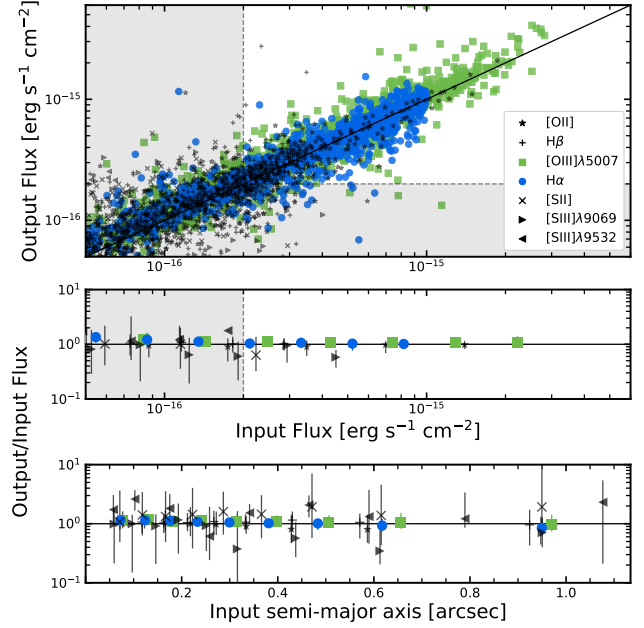


Figure 8. A comparison between the input and measured (or “output”) emission line fluxes for the simulated sources described in Section 2.1. The median flux ratios for each line along with 1σ error bars are shown in bins of input flux (middle panel) and input source semi-major axis (bottom panel). There is neither a dependence on source size nor on line flux down to the $\sim 6 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$, the flux limit of the Euclid Deep survey. The $H\alpha$ and [O III] $\lambda 5007$ lines are emphasized because they are the most common primary lines. The scatter in the relationship for other lines likely reflects the fact that these lines are often measured below the S/N threshold of the emission line detection process. We conclude from the flux agreement for $H\alpha$ and [O III] $\lambda 5007$ that we are not systematically missing flux in our measured spectra.

tially on the color and morphology of the galaxies (e.g., Brinchmann et al. 2004) and therefore is not a simple systematic flux offset. We can test the extent of the flux lost in WFC3 slitless grism data with the simulations described in Section 2.1. The aXeSIM software generates the synthetic spectrum of a source by convolving an imaging template with a template spectrum. We use two-dimensional Gaussians to model the sources, but in principle any image of the source can be used. Regardless, the shape and size of the emission at each wavelength in the synthetic spectrum is assumed to be the same as in the direct image. The one-dimensional spectrum is then produced by collapsing the extracted spectral stamp along the spatial axis. If the extraction window is too small in the spatial direction, the flux in the one-dimensional spectrum will underestimate the total. We can therefore determine what fraction of flux is lost

in the emission lines by comparing the input values with those recovered and measured by the full analysis process. The ratio of the measured to input flux is shown in Figure 8 as a function of input line flux and input semi-major axis, where we find that the fluxes are consistent for the primary lines $H\alpha$ and $[O\ III]\ \lambda 5007$ down to the flux limit of the Euclid Deep survey. Additionally, there is no clear dependence on source size (bottom panel), indicating that the extraction windows are adequate even for the largest sources, i.e., those most likely to have a surface brightness that drops below our detection threshold. However, we note that due to incompleteness, there are very few sources with semi-major axis $a > 0''.7$.

4.2.2. $H\alpha+[N\ II]$ Emission Size Measurements

As discussed in Section 3.2, we fit Sérsic models to the continuum images and emission line maps. We show the size distributions as a function of redshift, $H\alpha+[N\ II]$ flux, and H magnitude in Figure 9, where R_{eff} refers to the half-light radius of the Sérsic profile. We have removed from this figure and analysis six sources⁸ for which the models could not be successfully fit ($< 1\%$ of the sample). The R_{eff} measured in the $H\alpha+[N\ II]$ emission line maps are shown as black points while the continuum R_{eff} are represented by the shaded, two-dimensional histogram calculated using a Gaussian kernel density estimation. The continuum and $H\alpha+[N\ II]$ size distributions are shown in the right-most panel along with the median and quartiles in blue dotted and black dashed lines, respectively. The median continuum R_{eff} is $0''.37$ ($\sim 2.9\text{--}3.1$ kpc for redshifts $0.9\text{--}1.5$) with an interquartile range of $0''.2$ ($= 0''.48 - 0''.28$). The $H\alpha+[N\ II]$ size distribution is slightly wider with a median of $0''.39$ ($\sim 3.0\text{--}3.3$ kpc) and an interquartile range of $0''.27$ ($= 0''.55 - 0''.28$).

These R_{eff} values are on the low end of what is presented for continuum emission by van der Wel et al. (2014) and for $H\alpha$ and continuum emission by Nelson et al. (2016). For example, Nelson et al. (2016) find $r_{1/2, H\alpha} = 2.91$ kpc and 3.10 kpc for galaxies in the mass ranges $9.5 < \log(M_*) < 10.0$ and $10.0 < \log(M_*) < 10.5$, respectively, whereas we expect some if not all of the bright ($H \lesssim 24$) galaxies in the WS to be in a higher stellar mass bin. The discrepancy between our measurements and those of these other works is most

likely due to the lower surface brightness limits these authors reach by stacking images and spectral stamps (e.g., $\sim 1 \times 10^{-18}$ erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$ by Nelson et al. 2016), enabling them to recover more of the flux in the wings of each source. In this paper, we measured R_{eff} on individual stamps to reflect the role the continuum and emission line sizes have on the selection function of slitless spectroscopic surveys, but we note that stacking would be required to statistically recover and measure the sizes of such sources.

These half-light radii have been deconvolved with the empirical WFC3 PSF and therefore represent the intrinsic sizes measured to the depth of the *HST* grism observations. The median R_{eff} measured in both the continuum and $H\alpha+[N\ II]$ emission is $< 0''.1$ larger than the size of one pixel on the NISP instrument ($0''.3$). Approximately 20% (40%) of the WS presented here have half-light radii smaller than the NISP pixel in both (either) the continuum and (or) $H\alpha+[N\ II]$. As more flux will be concentrated in each source's central pixel on the NISP detector, sources will be more under-sampled in Euclid observations than they are when observed by *HST*. However, the planned multiple dithers will help compensate for the larger pixel scale.

We next compare the R_{eff} measured in the continuum to that of the $H\alpha+[N\ II]$ emission in Figure 10. The two sizes are correlated, but with significant scatter. The standard deviation of the relation between the continuum and emission line sizes is $\sim 0''.2 - 0''.35$, compared to the $0''.05 - 0''.15$ measured for the simulated sources. As the observed and simulated data have been fit with different models, we also fit the observations with Gaussian models to test whether this increase in scatter is due to model choice. However, the Gaussian R_{eff} of the observed galaxies is very similar to what is shown in Figure 10, and so the observed scatter must be due in part to other causes.

Many of the sources above the one-to-one correlation in the left panel of Figure 10, where the measured $H\alpha+[N\ II]$ R_{eff} is larger than that of the continuum, have broad $H\alpha+[N\ II]$ line profiles along the dispersion direction. The extent of the emission in these cases is not spatial, and these sources are erroneously fit with elongated profiles. For others, the $H\alpha+[N\ II]$ emission is more extended than the continuum as discussed by, e.g., Nelson et al. (2016). For some of the sources with $H\alpha+[N\ II]$ R_{eff} smaller than the continuum, we may be measuring small knots of emission concentrated within a smaller radius than the full galaxy. In these cases, we may be detecting $H\alpha$ from star-forming clumps (e.g., Bournaud et al. 2014; Zanella et al. 2015; Mandelker et al. 2017) while any more extended line emission has

⁸ The spectra of four of these six sources were contaminated by continuum emission from bright neighbors. While this contamination did not overlap with the emission lines, it did result in an over-subtracted continuum in the $H\alpha+[N\ II]$ maps. The other two sources were very close to detector artifacts in the direct images and therefore had incorrectly-measured continuum sizes.

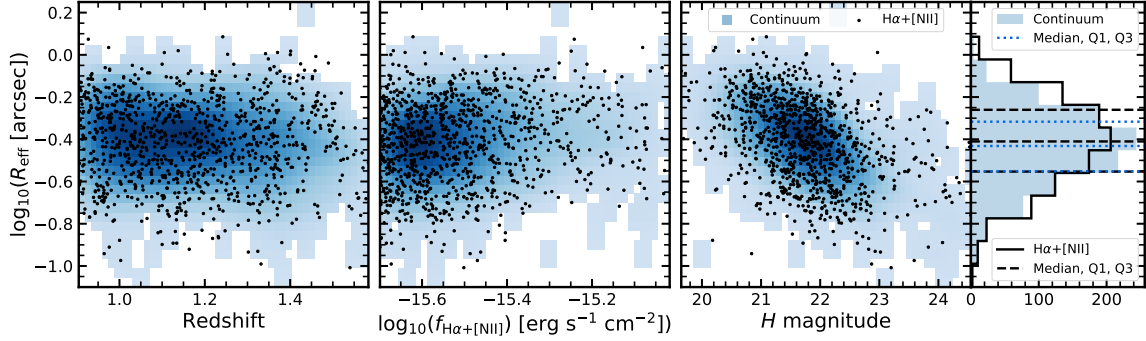


Figure 9. The half-light radii (R_{eff}) measured in the continuum and $\text{H}\alpha + [\text{N II}]$ emission line maps as a function of redshift (left), $\text{H}\alpha + [\text{N II}]$ line flux (middle), and H magnitude (right). The continuum sizes are represented by a Gaussian kernel density estimation shown in blue, where darker colors indicate a larger concentration of sources. The $\text{H}\alpha + [\text{N II}]$ sizes are shown as black points. The two size distributions are plotted in the right-most panel with blue dotted and black dashed lines indicating the median values and interquartile ranges of the continuum and $\text{H}\alpha + [\text{N II}]$ sizes, respectively. The median R_{eff} are $\sim 0''.37 - 0''.39$, and for reference, the Euclid NISP pixel size is $0''.3$.

