3D-HST: A Spectroscopic Galaxy Evolution Treasury

Principal Investigator: Prof. Pieter van Dokkum
Institution: Yale University
Electronic Mail: pieter.vandokkum@yale.edu

Scientific Category: COSMOLOGY

Scientific Keywords: Galaxy Formation And Evolution, Galaxy Morphology And Structure, High Redshift Galaxies, Stellar Populations In External Galaxies, Survey

Instruments: WFC3, ACS

Proprietary Period: 0 Treasury: Yes

Orbit Request	Prime	Parallel
Cycle 18	248	248

Abstract

The Hubble Space Telescope has given us a dazzling imaging legacy, which has enabled us to establish a broad picture across cosmic epochs of how galaxies came to be. Here we propose to extend this legacy with 3D-HST, a peerless near-IR spectroscopic program for studying the physical processes that shape galaxies in the distant Universe. Ground-based optical spectroscopy has provided redshifts of large numbers of UV-bright Lyman break galaxies, but they make up only a fraction of the general galaxy population at $z>1$. 3D-HST will provide rest-frame optical spectra for a complete sample of ~9000 galaxies at $1<z<3.5$, when ~60% of all star formation took place, the number density of quasars peaked, the first galaxies stopped forming stars, and the structural regularity that we see in galaxies today must have emerged. The proposed rest-frame optical spectra not only provide redshifts but also spatially-resolved maps of well-calibrated diagnostics of star formation, stellar age, metallicity, stellar mass-to-light ratio and AGN activity, diagnostics that are completely inaccessible otherwise. Combined with already planned WFC3 imaging, the spectra track the emergence and growth of disks and bulges, identify the processes responsible for shutting off star formation in galaxies, and determine the roles of mergers and the larger environment in the shaping of today's galaxies. The survey also has immense legacy value as it provides spectra for all objects in the target fields: 3D-HST should reveal faint quasars at $z\sim7$-8 and identify the first spectroscopically-confirmed galaxies at $z\sim9$. We waive all proprietary rights and also commit to making the extracted spectra, redshifts, and other derived quantities publicly available. The survey area will cover most of the Faber et al. MCT imaging area, leveraging this 912-orbit WFC3 imaging investment and greatly enhancing the scientific returns from that program. The combination of the two surveys will provide the definitive imaging and spectroscopic dataset for studies of the distant Universe until JWST.

Investigators:

	Investigator	Institution	Country
PI	Prof. Pieter van Dokkum	Yale University	USA/CT
CoI	Prof. Charles C. Steidel	California Institute of Technology	USA/CA
CoI*	Dr. Hans-Walter Rix	Max-Planck-Institut fur Astronomie, Heidelberg	Germany
CoI	Dr. Mariska Kriek	Princeton University	USA/NJ
CoI*	Dr. Guinevere Kauffmann	Max-Planck-Institut fur Astrophysik	Germany
CoI	Mr. Gabriel Brammer	Yale University	USA/CT
CoI	Prof. Dawn K. Erb	University of Wisconsin - Milwaukee	USA/WI
CoI*	Prof. Marijn Franx	Universiteit Leiden	Netherlands
CoI*	Dr. N. Forster Schreiber	Max-Planck-Institut fur extraterrestrische Physik	Germany
CoI	Dr. Xiaohui Fan	University of Arizona	USA/AZ
CoI*	Dr. Ryan Quadri	Universiteit Leiden	Netherlands
CoI	Dr. Ivo Labbe	Carnegie Institution of Washington	USA/DC
CoI	Dr. Patrick J. McCarthy	Carnegie Institution of Washington	USA/DC
CoI	Dr. Danilo Marchesini	Tufts University	USA/MA
CoI*	Dr. Anna Pasquali	Max-Planck-Institut fur Astronomie, Heidelberg	Germany
CoI	Prof. Garth D. Illingworth	University of California - Santa Cruz	USA/CA
CoI	Ms. Katherine E. Whitaker	Yale University	USA/CT
CoI*	Prof. Joseph Hennawi	Max-Planck-Institut fur Astronomie, Heidelberg	Germany
CoI	Dr. David Wake	Yale University	USA/CT
CoI	Mr. Shannon Patel	University of California - Santa Cruz	USA/CA