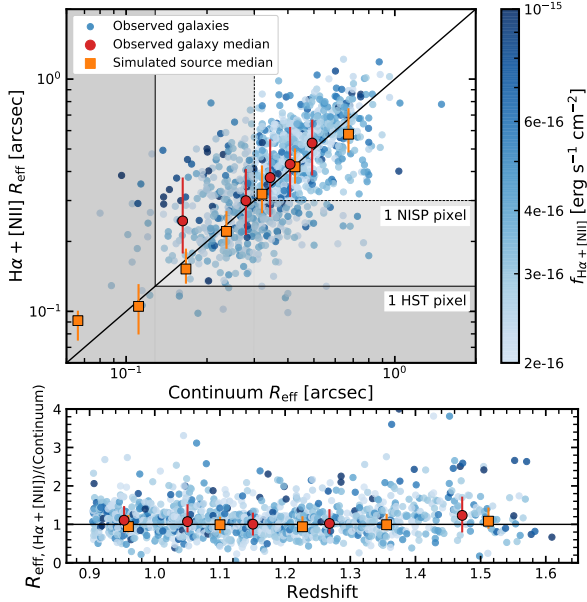


Figure 10. The effective radii of sources measured in both the continuum and $\text{H}\alpha + [\text{N II}]$ emission line maps, color-coded by $\text{H}\alpha + [\text{N II}]$ flux (top panel). The ratio of $R_{\text{eff,H}\alpha + [\text{N II}]} / R_{\text{eff,continuum}}$ is plotted as a function of redshift in the bottom panel. Though there is large scatter, the relation between the two sizes depends on neither line flux nor redshift. The red circles show the median values and 1σ scatter measured for an equal number of sources per bin. The median values and scatter calculated for the simulated sources from Figure 6 are shown as orange squares for comparison. For reference, the shaded regions indicate the size of one WFC3 pixel ($0''.13$, darker region) and one Euclid NISP pixel ($0''.3$, lighter region).

a surface brightness below our detection sensitivity. We note that such sources may have increased noise in the extracted, one-dimensional spectra, as the extraction windows and extraction weights are determined by the

size of sources in the direct imaging (see Section 2.1). The scatter in the $\text{H}\alpha + [\text{N II}]$ -continuum R_{eff} relation in Figure 10 can therefore reveal important information about the optimization of the spectral extraction process and the resulting S/N measured for emission lines.

Part of the scatter may be due to the fact that Sérsic models are simplified representations of galactic light profiles. For example, approximately 25% of the WS sample have either continuum or line emission characterized by clumps or other structure that may indicate merging or interacting systems. In these cases, the single-component fits are too simple to properly model the emission. However, much of this sub-structure will be unresolved when observed with the larger NISP pixel, and single-component models may provide better fits to source continuum and line emission. On the other hand, most disk galaxies have a bulge component that is best fit with larger n . More realistic models may be achieved by allowing for a two-component model fit consisting of both disk-like and bulge-like profiles. The resulting measurements could then be compared with the distributions of bulge and disk lengths and axis ratios in the Euclid Flagship mock catalog.

Regardless, the distribution of emission sizes measured in slitless data, the relation between the continuum and line emission, and the observed scatter in this relation are important quantities for evaluating the effects of the selection function of future grism-based galaxy redshift surveys.

4.3. Equivalent Width of $\text{H}\alpha + [\text{N II}]$

The emission line EW, a measure of the strength of the emission, is a very important property of ELGs that must be correctly included in forecasts for emission line studies. Hydrogen recombination lines such as $\text{H}\alpha$ and $\text{H}\beta$ are produced by the ionizing radiation from young,

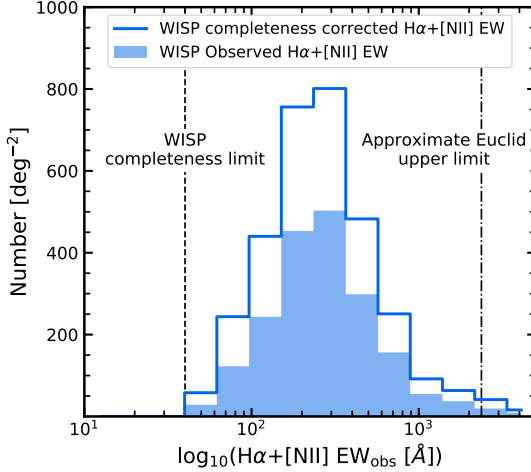


Figure 11. The distribution of $H\alpha+[N II]$ EW in the Euclid WS. The median $EW_{obs, H\alpha+[N II]} \sim 250 \text{ \AA}$. The distributions of the observed and completeness-corrected samples are shown as filled and empty histograms, respectively.

massive stars while the strength of the stellar continuum reflects the buildup of emission from the older, less massive population. The EW of $H\alpha$ is therefore an estimate of the ratio between the average star formation from current and past events. It is a measure of a galaxy’s specific star formation rate, or the star formation rate per unit stellar mass. Given an assumed star formation history, the specific star formation rate can be converted to an age for the galaxy. The addition of $[N II]$ complicates this picture, as the $[N II]$ contribution to the $H\alpha+[N II]$ line flux depends on factors such as mass, metallicity, star formation rate, ionization parameter, and AGN activity and also varies with redshift (e.g., Baldwin et al. 1981; Erb et al. 2006; Kewley et al. 2013; Masters et al. 2016; Kashino et al. 2017; Faisst et al. 2018). It is crucial that the simulations created to evaluate the survey design of missions such as Euclid reproduce the physical properties, and not just the number counts, of the selected population that will be observed. As discussed in Section 4.1, $H\alpha$ and $[N II]$ will be blended at the resolution of the Euclid Red grism for all but the most compact sources, and so the observed joint $H\alpha+[N II]$ EW distribution should also be reproduced in the simulations.

In Figure 11, we present both the observed and completeness-corrected $H\alpha+[N II]$ EW distributions of the Euclid WS. The median observed $H\alpha+[N II]$ EW is $250 \text{ \AA}$, which corresponds to $100 - 125 \text{ \AA}$ for galaxies at $z \sim 1 - 1.5$. The interquartile range of the observed EW is $160.2 - 397.5 \text{ \AA}$. The EW distribution ranges from $40 \text{ \AA}$ (the EW completeness limit for the WISP emission line detection algorithm) to $\gtrsim 4000 \text{ \AA}$.

The WISP completeness limit represents the EW below which the detection algorithm does not reliably detect emission peaks in the grism spectra (see Section 2.1) and is therefore applicable to all grism observations run through this software. The Euclid Wide survey will have an approximate upper EW limit of $\sim 2370 \text{ \AA}$, calculated for the $2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ flux limit and a $H = 24$ (for $\lambda_{pivot} = 18000 \text{ \AA}$). While there are $\sim 32 \text{ sources deg}^{-2}$ in the WS above this approximate limit, only $\sim 4 \text{ deg}^{-2}$ are also fainter than $H = 24$. The WISP completeness limit and approximate Euclid Wide Survey limit are indicated in Figure 11 by dashed and dot-dashed lines, respectively.

4.4. $[O III]$ Line Profile

As described in Section 2.1.1, we assume single emission lines in the grism spectra are $H\alpha$ unless the line has noticeable asymmetry indicative of the $[O III]+H\beta$ line profile. We now briefly consider whether this assumption leads us to selectively identify $[O III]$ lines with asymmetric profiles.

We compare the $[O III]$ line profiles of sources with multiple lines, and therefore secure redshifts, with the profiles of single line emitters that have been identified as $[O III]$. The question is whether a sample of sources with multiple lines have, on average, a more symmetric profile because the characteristic asymmetry is not needed for line identification. We create two subsets of $[O III]$ -emitters randomly sampled from the WISP emission line catalog. All sources have $[O III]$ fluxes with $S/N \geq 5$. The $H\alpha+[N II]$ fluxes in the first subset also have a $S/N \geq 5$, making this a sample of confirmed $[O III]$ -emitters. The second subset is taken at $z \geq 1.6$, where $H\alpha+[N II]$ has redshifted out of G141, and excludes any sources with an $[O II]$ $S/N \geq 2$. We restrict both selections to $z \geq 1.24$ so all emission lines are measured in G141 with the same resolution and dispersion. There are ~ 120 sources in each sample. The individual one-dimensional spectra are represented by faint dots in Figure 12, and the median spectrum is shown as the black curve. We also median combine 20% of the two-dimensional spectra for each sample, displayed below the one-dimensional spectra. All spectra (one- and two-dimensional) are shifted to the restframe and normalized by the integrated $[O III]$ line flux.

The $[O III]$ line profiles for each sample are indicated in blue (confirmed) and red (unconfirmed). As can be seen in the inset in the bottom panel, the median profile of confirmed $[O III]$ -emitters is indeed more symmetric than that of the unconfirmed. To quantify the level of asymmetry, we fit both line profiles with a Gaussian function and measure the residuals. Within $\pm 20 \text{ \AA}$ of

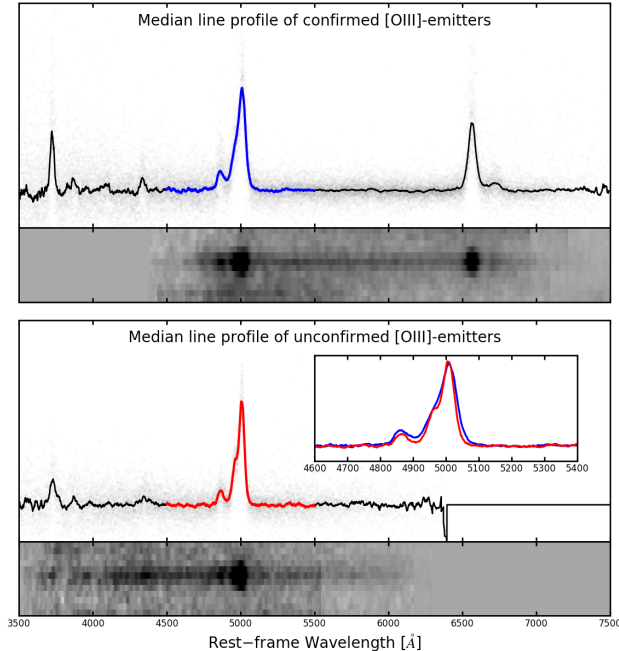


Figure 12. The [O III] line profile of sources with secure redshifts (blue, top panel) is compared with that from sources with redshifts based on the detection of a single emission line (red, bottom panel). The line profile of the unconfirmed [O III]-emitters is more asymmetric than that of confirmed [O III]-emitters. When fit with a symmetric profile, the residuals around the wavelength of the [O III] $\lambda 4959$ line are $> 5\times$ larger for the red profile than for the blue. The asymmetry is needed to make a reliable line identification in the absence of additional emission lines.

the [O III] $\lambda 4959$ line, the residuals of the fit to the red profile in Figure 12 are a factor of > 5 times larger than that of the fit to the blue profile. The median 5σ depth in the WISP spectra at the wavelengths of the [O III] lines is $6 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. This bias could be even more pronounced for shallower data such as that of the Euclid Wide survey, where the [O III] $\lambda 4959$ line will fall below the detection limit more often than in deeper spectra. The resulting [O III] $\lambda 5007$ line profiles may appear symmetric and be more likely to be identified as $\text{H}\alpha$ under visual inspection. However, the Euclid Redgrism will have a higher spectral resolution ($R \sim 380$ compared with $R \sim 130$ for G141), and galaxies will appear more compact on the larger pixel scale ($0''.3$ versus $0''.13$). Additionally, as discussed in Section 2.2, unaided human classification will not be a feasible method for line identification in the Euclid data.

4.5. Redshift Accuracy

The measurement of the BAO signal in galaxy clustering requires accurate distance measurements to a large

sample of galaxies. It has been shown through simulations that the redshift accuracy for a survey such as Euclid must be $\sigma_z/(1+z) \leq 0.1\%$ (Wang et al. 2010; Laureijs et al. 2011). As shown by Colbert et al. (2013) with simulated sources added to real WISP fields, the required redshift accuracy is achievable with $R > 200$ grism spectroscopy (see their Figure 5). Here we provide empirical confirmation of the redshift accuracy that can be expected from slitless spectroscopy.

We perform an empirical measurement of the redshift accuracy using fits to the grism spectra of WISP sources that were observed more than once. Over the six cycles of parallel observations, there are 36 WISP fields that overlap to some degree with another field. There are therefore ~ 140 sources that have been observed multiple times, often with very different exposure times, field depths, and roll angles. In order to increase the sample size, we consider all possible permutations of pairs of observations of a given source. We randomize the order in which we calculate the delta redshift to avoid systematic shifts that may be introduced if a subset of these WISP fields have problems. Such problems could include issues with the wavelength calibration or noisy grism data, which would increase the uncertainty in the measured emission line centers. In Figure 13, we show this empirical measurement of the redshift accuracy ($\sigma_z/(1+z) = 0.00136$) as well as a similar measurement of the accuracy of the $\text{H}\alpha + [\text{N II}]$ fluxes of these sources. Note that the redshift accuracy presented here of $\sim 0.14\%$ is the result of a fit to the difference in two redshift measurements, and therefore has twice the variance of either measurement alone.

In both the simulated data (Colbert et al. 2013) and the empirical measurement presented here, the redshift accuracy measured from the WFC3 slitless data is on the order of 0.1%, indicating the level achievable for future grism-based galaxy redshift surveys. However, such surveys will also have to contend with redshift contamination from misidentified emission lines. We quantify the expected fraction of contamination as a function of survey flux limit in the following section.

4.6. Contaminating Redshifts

For proper forecasts of dark energy experiments, a critical parameter is the purity of the measured redshifts of galaxies, which can be quantified by the fraction of targets with incorrectly identified emission-lines. There are two possible sources of contamination: spurious sources such as noise peaks incorrectly identified as emission features, and real lines that have been misidentified and are therefore assumed to be at the wrong redshift. The first case depends on the method used for line

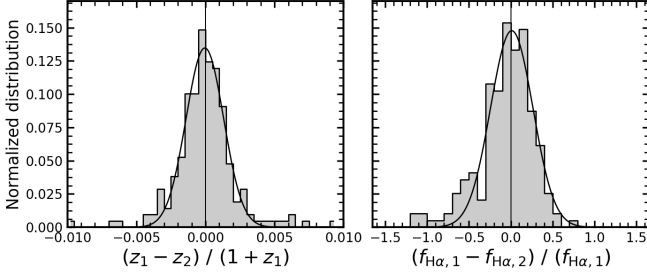


Figure 13. The redshift and $H\alpha + [N II]$ flux accuracies measured empirically from WISP data are shown in the left and right panels, respectively. Here we are comparing the redshifts and $H\alpha + [N II]$ fluxes from multiple measurements of the same set of sources observed in overlapping WISP fields.

identification. For example, [Colbert et al. \(2013\)](#) find that $\sim 8.5\%$ of emission lines in the first version of the WISP emission line catalog are in fact hot pixels, cosmic rays, or other artifacts. Though we have not quantified this fraction in the new catalog, the updated procedure using a continuous wavelet transform should improve upon this false detection rate (see Section 2.1.1).

To evaluate the contamination from misidentified redshifts, we use the CANDELS multi-wavelength observations available for the 3D-HST fields and the full wavelength coverage of the G102+G141 WISP observations to evaluate the purity of spectroscopic redshifts measured with grism data. Figure 1 shows the redshift ranges for which multiple lines will be identified in Euclid spectra. For many redshifts only one line will be available. In addition, depending on the intrinsic $H\alpha + [N II]/[O III] \lambda 5007$ ratio and the amount of dust extinction, it is likely that $H\alpha + [N II]$ will still be the only line detected, even in the redshift range where both $[O III] \lambda 5007$ and $H\alpha + [N II]$ are present. Indeed, only about 10% of the WS sources in the proper redshift range have both $H\alpha + [N II]$ and $[O III] \lambda 5007$. When only individual lines are detected, these are operationally identified as $H\alpha$ unless other information such as the emission line shape or galaxy color is available. However, it is possible that a substantial fraction of these single lines are in fact $[O III]$ at $z_{[O III]} + 1 = (z_{H\alpha} + 1) \lambda_{H\alpha} / \lambda_{[O III]}$. We aim to constrain the purity of slitless-selected samples with two complementary approaches: (1) a comparison with spectroscopically-confirmed and photometrically determined redshifts, and (2) an analysis of the additional secure redshifts made possible by increasing the survey wavelength range.