Number of investigators: 20

* ESA investigators: 7

Target Summary:

Target	RA	Dec	Magnitude
COSMOS	10 00 31.0000	+02 24 0.00	
AEGIS	14 18 36.0000	+52 39 0.00	
UDS	02 17 49.0000	-05 12 2.00	
GOODS-SOUTH	03 32 30.0000	-27 47 19.00	
UDF	03 32 39.0000	-27 47 29.10	

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
COSMOS	WFC3/IR Spectroscopic G141		60 (2x30)
COSMOS	ACS/WFC Spectroscopic G800L	CPAR	60 (2x30)
AEGIS	WFC3/IR Spectroscopic G141		60 (2x30)
AEGIS	ACS/WFC Spectroscopic G800L	CPAR	60 (2x30)
UDS	WFC3/IR Spectroscopic G141		60 (2x30)
UDS	ACS/WFC Spectroscopic G800L	CPAR	60 (2x30)
GOODS-SOUTH	WFC3/IR Spectroscopic G141		64 (2x32)
GOODS-SOUTH	ACS/WFC Spectroscopic G800L	CPAR	64 (2x32)
UDF	WFC3/IR Spectroscopic G141		4
UDF	ACS/WFC Spectroscopic G800L	CPAR	4
		Total prime orbits:	248
		Total coordinated parallel orbits:	248

■ Scientific Justification

A SPECTROSCOPIC GALAXY EVOLUTION SURVEY WITH HST

HST's imaging legacy: Through an investment of thousands of orbits HST has created an incomparable imaging legacy that has revolutionized observational galaxy formation. Hubble not only provides the angular resolution to resolve galaxies in the distant Universe but also the sensitivity to detect them to much fainter limits than is possible from the ground: at near-infrared wavelengths Hubble is as sensitive as a ground-based 30 m telescope. From the Hubble Deep Fields, the Ultra Deep Field, the GOODS fields, and the wider-area GEMS, AEGIS and COSMOS programs it has become clear that the epoch $1 < z < 3$ was the "heyday" of galaxy formation, when $\sim 60\,\%$ of all star formation took place, the number density of quasars peaked, the first galaxies stopped forming stars, and the structural regularity seen in galaxies today must have emerged. The pinnacle of HST's imaging surveys are the three Multi-Cycle Treasury programs, which together will devote > 2000 orbits to image galaxies from M31 to $z > 10$.

The problem: The most important limitation in interpreting the deep Hubble images is the *lack of spectra at* $z = 1 - 3.5$, which provide the crucial third dimension, redshift, as well as indispensable physical diagnostics of galaxies. Although optical multi-object spectrographs have provided rest-frame UV spectra of numerous high redshift galaxies (e.g., Steidel et al. 1999, 2003), UV-luminous galaxies make up a relatively small and biased subset of the $M > M_*$ galaxy population (e.g., van Dokkum et al. 2006). The only way to obtain representative spectroscopic samples of galaxies at $z > 1$ is to observe them in the near-IR. This enables us to access the rest-frame optical emission of galaxies, which comes primarily from long-lived stars and contains strong and well-calibrated spectral features such as Hα, [O III], and the 4000 Å break. Unfortunately, the high sky background in the near-IR is a nearly insurmountable obstacle, limiting ground-based near-IR spectroscopy to the brightest high redshift galaxies. Out of necessity studies of mass-limited samples at $z > 1$ rely almost completely on multi-color photometry, which leads to uncertain and model-dependent redshift estimates ($\delta z \gtrsim 0.15$ at $z = 2$, or > 200 co-moving Mpc!) and crude spectral diagnostics.

The solution: Thanks to WFC3's peerless grism capability, HST now offers the opportunity to carry out a deep, wide area, near-IR spectroscopic survey. **This survey, *3D-HST*, will provide rest-frame optical spectra for a very large, well-defined sample of $L_{\mathbf{B}} \gtrsim 0.5\,L_*$ galaxies across $1 \lesssim z \lesssim 3.5$ at 0.″1 resolution,** from which precise redshifts, galaxy masses, galaxy environments, correlation functions, stellar population diagnostics, star-formation rates, and metallicities will be derived. By surveying a sufficiently large volume to obtain representative samples of high redshift galaxies, 3D-HST will answer several key questions of galaxy formation: • *How did galaxy disks and bulges grow?* • *What causes galaxies to stop forming stars?* • *To what extent are galaxies shaped by their environment?* • *What is the role of mergers in galaxy formation?* The survey will be done in the same fields as the 912-orbit Faber/Ferguson MCT imaging program; the combination will be the definitive imaging and spectroscopic dataset for studies of the distant Universe until JWST.

WHAT THE 3D-HST SURVEY WILL PROVIDE:

The survey comprises 2-orbit depth WFC3 G141 slitless spectroscopy of 580 arcmin^2 of the Faber MCT WFC3 imaging area, which will be combined with existing data in GOODS-North for a total of 713 arcmin^2 (see Fig. 6). The survey will provide:

• **Redshifts of a representative sample of 10^4 galaxies at z > 1:** 3D-HST will give rest-frame optical spectra and redshifts for all $\sim 10^4$ galaxies with $1 < z < 3.5$ and $H_{140} \lesssim 23$ in the survey fields. Accurate redshifts remove a major source of uncertainty in measurements of the evolution of the mass- and luminosity functions, the size–mass relation, the correlation function, and the color-mass and color-magnitude relations. Furthermore, they uniquely allow the definition of a galaxy's environment through nearest neighbor statistics, enable the secure identification of physically-associated galaxy pairs, and are the only way to reliably find extreme objects, such as very massive high-z galaxies.

• **Spatially-resolved spectral diagnostics from emission and absorption lines:** The G141 grism spectra cover the observed wavelengths 1.05 μm–1.70 μm, which includes the redshifted [O II] λ3727 and Balmer break at $1.8 < z < 3.5$, the 4000 Å break at $1.6 < z < 3.3$, Hβ at $1.2 < z < 2.5$, [O III] λ4959,5007 at $1.1 < z < 2.4$, and Hα at $0.6 < z < 1.6$ (Fig. 1). The strength of the 4000 Å break (D_{4000}) provides robust M/L measurements (see Kauffmann et al. 2003) and allows the secure identification of "quiescent" galaxies at high redshift, measuring D_{4000} to 0.1 (see Fig. 3). The emission lines provide well-calibrated and robust measurements of: **a)** Star formation rates (SFRs), from Hα when available, else from Hβ or [O II]; **b)** Metallicities from the R_{23} index at $1.8 < z < 2.4$ (and $1.1 < z < 1.5$ when including [O II] from the ACS grism); and **c)** AGN diagnostics, such as a strong increase [O III]/Hβ toward the central regions of a galaxy. As Figs. 2-5 show we have verified the feasibility of measuring these diagnostics by analysing existing WFC3 grism observations.

CORE SCIENCE: THE EMERGENCE OF TODAY'S GALAXIES

The key science of the program is centered around the sample of $\sim 10^4$ galaxies at $1 < z < 3.5$ with rest-frame optical WFC3 spectra from 3D-HST and imaging from the Faber/Ferguson MCT program. During this 4 Gyr period the cosmic SFR and the abundance of bright quasars peaked and the majority of all star formation and black hole accretion in the history of the Universe took place. 3D-HST's spectroscopic survey of the $1 < z < 3.5$ Universe enables us to answer fundamental questions of galaxy formation:

1) What causes galaxies to stop forming stars?