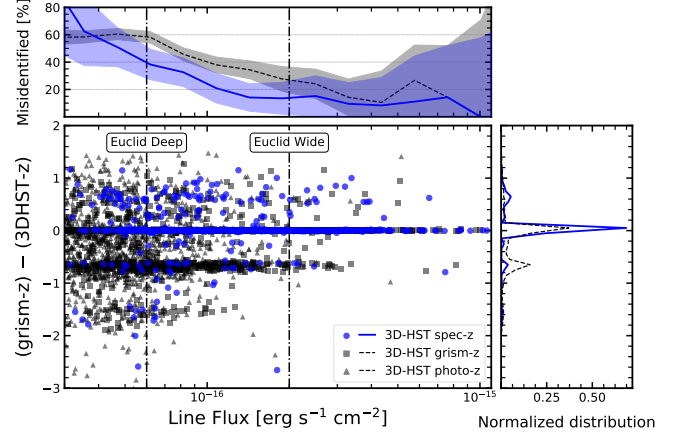


Figure 14. The difference between the grism-identified redshifts used in the WS and the redshifts compiled in version 4.1.5 of the 3D-HST catalog for single line emitters is shown as a function of line flux. All sources were identified as $H\alpha + [N II]$ -emitters in the grism spectra using the emission line detection software discussed in Section 2. Yet many appear to be lines at a different redshift (typically $[O III]$) based on their spectroscopic redshifts (blue circles), photometric redshifts (black triangles), or grism redshifts fit using photometric redshifts as a prior (black squares). This redshift misidentification rate depends on the survey flux limit. Approximately 14% (40%) of the single line emitters plotted in blue are misidentified at the depth of the Euclid Wide (Deep) Survey.

First, we use the redshifts compiled in version 4.1.5 of the 3D-HST catalog⁹ to determine the fraction of 3D-HST grism redshifts assigned through the WISP emission line detection procedure that have been misidentified. In Figure 14, we explore this redshift misidentification as a function of line flux using the best available redshift for each source (“z_{best}”) from the 3D-HST catalog. Sources where “z_{best}” is a spectroscopic redshift from [Skelton et al. \(2014\)](#) are shown as blue circles. All other redshifts are determined either from grism measurements (black squares) or from spectral energy distribution fitting using the full suite of available CANDELS photometry (black triangles). Note that here the grism redshifts are those from the 3D-HST data release, which include the CANDELS photometric redshifts as a prior, rather than the measurements performed using the WISP emission line detection described in Section 2.2. We consider all $H\alpha + [N II]$ -emitters in the 3D-HST catalog where the redshift is based on a single line. We select galaxies with a “z_{best}” ≥ 0.9 to match the WS selection.

⁹ <http://3dhst.research.yale.edu/Data.php>

The prevalence of misidentified single emission lines depends on the survey depth. At the depth of the Euclid Wide Survey $\sim 14\%$ of the single line emitters with spectroscopic redshifts (blue circles) assumed to be $\text{H}\alpha + [\text{N II}]$ are in fact a different emission line. This percentage increases to $\sim 40\%$ at the depth of the Euclid Deep Survey, below which the sample size of sources confirmed spectroscopically decreases. As it is prohibitively difficult to follow-up every grism detection of an ELG from the ground, we also show the misidentification percentage for the sources with no slit-based spectroscopic redshift, where $\sim 25\%$ to $\sim 60\%$ of sources with single emission lines are misidentified. For the majority of the Euclid Wide Survey, photometry — and efforts to calibrate photometric redshifts (e.g., Masters et al. 2015) — will be critical for correctly identifying single emission lines in the grism spectra and improving the sample purity attained in the Wide Survey.

Measuring the BAO signal from galaxy clustering measurements requires a full understanding of the sample redshift contamination, as galaxies with misidentified redshifts will reduce the strength of the clustering signal. The Euclid Deep Survey will therefore provide a redshift calibration sample, which will be used to quantify the contamination fraction present in the Wide Survey. For this calibration effort, the Deep Survey will aim to achieve a purity of $p > 99\%$ over the 40 deg^2 region, where p is the number of sources with correctly identified redshifts divided by the total number measured (Laureijs et al. 2011), $p = N_{\text{correct}}/N_{\text{measured}}$. We use the WISP emission line catalog to estimate the purity of the emission line sample observed in the Euclid Deep Survey. From the full WISP emission line catalog (Section 2.1.1), we only consider fields with spectral coverage in both the G102 and the G141 grisms. Additionally, we include in the following analysis only emission line galaxies with secure redshifts (i.e., measured with at least two emission lines). Having observations in both grisms ensures a spectral coverage between $0.85 \leq \lambda \leq 1.65 \mu\text{m}$. Given the emission lines considered in the redshift determination ($[\text{O II}]$, $\text{H}\gamma$, $\text{H}\beta$, $[\text{O III}]$, $\text{H}\alpha + [\text{N II}]$, $[\text{S II}]$, $[\text{S III}]\lambda 9069$, $[\text{S III}]\lambda 9532$, and $\text{He I}\lambda 10830$), the catalog derived for the fields with both grisms spans the redshift range between $z \sim 0.25$ and $z \sim 2.3$. The approximate 5σ depth of the selected WISP fields is $5 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$, consistent with the expected line flux limit in the Euclid Deep Survey observations with the Red grism.

From this two-grism WISP catalog, we apply the same selection criteria described in Section 2.4 to create a sample analogous to that which will be selected using the NISP Red Euclid grism. We call this sample the Euclid Shallow (ES) sample, and it is the same as the

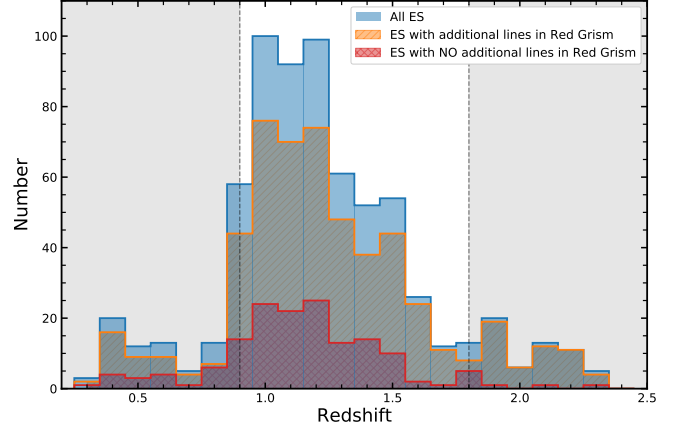


Figure 15. Redshift distribution of galaxies in the Euclid Shallow sample, defined as all WISP sources with at least one emission line with $\lambda_{\text{line}} > 1.25 \mu\text{m}$ and $f_{\text{line}} > 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$, regardless of their redshifts (blue histogram). The orange and red histograms split the sample into objects with and without additional emission lines in the Euclid Red grism at the depth of the Deep Survey. The objects in the red histogram that fall in the shaded region, those with $z < 0.9$ or $z > 1.8$, would result in incorrect redshift determinations and correspond to about 6% of the ES sample.

WS of Section 2.4 but only includes WISP sources from fields observed with both grisms. The redshift distribution of the ES sample is shown in Figure 15 (blue histogram). In the WISP catalog, sources with redshift in the $0.4 < z < 1.6$ are mostly selected via their $\text{H}\alpha$ emission line. At redshifts $z \gtrsim 1.6$, galaxies are selected via the $[\text{O III}]$ emission lines, while at redshifts $z \lesssim 0.4$, galaxies are identified because of the $[\text{S III}]$ and He I lines. We stress that the WISP sample considered in this analysis only includes secure redshifts measured with two or more emission lines.

Multiple emission lines are required in order to be able to perform an unambiguous redshift identification. Thus, we look at the fraction of galaxies in the ES sample that would show additional lines in the wavelength range of the Euclid Red grism, with $f_{\text{line}}^{\text{add}} > 2\sigma$ (where $\sigma = 1.4 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ is the required spectroscopic depth of the Euclid deep survey). We find that 77% of the ES sample have multiple emission lines in the wavelength range of the Euclid Red grism and at the depth of the Deep Survey. The redshift distribution for this population is shown in Figure 15 (orange histogram). The red histogram in Figure 15 shows the redshift distribution of the remaining 23% of galaxies in the ES sample that would be single line emitters in the Euclid Red grism even at the depth of the Deep Survey.

For single line emitters the simplest assumption is that the line is $\text{H}\alpha$. The red histogram, however, clearly

shows that this assumption would get the redshift wrong for single-line emitters at $z < 0.9$ and $z > 1.8$. Here we are assuming that Euclid would detect $H\alpha$ for the [O III]-selected WISP sources in the $1.6 < z < 1.8$ redshift range. We find that 6% of all ES galaxies would have incorrect redshift measurements in a Deep Survey observed with only the Euclid Red grism, corresponding to a sample purity of 94%. These incorrect redshifts would make quantifying the redshift contamination and purity of the Euclid Wide Sample more challenging.

Given the wavelength range of the G102 grism, we can quantify the extent to which the addition of the Euclid Blue grism would improve the sample purity. The Euclid Blue grism extends the survey wavelength coverage down to $0.92 \mu\text{m}$. Encouragingly, almost all of the 6% of objects with misidentified redshifts have additional detectable emission lines in this extended blue wavelength coverage. Specifically, 85% of the misidentified redshifts would be removed, bringing the purity of the ES sample up to 99.1%. The Blue grism would be a valuable addition to the Euclid Deep Survey and would allow for a better understanding of the fraction of single-line emitters with incorrect redshifts in the Wide Survey.

5. SUMMARY

Upcoming galaxy redshift surveys such as ESA’s Euclid mission and NASA’s *Roman* mission will use $H\alpha$ and [O III]-selected galaxies to trace the large scale structure at redshifts of $z \sim 1 - 2.5$, aiming to understand the nature of the accelerated expansion of the universe. The constraining power of such surveys is limited by the number density of galaxies detected in the survey volumes as well as the redshift accuracy of the resulting samples. Additionally, as slitless grism surveys, their samples will be the result of complex selection functions that depend not only on redshift, but also on line S/N, EW, and galaxy size and shape in both the continuum and emission lines. The wavelength coverage and resolution of the *HST* infrared grisms provide the valuable opportunity to evaluate the expected selection functions of future galaxy redshift surveys and their effects on the requirements of the dark energy missions.

In this paper we create a sample of emission line galaxies from the *HST* programs WISP and 3D-HST+AGHAST and explore aspects of the sample to present predictions for the Euclid Wide Survey. The grism data cover 0.56 deg^2 , approximately equal to the NISP field of view. We apply a selection function to match that expected for the Euclid Wide Survey, requiring emission line fluxes $\geq 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ and observed wavelengths $\geq 1.25 \mu\text{m}$ in addition to S/N and EW cuts necessitated by the completeness of the

slitless WFC3 data. We find $\sim 3270 H\alpha + [\text{N II}]$ -emitters deg^{-2} from $0.9 \leq z \leq 1.6$ and $\sim 440 [\text{O III}] \lambda 5007$ -emitters deg^{-2} from $1.5 \leq z \leq 2.3$ in the WS, where these number densities have been corrected for the incompleteness of the WFC3 grism data. The observed number counts are in agreement with predictive models from works in the literature, including Model 3 from Pozzetti et al. (2016) that has been used to calibrate the Euclid Flagship Mock catalog.

We next measure the size and EW distributions for all $H\alpha + [\text{N II}]$ -selected galaxies in the WS. As the extraction of spectra in slitless data depends on the location, size, and concentration of the sources in direct imaging, it is crucial that we understand the relationship between the size of galaxies in the continuum and the emission line of interest. We fit the galaxies in the H band images and $H\alpha + [\text{N II}]$ emission line maps with Sérsic profiles, deconvolved with an empirically-determined, wavelength-dependent PSF. The median half-light radii of the galaxies in the continuum and $H\alpha + [\text{N II}]$ emission are $R_{\text{eff,cont}} = 0''.37$ and $R_{\text{eff},H\alpha + [\text{NII}]} = 0''.39$, respectively. The sizes of the continuum and emission lines are correlated, but with significant scatter ($\sigma \sim 0''.2 - 0''.35$). The median $H\alpha + [\text{N II}]$ EW in the observed frame is $\text{EW}_{\text{obs},H\alpha + [\text{NII}]} \sim 250 \text{ \AA}$. These distributions reflect the properties of the galaxy population accessible to redshift surveys performed with slitless spectroscopy, and are therefore important quantities to include in mock catalogs used to test survey strategies.

Finally, we use the full depth of the emission line catalogs to quantify the redshift accuracy and contamination that can be expected for Euclid. Using overlapping WFC3 fields where the same sources are observed multiple times, we measure a redshift accuracy of $\sigma_z/(1+z) = 0.0014$, indicative of that which can be achieved by $R \sim 200$ slitless spectroscopy. We then explore the effect of redshift contamination from misidentified emission lines if all single lines are assumed to be $H\alpha$. By comparing the grism redshifts with the spectroscopic and photometric redshifts from the CANDELS catalogs, we find that at the depth of the Euclid Wide Survey, $\sim 14\text{-}20\%$ of the resulting sample is likely to be incorrectly identified. As the majority of galaxies Euclid will detect in the Wide Survey will have only one emission line in the NISP Red grism wavelength range, it is very important to properly quantify this type of redshift contamination. The Euclid Deep Survey will be used to calibrate the Wide Survey observations and to quantify the redshift contamination rate. We additionally show that even at the depth of the Deep Survey, approximately 6% of emission line galaxies could still be misidentified in the Red grism wavelength range. How-

ever, the addition of the Blue grism to the Deep Survey calibrations would significantly reduce the redshift misidentifications and allow for a more complete assessment of the Wide Survey redshift contamination.

The predictions presented in this paper are specific to ESA’s Euclid galaxy redshift survey as part of the dark energy mission, yet these observations can be used as a valuable testbed for other grism-based surveys such as *Roman* or for preparations for the NIRC*am* grism on *JWST*.

We thank the anonymous referee for a careful review and for helpful comments that improved this paper. We would also like to thank Karlen Shahinyan, Ben Sunquist, Marc Rafelski, Y. Sofia Dai, and Melanie Beck for help with the visual inspection and identification of emission lines. We would also like to thank Ginevra Favole for her contributions to the WISP catalog completeness analysis, and Hervé Aussel for helpful discussions regarding the Euclid Science Performance Verification efforts. MBB would like to thank Francesco Valentino for his generosity in providing number counts

and discussing his analysis. This research was partially supported by NASA ROSES grant 12-EUCLID12-0004. YW was supported in part by NASA grant 15-WFIRST15-0008 Cosmology with the High Latitude Survey WFIRST Science Investigation Team. AC and LP acknowledge the support from the grants PRIN-MIUR 2015 and ASI n.2018-23-HH.0. Support for WISP (HST Programs GO-11696, 12283, 12568, 12902, 13517, 13352, and 14178) was provided by NASA through grants from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. This work is partially based on observations taken by the 3D-HST Treasury Program (GO 12177 and 12328) with the NASA/ESA HST, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

Facilities: HST (WFC3)

Software: Astropy (Astropy Collaboration et al. 2013), aXe (Kümme et al. 2009b), aXeSIM (Kümme et al. 2007), SciPy (Jones et al. 2001–), Source Extractor (Bertin & Arnouts 1996), GALFIT (Peng et al. 2010)

APPENDIX

A. COMPLETENESS CORRECTIONS

As mentioned in Section 2.3, we use two sets of completeness corrections in our analysis, one each for the WISP and 3D-HST+AGHAST emission line catalogs. In this way we ensure that the corrections are derived using the same procedure as the catalogs to which they are applied. In both cases, the completeness is calculated with sets of simulated sources that are added to real images and processed identically as the real data. We discuss the derivation of the completeness corrections for both catalogs in the following sections and compare the two line finding algorithms in Section A.3.

A.1. WISP Completeness Corrections

In order to assess the completeness of the WISP Survey and the line finding procedure, we create a simulated catalog of 10000 synthetic sources and their spectra. The parameters for each source — redshift, source size and shape, $H\alpha$ line flux, $H\alpha$ EW, and $H\alpha/[O\ III]\ \lambda 5007$ line ratio — are pulled randomly from uniform distributions chosen to bracket the observed values in the emission line catalog. The one exception is the $H\alpha/[O\ III]\ \lambda 5007$ line ratio, which is pulled from a Gaussian distribution centered at the measured ratio for real sources but with a standard deviation two times larger. We create synthetic direct and grism images of each source using aXeSIM (Kümme et al. 2007). The source images are elliptical Gaussians, which aXeSIM convolves with input template spectra to create the dispersed grism stamps. The simulated sources therefore have the same size and shape at all wavelengths. We insert the simulated sources into real WISP images from 20 fields, chosen to cover the range of exposure times, depths, and filter coverage that exist in a survey comprised of parallel opportunities of varied length. We produce 20 realizations of each field, with 25 simulated sources per realization. We then process all fields through the full WISP reduction pipeline and emission line detection software.

The completeness is calculated in bins of emission line EW and “scaled flux”, or the line flux scaled by the grism sensitivity in that particular field at the wavelength of the line. This scaled flux is a tracer for line S/N, but also reflects the effect of the varying depths reached in each field of a parallel survey such as WISP. The bin edges are determined by the distribution of sources in the real WISP emission line catalog such that there are an approximately equal number of real sources in each bin. The one exception is the bin of lowest EW, which we add in order to probe

an area of the parameter space with low completeness ($EW_{\text{obs}} < 40 \text{ \AA}$, see [Colbert et al. 2013](#)). We note that source size and shape can strongly affect the completeness of both the imaging and emission line catalogs, as extended, low surface brightness sources may fall below the adopted *Source Extractor* detection thresholds and their low emission line EWs may be missed by the line detection algorithm. However, the large sources that suffer from the highest levels of incompleteness (with semi-major axis $a \geq 0''.7$), constitute less than 1% of either the imaging or the emission line catalogs. We therefore weight the distribution of input sources by the distribution of observed sizes in the emission line catalog, allowing us to account for the effect of source size while considering a two-parameter completeness correction. We use a radial basis function to interpolate the recovery fractions across all bins, smoothing over sharp jumps in the completeness at bin edges. Uncertainties on the completeness corrections are taken as $1/\sqrt{N_{\text{rec}}}$, where N_{rec} is the number of recovered sources in each bin of EW and scaled flux. Completeness corrections are calculated using the line with the highest “scaled flux” in each spectrum as a proxy for the “primary” lines identified by the detection software. Accordingly, these completeness corrections are applied to each source in the emission line catalog – given the flux and EW of its strongest line – rather than to individual emission lines.