In the low-redshift Universe many galaxies are observed to be quiescent, with current SFRs only $\lesssim 1\,\%$ of their past average (e.g., Pasquali et al. 2006). These quiescent galaxies tend to be massive early-type galaxies, forming the striking and puzzling "red sequence" in the color-mass distribution of galaxies. Recent work has shown that at $z \sim 2$ many massive galaxies ($M \gtrsim 10^{11}\,\mathrm{M}_\odot$) exhibit spectacularly high SFRs of 100s of $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ whereas others were already quiescent, mostly those that are extremely compact for their mass (Kriek et al. 2006, van Dokkum et al. 2008). AGN feedback is a possible mechanism to suppress gas cooling and star formation (e.g., Croton et al. 2006), but direct evidence is scarce.

Proposed test: We will correlate spectroscopically-determined diagnostics of quiescence (e.g., D_{4000}) with stellar mass, surface density (compactness), and the environment of the galaxies on Mpc scales. If the simultaneous presence of quiescent and star-bursting massive galaxies at $z \sim 2$ is the result of their surface density or their environment, correlations should exist between the SFR and these parameters. We will also test whether there is a higher incidence of AGN in galaxies that are transforming from star-forming to quiescence.
Why spectroscopy is required: Quiescent galaxies can only be identified reliably spectroscopically, through the existence of a Balmer- or 4000 Å break and the absence of emission lines (Kriek et al. 2006, Fig. 3; 3σ upper limits on the SFR will range from $\approx 0.5\,M_\odot\,yr^{-1}$ at $z = 1$ to $\approx 5\,M_\odot\,yr^{-1}$ at $z = 3$).

2) To what extent were galaxies shaped by their environment?
The morphology-density relation (Dressler 1980) is a classic result of galaxy evolution, stating that "early-type" galaxies (mostly massive quiescent galaxies) are relatively more abundant in dense environments, such as galaxy groups and clusters. However, at low redshift most massive galaxies are quiescent regardless of environment, so it is difficult to determine whether the environment provides a physical mechanism that alters the galaxies (e.g., through gas stripping), or whether dense environments simply are the place where quiescent galaxies tend to end up (the "nature versus nurture" debate).
Proposed test: To disentangle the roles of mass and environment one should look at an epoch when "massive" did not yet imply "quiescent". The 3D-HST sample is sufficiently large to determine the relation between star formation rate and environment *at fixed mass and redshift*, with ~ 100 galaxies for each mass and redshift bin (with mass bins of 0.2 dex width and redshift bins of $\Delta z = 0.5$). If we see no environmental dependence at fixed mass then the relations between galaxy properties and environment are simply a by-product of underlying relations of both quantities with mass.
Why spectroscopy is required: Even excellent photometric redshifts with errors $\delta z \approx 0.04(1 + z)$ make for a co-moving radial distance error of > 150 Mpc at $z \sim 2$, larger than the distance to the Coma cluster. Therefore, only spectroscopy allows a sensible definition of an environmental galaxy density on the scale of a few co-moving Mpc (see Fig. 5 for a direct demonstration), and it is clearly crucial for diagnosing "quiescence".

3) How did disks and bulges grow?
The $1 < z < 3$ epoch saw the wholesale transition from small, star forming clumps evident in the deepest Hubble images (e.g., Bouwens et al. 2009) to the ordered "realm of galaxies" seen today. Since $z \sim 1$, most star formation has taken place in large spiral disks, but different modes may have been prevalent at earlier times, such as highly concentrated star-bursts making spheroids directly.
Proposed test: If bulges formed before disks we expect to see objects with stellar masses 1–$5 \times 10^{10}\,M_\odot$ and concentrated (~ 1 kpc scales) star formation at $z \sim 3$; these should evolve into young compact bulges surrounded by disk-like (~ 5 kpc) star formation at $z \sim 2$, and then to old bulges and regular disks at $z \sim 1$. By contrast, if bulges formed mostly from subsequent merging of disks, extended star forming disks should be pervasive at $z \sim 3$.

Why spectroscopy is required: Spectroscopy can measure the ages of the subcomponents (from the Balmer and 4000 Å break) and map the star formation rate (Hα, OII) and metallicity separately for galaxy centers and outer regions. From the spatial extent of emission lines (see Fig. 2) we can directly determine whether stars form in a galaxy's bulge, its disk, or both. Ground-based IFUs have demonstrated the power (and necessity) of spatially-resolved spectroscopy (e.g., Förster Schreiber et al. 2009), but are limited to luminous, rare objects.

4) The role of mergers in galaxy formation

Although the merger-driven growth of massive galaxies is a common prediction of galaxy formation models it has been difficult to test at higher redshift, where mergers should be very common (e.g., Guo & White 2008). The merger rate can be determined from (physical) pair statistics, but these have been notoriously difficult to measure due to insufficient spatial resolution and contamination by chance superpositions. Furthermore, mergers should play a large role in driving star formation activity and black hole accretion (e.g., Cox et al. 2006). ***Proposed test:*** With its resolution of $0\farcs1$ and $\delta v \approx 1000\,\mathrm{km\,s^{-1}}$ the grism data can *spectroscopically* identify true physical pairs down to separations $< 5\,\mathrm{kpc}$, weeding out projected galaxy pairs (Figs. 2, 5). We will measure the pair fraction as a function of mass and redshift, and turn the fractions into a merger rate using models (e.g., Kitzbichler & White 2008). We will compare the growth due to mergers with the growth due to star formation. The sizes, densities, AGN content, and star formation rates of the paired or merging galaxies will be compared to predictions of hydrodynamical simulations.

Why spectroscopy is required: Identifying physically associated pairs is only possible with spectroscopy, and only practical with slitless spectroscopy. Determining accurate star formation rates in the paired galaxies also requires spectroscopy.

FURTHER SCIENCE ENABLED BY 3D-HST

Beyond the core science goals outlined above many other projects are enabled by the deep grism spectroscopy, such as:

• **Ly α emitters at** $7.8 < z < 9.5$**:** 3D-HST opens up the exciting possibility of spectroscopically confirming a population of galaxies at $z \gtrsim 8$. Galaxies at $z > 8$ can be reliably distinguished from foreground line emitters through detections in the MCT WFC3 imaging and non-detections in V_{606} and I_{814}. Ota et al. (2008) find two candidate Ly α emitters at $z \sim 7$, one of which has a confirmed spectroscopic redshift, $z = 6.96$. Assuming that the luminosity function does not evolve between $z \sim 8$ and $z \sim 7$, the space density of Ly α emitters with $L > 1.5 \times 10^{43}\,\mathrm{ergs\,s^{-1}}$ is $10^{-5.5}\,\mathrm{Mpc^{-3}}$, which implies that ***3D-HST should spectroscopically discover 3-20 emitters at 7.8 < z < 9.5***. The actual number will constrain the evolution of the luminosity function from $z \sim 8$ to $z \sim 7$ and the effects of attenuation of the Ly α photons by neutral hydrogen prior to full reionization.