In the top row of Figure 16, we compare the completeness corrections from this new line finding method and that of [Colbert et al. \(2013\)](#). The completeness corrections for sources identified with the new method (WISP catalog) are shown on the left, and those for the 3D-HST+AGHAST catalog using the method described by [Colbert et al. \(2013\)](#) are displayed on the right. In both cases we plot the corrections as a function of line S/N and observed EW to allow for a direct comparison.

Finally, this analysis identified two thresholds below which the completeness corrections are highly uncertain: line $EW_{\text{obs}} < 40 \text{ \AA}$ and $S/N < 5$, identified in Figure 16 by dashed and dot-dashed lines, respectively. In the bottom left panel of Figure 16, we show the fraction of simulated sources that were recovered by the automatic detection algorithm binned by observed EW. The fraction drops rapidly for $EW_{\text{obs}} < 40 \text{ \AA}$, indicating that $40 \text{ \AA}$ is an effective limiting EW for which the automatic algorithm can detect a significant peak above the continuum in the WISP spectra. Overall, fewer than 10% of input emission lines with $EW_{\text{obs}} < 40 \text{ \AA}$ were recovered by the automatic detection algorithm, while this fraction increases to 28% for $40 < EW_{\text{obs}} < 60 \text{ \AA}$.

In the bottom right panel of Figure 16, we show the distribution of emission line S/N as measured in both the simulated (grey distribution) and real (purple distribution) WISP emission line catalogs. There is a decrease in the number of sources in both catalogs where the strongest emission line present in the spectrum is detected with $S/N < 5$. We have included in the simulated catalog emission lines with fluxes pulled from a uniform distribution reaching well below the flux limit of the survey. The bottom right panel of Figure 16 therefore demonstrates that we are not complete to sources with emission lines below this cutoff. Additionally, during visual inspection, reviewers are less consistent in their treatment of $S/N < 5$ emission lines. The fraction of lines accepted by only one reviewer, i.e., when the reviewers do not agree that the emission line candidate is real, doubles for lines with $S/N < 5$. We note that these same EW and S/N thresholds were adopted by [Colbert et al. \(2013\)](#) in their completeness analysis that is used for the 3D-HST+AGHAST emission line catalog described in Section 2.2, where the motivation is similar. We therefore include these thresholds in our sample selection criteria described in Section 2.4.

A.2. 3D-HST+AGHAST

[Colbert et al. \(2013\)](#) derive completeness corrections for the earlier version of the WISP emission line detection process following a similar procedure, by adding simulated sources to WISP images and processing them all the way through the visual inspection stage. We briefly summarize the steps here and refer the reader to [Colbert et al. \(2013\)](#) for more details.

A total of 923 model ELGs are generated pulling parameters such as redshift, source size, emission line flux, and EW randomly from distributions informed by real measurements in WISP data. These are added to 74 realizations of WISP fields, with 10-20 simulated sources per field. The automatic line detection algorithm identifies sets of 3 or more contiguous pixels above the continuum that each have a $S/N > \sqrt{3}$ (or 2 contiguous pixels that are each at a $S/N > \sqrt{5}$ to account for unresolved objects). Each emission line candidate is then inspected by two reviewers, where the criteria for accepting or rejecting a candidate is the same as in the updated line finding procedure. The reviewers identify each emission line, thereby assigning a redshift, and measure line properties by fitting Gaussians to the line profiles. The completeness corrections of [Colbert et al. \(2013\)](#) are calculated in bins of line S/N and observed EW, with input distributions weighted by source size as described in Section A.1. These corrections are applied to the 3D-HST+AGHAST catalog in the top right panel of Figure 16.

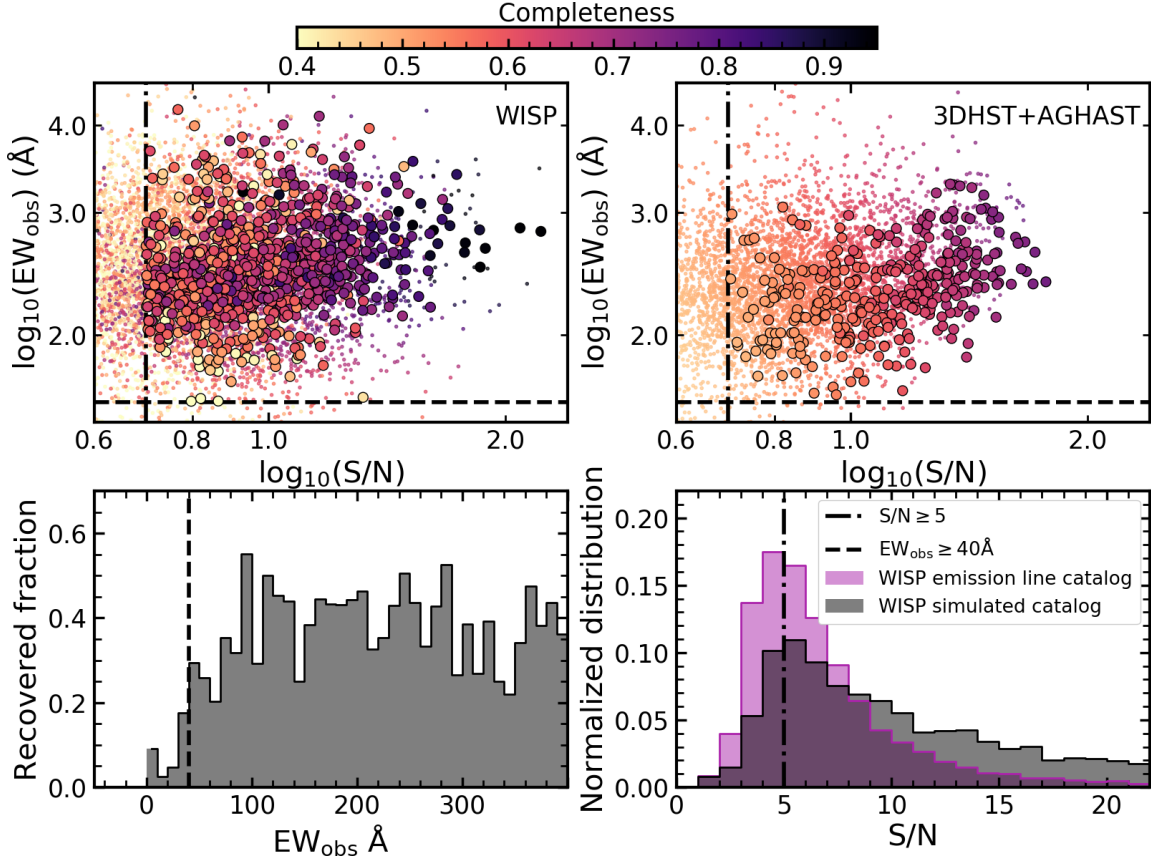


Figure 16. A comparison between the completeness corrections applied to the WISP (top left) and 3D-HST+AGHAST (top right) catalogs as a function of emission line S/N and observed EW. In both panels, the larger circles indicate the sources selected as part of the WS, and the smaller points indicate sources from the full emission line catalogs. As the corrections for the new method are calculated using a scaled flux rather than a line S/N, the transition from low to high completeness does not progress as smoothly in the left panel as it does in the right. In the bottom panels, we use the simulated sources from the updated completeness analysis (grey distributions) to demonstrate the EW_{obs} and S/N thresholds we adopt as part of our sample selection. In the bottom left panel, the recovery of simulated sources drops rapidly for $\text{EW}_{\text{obs}} < 40 \text{ Å}$. In the right panel, the number of sources in both the real (purple) and simulated catalogs drops off for line $\text{S/N} < 5$. For all panels, the adopted S/N and EW_{obs} thresholds are shown as dot-dashed and dashed lines, respectively.

A.3. Comparing completeness and contamination

The completeness analysis of [Colbert et al. \(2013\)](#) differs in three ways from the analysis described in Section A.1. First, the automatic line detection identifies candidate emission lines through the detection of contiguous pixels above the measured continuum. Many hot pixels and noise spikes were detected in this way and needed to be rejected during the visual inspection phase. In the updated procedure, this step is supplemented by the continuous wavelet transform that selects for emission line shape as well as strength above the continuum. This addition, more than any other, serves to remove the majority of spurious detections that were identified by the original algorithm. The new procedure also implements additional quality checks, including a cut on very low EW emission lines designed to remove noise spikes and a higher S/N threshold of $\text{S/N} > 2.31$ per pixel (compared with the $\sqrt{3} = 1.73$). The algorithm automatically rejects any emission line candidates detected within 5 pixels of the edge of each spectrum, a region where the grism sensitivity decreases rapidly and in which many spurious lines were identified by the first version. Finally, the continuum is estimated on a median-filtered spectrum rather than with a spline fit as was used in the first version. This approach produces a better fit, especially in regions where the continuum changes rapidly. Detecting lines as pixels with excess flux above the continuum requires a properly-fit continuum.