• **The quasar luminosity function at 6 < z < 9:** 3D-HST will be able to detect QSOs at $z > 6$ from C IV and at $z > 7.5$ from Ly α down to $J = 25 - 26$, providing either direct measurements or tight constraints on the faint end of the QSO luminosity function at the epoch of reionization. This is uncharted territory for quasar/AGN research at high-redshift, reaching 2-3 mag deeper than the deepest QSO survey carried out from the ground and 5-6 mag deeper than SDSS and UKIDSS. The broad emission lines ($3000\,\mathrm{km\,s^{-1}}$ – $6000\,\mathrm{km\,s^{-1}}$) are marginally resolved by the grism, which means quasars have the unique signature of a pointsource in the WFC3 imaging and an extended source in the grism data. Combined with optical/IR colors identification will be straightforward. Extrapolating the power-law LF and redshift evolution measured in the SDSS, ***we could detect 10 quasars at $z > 6$ using C*IV*, and 5 quasars at $z > 7.5$ using Lyα.*** However, the shape of the quasar luminosity function at $z > 6$ is completely unknown. This is a high risk, high return prospect: any detections of faint quasars at $z > 6$–7 will provide direct constraints on the early growth of supermassive black holes, and potentially interesting targets for JWST/NIRSPEC for absorption line spectroscopy to probe the reionization history.

• **Mapping galaxies to dark matter at high redshift:** The only way to measure the effects of dark matter at $z > 1$ (which is beyond the lensing regime) is through the clustering of galaxies. The first measurements of the clustering of near-IR selected galaxies at $z = 2 - 3$ show puzzling inconsistencies, as they indicate that dark matter halos at these redshifts harbor too few galaxies given their mass (Quadri et al. 2008, Tinker et al. 2009). All clustering results for massive galaxies at $z > 1$ are currently based on photometric redshifts, and the interpretation is extremely sensitive to small systematic errors in the redshift distribution of the galaxies. *Uncertainties in the small-scale clustering of galaxies essentially go away* when using spectroscopic redshifts. 3D-HST will give unambiguous clustering results, thereby directly providing the typical halo masses of different galaxy types.

SURVEY REQUIREMENTS AND FEASIBILITY

Required depth: The survey depth (2 orbits/pointing) is determined by the requirement to get spectra for those galaxies that contribute most importantly to the stellar mass budget, i.e., $\sim L_*$, across the entire redshift range. A limit of $H \lesssim 23$ corresponds to $L \gtrsim L_*$ at $z = 3$ and $L \gtrsim 0.5L_*$ at $z = 2$ (e.g. Marchesini et al. 2007). Two orbits are required for a S/N of 5 per spectral pixel (at $1.4\,\mu$m, for $H = 23$) in the continuum of a compact galaxy. We verified this using actual 2-orbit depth data from Cycle 17. As shown in Fig. 3 and 4 we can indeed measure absorption-line redshifts of galaxies down to $H \sim 23$ and emission-line redshifts to even fainter magnitudes. The feasibility of the program and the power of the grism approach is further demonstrated in Figs. 2 and 5, which show that we obtain accurate redshifts and spectral diagnostics for all reasonably bright galaxies in the survey area.

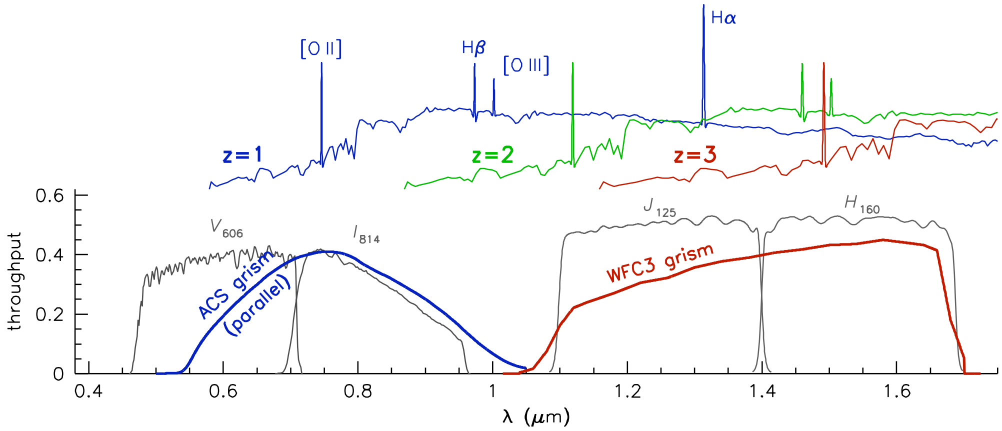
Required area: With 122 pointings we cover an area of $\approx 580\,\mathrm{arcmin}^2$, corresponding to a co-moving survey volume of $5 \times 10^6\,\mathrm{Mpc}^3$ at $1 < z < 3.5$. This volume is just large enough to contain the future sites of a few massive, present-day Abell galaxy clusters (e.g., Bahcall et al 2003), i.e., is the minimum volume required to sample all environments. Within this volume we expect a dozen ongoing major mergers at $z > 2$ among massive galaxies (e.g. Somerville et al 2008), the minimum to get a sense of what role these cataclysmic events play, and 10–20 very high redshift galaxies and quasars (see above). In this volume the total number of $1 < z < 3.5$ galaxies with good near-IR spectra is expected to be ~ 9000 (see