Second, in the original procedure, the reviewers identified and fit emission lines individually for each source. Once they selected an emission feature for fitting – thus assigning a redshift to the source – they would step through the

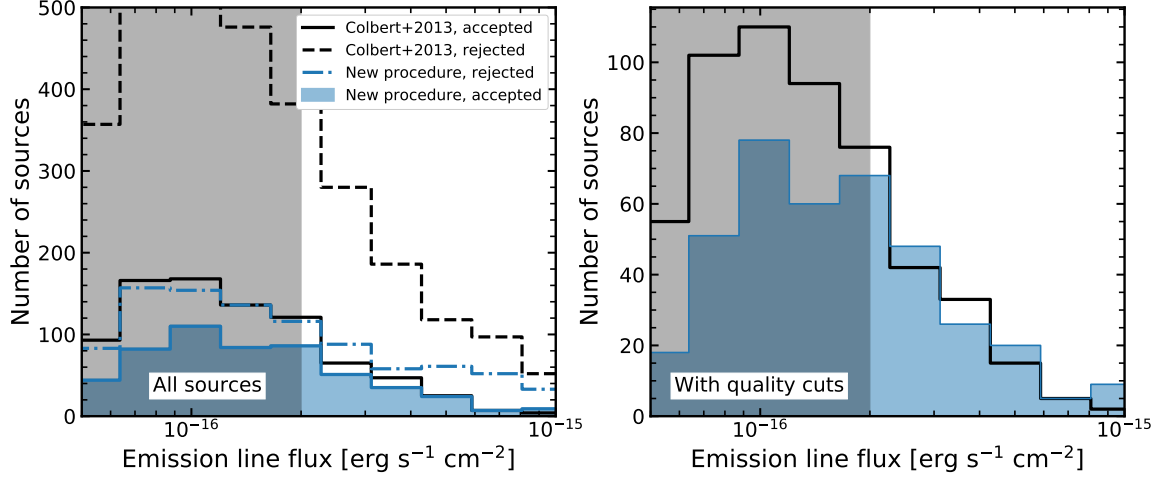


Figure 17. A comparison between the number of emission lines identified as a function of line flux by the two versions of the line finding procedure. We include the output catalogs from 20 WISP fields that were processed with both versions. The left panel shows the number of automatically-identified sources that were later rejected by reviewers for the original (black dashed line) and updated (blue dot-dashed line) versions. The corresponding distributions of sources that were accepted during visual inspection are displayed as a black solid line and a blue filled histogram, respectively. In the right panel, we show the number of accepted sources with quality flags indicating secure redshifts. The automatic detection portion of the original procedure identified far more spurious sources, which were then removed by reviewers during the visual inspection phase. After visual inspection, and especially after applying quality cuts, both versions of the procedure identify very similar distributions of sources down to the flux limit of the Euclid Wide Survey. As final emission line fluxes are measured for accepted sources during visual inspection, we note that the emission line fluxes of the rejected sources shown here are preliminary estimates produced by the automatic detection processes.

spectrum fitting Gaussians at the wavelengths expected for other lines given the assumed redshift. The widths and central wavelengths of these Gaussians were not constrained, and so could vary from line to line in the same spectrum. The new procedure fits each spectrum simultaneously, including the continuum and all emission lines, and each line is constrained to have the same FWHM. Additionally, the reviewer has the option of refitting the global continuum during the spectral fitting process, an option that can provide better emission line fits and more accurate EW measurements.

The two differences discussed so far refer to the line finding and fitting procedure, while the third difference relates specifically to the completeness analysis from Colbert et al. (2013). During the visual inspection used to calculate the completeness, the reviewers inspected a random collection of spectra from real and simulated sources. The goal was to avoid the bias that can be introduced when reviewers expect all spectra to have emission lines. This step allowed Colbert et al. (2013) to calculate a contamination rate of 8.5% due to false emission lines. While we have not calculated this for the new line finding procedure, we emphasize that the criteria for accepting or rejecting emission line candidates as well as the data products included in the inspection (direct images, 2D spectral stamps, S/N spectra, and 1D spectra) are the same for both procedures.

We have explored the results of the two emission line detection methods using 20 WISP fields that have been processed with both versions. In Figure 17, we show the number of accepted and rejected sources as a function of emission line flux. In the left panel, the dashed and dot-dashed lines show the number of sources identified by the two algorithms that were later rejected by reviewers. For a given emission line flux, the first version of the line finding algorithm identified $> 2\times$ more sources, the majority of which were rejected during inspection. Yet the distributions of algorithm-identified and reviewer-accepted sources are similar down to the flux limit of the Euclid Wide Survey, which is indicated by the grey shaded region. This similarity is even greater in the right panel, where we show the same comparison after applying quality cuts to the samples that select sources with secure redshifts. We emphasize here that the y-axes of both panels show the number of sources and not a fraction or normalized distribution. As we apply the same quality cuts to the WISP and 3D-HST+AGHAST catalogs during the creation of the WS in Section 2.4, the distributions in the right panel are indicative of the performance of the two algorithms in our full analysis.

REFERENCES

- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33, doi: [10.1051/0004-6361/201322068](https://doi.org/10.1051/0004-6361/201322068)
- Atek, H., Malkan, M., McCarthy, P., et al. 2010, *ApJ*, 723, 104, doi: [10.1088/0004-637X/723/1/104](https://doi.org/10.1088/0004-637X/723/1/104)
- Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, *PASP*, 93, 5, doi: [10.1086/130766](https://doi.org/10.1086/130766)
- Beck, M. R., Scarlata, C., Fortson, L. F., et al. 2018, *MNRAS*, 476, 5516, doi: [10.1093/mnras/sty503](https://doi.org/10.1093/mnras/sty503)
- Benson, A. J. 2012, *NewA*, 17, 175, doi: [10.1016/j.newast.2011.07.004](https://doi.org/10.1016/j.newast.2011.07.004)
- Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
- Bournaud, F., Perret, V., Renaud, F., et al. 2014, *ApJ*, 780, 57, doi: [10.1088/0004-637X/780/1/57](https://doi.org/10.1088/0004-637X/780/1/57)
- Brammer, G. B., van Dokkum, P. G., Franx, M., et al. 2012, *ApJS*, 200, 13, doi: [10.1088/0067-0049/200/2/13](https://doi.org/10.1088/0067-0049/200/2/13)
- Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, *MNRAS*, 351, 1151, doi: [10.1111/j.1365-2966.2004.07881.x](https://doi.org/10.1111/j.1365-2966.2004.07881.x)
- Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682, doi: [10.1086/308692](https://doi.org/10.1086/308692)
- Charlot, S., & Fall, S. M. 2000, *ApJ*, 539, 718, doi: [10.1086/309250](https://doi.org/10.1086/309250)
- Colbert, J. W., Teplitz, H., Atek, H., et al. 2013, *ApJ*, 779, 34, doi: [10.1088/0004-637X/779/1/34](https://doi.org/10.1088/0004-637X/779/1/34)
- de Vaucouleurs, G. 1948, *Annales d'Astrophysique*, 11, 247
- Dickinson, H., Scarlata, C., Fortson, L., et al. 2018, *ArXiv e-prints*. <https://arxiv.org/abs/1807.01687>
- Eddington, A. S. 1913, *MNRAS*, 73, 359, doi: [10.1093/mnras/73.5.359](https://doi.org/10.1093/mnras/73.5.359)
- Erb, D. K., Shapley, A. E., Pettini, M., et al. 2006, *ApJ*, 644, 813, doi: [10.1086/503623](https://doi.org/10.1086/503623)
- Faisst, A. L., Masters, D., Wang, Y., et al. 2018, *ApJ*, 855, 132, doi: [10.3847/1538-4357/aab1fc](https://doi.org/10.3847/1538-4357/aab1fc)
- Ferrara, A., Bianchi, S., Cimatti, A., & Giovanardi, C. 1999, *ApJS*, 123, 437, doi: [10.1086/313244](https://doi.org/10.1086/313244)
- Froning, C. S., & Green, J. C. 2009, *Ap&SS*, 320, 181, doi: [10.1007/s10509-008-9758-y](https://doi.org/10.1007/s10509-008-9758-y)
- Geach, J. E., Smail, I., Best, P. N., et al. 2008, *MNRAS*, 388, 1473, doi: [10.1111/j.1365-2966.2008.13481.x](https://doi.org/10.1111/j.1365-2966.2008.13481.x)
- Gonzaga, S., e. 2012, *The DrizzlePac Handbook*
- Green, J., Schechter, P., Baltay, C., et al. 2012, *ArXiv e-prints*. <https://arxiv.org/abs/1208.4012>
- Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, *ApJS*, 197, 35, doi: [10.1088/0067-0049/197/2/35](https://doi.org/10.1088/0067-0049/197/2/35)
- Guzzo, L., Pierleoni, M., Meneux, B., et al. 2008, *Nature*, 451, 541, doi: [10.1038/nature06555](https://doi.org/10.1038/nature06555)
- Hayes, M., Schaerer, D., & Östlin, G. 2010, *A&A*, 509, L5, doi: [10.1051/0004-6361/200913217](https://doi.org/10.1051/0004-6361/200913217)
- Hopkins, A. M., Connolly, A. J., & Szalay, A. S. 2000, *AJ*, 120, 2843, doi: [10.1086/316857](https://doi.org/10.1086/316857)
- Jamal, S., Le Brun, V., Le Fèvre, O., et al. 2018, *A&A*, 611, A53, doi: [10.1051/0004-6361/201731305](https://doi.org/10.1051/0004-6361/201731305)
- Jones, E., Oliphant, T., Peterson, P., et al. 2001–, *SciPy: Open source scientific tools for Python*
- Kashino, D., Silverman, J. D., Sanders, D., et al. 2017, *ApJ*, 835, 88, doi: [10.3847/1538-4357/835/1/88](https://doi.org/10.3847/1538-4357/835/1/88)
- Kewley, L. J., Maier, C., Yabe, K., et al. 2013, *ApJL*, 774, L10, doi: [10.1088/2041-8205/774/1/L10](https://doi.org/10.1088/2041-8205/774/1/L10)
- Kimble, R. A., MacKenty, J. W., O’Connell, R. W., & Townsend, J. A. 2008, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 7010, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*
- Kimble, R. A., Woodgate, B. E., Bowers, C. W., et al. 1998, *ApJL*, 492, L83, doi: [10.1086/311102](https://doi.org/10.1086/311102)
- Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, *ApJS*, 197, 36, doi: [10.1088/0067-0049/197/2/36](https://doi.org/10.1088/0067-0049/197/2/36)
- Kümmel, M., Kuntschner, H., & Walsh, J. 2007, *Space Telescope European Coordinating Facility Newsletter*, 43, 8
- Kümmel, M., Walsh, J. R., Pirzkal, N., Kuntschner, H., & Pasquali, A. 2009a, *PASP*, 121, 59, doi: [10.1086/596715](https://doi.org/10.1086/596715)
- . 2009b, *PASP*, 121, 59, doi: [10.1086/596715](https://doi.org/10.1086/596715)
- Laureijs, R., Amiaux, J., Arduini, S., et al. 2011, *ArXiv e-prints*. <https://arxiv.org/abs/1110.3193>
- Laureijs, R., Gondoin, P., Duvet, L., et al. 2012, in *Proc. SPIE*, Vol. 8442, *Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*, 84420T
- Mandelker, N., Dekel, A., Ceverino, D., et al. 2017, *MNRAS*, 464, 635, doi: [10.1093/mnras/stw2358](https://doi.org/10.1093/mnras/stw2358)
- Maseda, M. V., van der Wel, A., Rix, H.-W., et al. 2018, *ApJ*, 854, 29, doi: [10.3847/1538-4357/aaa76e](https://doi.org/10.3847/1538-4357/aaa76e)
- Masters, D., Faisst, A., & Capak, P. 2016, *ApJ*, 828, 18, doi: [10.3847/0004-637X/828/1/18](https://doi.org/10.3847/0004-637X/828/1/18)
- Masters, D., Capak, P., Stern, D., et al. 2015, *ApJ*, 813, 53, doi: [10.1088/0004-637X/813/1/53](https://doi.org/10.1088/0004-637X/813/1/53)
- Matthee, J., Sobral, D., Best, P., et al. 2017, *MNRAS*, 471, 629, doi: [10.1093/mnras/stx1569](https://doi.org/10.1093/mnras/stx1569)
- Mehta, V., Scarlata, C., Colbert, J. W., et al. 2015, *ApJ*, 811, 141, doi: [10.1088/0004-637X/811/2/141](https://doi.org/10.1088/0004-637X/811/2/141)
- Merson, A., Wang, Y., Benson, A., et al. 2018, *MNRAS*, 474, 177, doi: [10.1093/mnras/stx2649](https://doi.org/10.1093/mnras/stx2649)
- Momcheva, I. G., Brammer, G. B., van Dokkum, P. G., et al. 2016, *ApJS*, 225, 27, doi: [10.3847/0067-0049/225/2/27](https://doi.org/10.3847/0067-0049/225/2/27)

- Nelson, E. J., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2016, *ApJ*, 828, 27, doi: [10.3847/0004-637X/828/1/27](https://doi.org/10.3847/0004-637X/828/1/27)
- Oke, J. B., & Gunn, J. E. 1983, *ApJ*, 266, 713, doi: [10.1086/160817](https://doi.org/10.1086/160817)
- Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2010, *AJ*, 139, 2097, doi: [10.1088/0004-6256/139/6/2097](https://doi.org/10.1088/0004-6256/139/6/2097)
- Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, *ApJ*, 517, 565, doi: [10.1086/307221](https://doi.org/10.1086/307221)
- Pirzkal, N., Malhotra, S., Ryan, R. E., et al. 2017, *ApJ*, 846, 84, doi: [10.3847/1538-4357/aa81cc](https://doi.org/10.3847/1538-4357/aa81cc)
- Pozzetti, L., Hirata, C. M., Geach, J. E., et al. 2016, *A&A*, 590, A3, doi: [10.1051/0004-6361/201527081](https://doi.org/10.1051/0004-6361/201527081)
- Racca, G. D., Laureijs, R., Stagnaro, L., et al. 2016, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9904, The Euclid mission design, 99040O
- Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, *AJ*, 116, 1009, doi: [10.1086/300499](https://doi.org/10.1086/300499)
- Rutkowski, M. J., Scarlata, C., Haardt, F., et al. 2016, *ApJ*, 819, 81, doi: [10.3847/0004-637X/819/1/81](https://doi.org/10.3847/0004-637X/819/1/81)
- Savitzky, A., & Golay, M. J. E. 1964, *Analytical Chemistry*, 36, 1627, doi: [10.1021/ac60214a047](https://doi.org/10.1021/ac60214a047)
- Sérsic, J. L. 1963, *Boletín de la Asociacion Argentina de Astronomia La Plata Argentina*, 6, 41
- . 1968, *Atlas de Galaxias Australes*
- Shim, H., Colbert, J., Teplitz, H., et al. 2009, *ApJ*, 696, 785, doi: [10.1088/0004-637X/696/1/785](https://doi.org/10.1088/0004-637X/696/1/785)
- Silverman, J. D., Kashino, D., Sanders, D., et al. 2015, *ApJS*, 220, 12, doi: [10.1088/0067-0049/220/1/12](https://doi.org/10.1088/0067-0049/220/1/12)
- Skelton, R. E., Whitaker, K. E., Momcheva, I. G., et al. 2014, *ApJS*, 214, 24, doi: [10.1088/0067-0049/214/2/24](https://doi.org/10.1088/0067-0049/214/2/24)
- Sobral, D., Smail, I., Best, P. N., et al. 2013, *MNRAS*, 428, 1128, doi: [10.1093/mnras/sts096](https://doi.org/10.1093/mnras/sts096)
- Sobral, D., Best, P. N., Geach, J. E., et al. 2009, *MNRAS*, 398, 75, doi: [10.1111/j.1365-2966.2009.15129.x](https://doi.org/10.1111/j.1365-2966.2009.15129.x)
- Spergel, D., Gehrels, N., Baltay, C., et al. 2015, *ArXiv e-prints*. <https://arxiv.org/abs/1503.03757>
- Storey, P. J., & Zeppen, C. J. 2000, *MNRAS*, 312, 813, doi: [10.1046/j.1365-8711.2000.03184.x](https://doi.org/10.1046/j.1365-8711.2000.03184.x)
- Valentino, F., Daddi, E., Silverman, J. D., et al. 2017, *MNRAS*, 472, 4878, doi: [10.1093/mnras/stx2305](https://doi.org/10.1093/mnras/stx2305)
- van der Wel, A., Franx, M., van Dokkum, P. G., et al. 2014, *ApJ*, 788, 28, doi: [10.1088/0004-637X/788/1/28](https://doi.org/10.1088/0004-637X/788/1/28)
- Vavrek, R. D., Laureijs, R. J., Lorenzo Alvarez, J., et al. 2016, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9911, Modeling, Systems Engineering, and Project Management for Astronomy VI, 991105
- Wang, Y. 2008, *J. Cosmology Astropart. Phys.*, 5, 21, doi: [10.1088/1475-7516/2008/05/021](https://doi.org/10.1088/1475-7516/2008/05/021)
- Wang, Y., Percival, W., Cimatti, A., et al. 2010, *MNRAS*, 409, 737, doi: [10.1111/j.1365-2966.2010.17335.x](https://doi.org/10.1111/j.1365-2966.2010.17335.x)
- Weiner, B. 2009, Star formation, extinction and metallicity at $0.7 < z < 1.5$: H-alpha fluxes and sizes from a grism survey of GOODS-N, HST Proposal
- Whitaker, K. E., Labbé, I., van Dokkum, P. G., et al. 2011, *ApJ*, 735, 86, doi: [10.1088/0004-637X/735/2/86](https://doi.org/10.1088/0004-637X/735/2/86)
- Williams, R. J., Quadri, R. F., Franx, M., van Dokkum, P., & Labbé, I. 2009, *ApJ*, 691, 1879, doi: [10.1088/0004-637X/691/2/1879](https://doi.org/10.1088/0004-637X/691/2/1879)
- Yan, L., McCarthy, P. J., Freudling, W., et al. 1999, *ApJ*, 519, L47, doi: [10.1086/312099](https://doi.org/10.1086/312099)
- Zanella, A., Daddi, E., Le Floch, E., et al. 2015, *Nature*, 521, 54, doi: [10.1038/nature14409](https://doi.org/10.1038/nature14409)