Fig. 1), which we have verified by measuring redshifts in the single G141 pointing that was obtained as part of the ERS in GOODS-South: we find 76 $z > 1$ galaxies (see Fig. 5), fully consistent with the expected per-pointing number of ~ 65. Dividing the sample into 5 bins of redshift, mass, and environment we will have ~ 70 galaxies per bin, sufficient for measuring average properties (such as the fraction of quiescent galaxies) with 10-15 % accuracy.

Field choice: The observations will be divided over 4 independent fields to limit cosmic variance. For massive ($\geq 10^{11}\,\mathrm{M}_\odot$) galaxies the proposed survey geometry implies an uncertainty due to cosmic variance of 25% at $2.5 < z < 3$ (Moster et al. 2010), just enough to detect a factor of 2 in density evolution. We will place the WFC3 grism pointings inside the areas covered by WFC3 imaging in the Faber MCT program (Fig. 6), thus removing the need to spend an additional 122 orbits of imaging in support of the spectroscopy. Furthermore, 3D-HST greatly enhances the legacy value of the 912-orbit Faber program, as 75 % of the MCT area will have spectroscopic coverage. We note that it is not a coincidence that the Faber program covers a similar area as we are proposing here, as it focuses on the same redshift range and therefore has similar volume requirements.

Why existing data are not sufficient: • The existing 28 pointings in GOODS-North are not sufficient for reaching our science goals: the number of galaxies is simply too small (see above and Fig. 7); number densities would be completely dominated by cosmic variance; the data do not sample a sufficiently large range in environments; and we would expect only 0–2 very high redshift objects. • The pure parallel Cycle 17 program of Malkan et al. is only suitable for emission line studies of bright galaxies as the observations cannot be dithered. Furthermore, as it targets "random" fields it lacks imaging and other supporting data.

Why this cannot be done from the ground: Even with the most optimistic assumptions the core science goals of the proposed WFC3 grism survey cannot be reached from the ground. • *Survey speed:* X-Shooter on VLT is the most sensitive near-IR specrograph in existence; coming very close to the theoretical background between the night sky lines by cross-dispersing the spectrum to a resolution of $R = 8,000$, it is nevertheless $5\times$ slower than the WFC3 grism *per pointing*. Furthermore, X-Shooter can only target one object at a time, whereas we extract $200 - 250$ galaxy spectra per WFC3 pointing ($60 - 80$ of which are at $z > 1$). New ground-based multi-object near-IR spectrographs (LUCIFER, MOSFIRE) can target 40 objects at a time at lower dispersion, but they are $3 - 4\times$ slower for any given object than X-Shooter. Obtaining a complete sample of 10^4 $H \lesssim 23$ galaxies at $z > 1$ (as proposed here) would require ~ 1000 nights on an 8-10m class telescope. • *Spatial resolution:* Spatial information on $0''.1$ scales can only be obtained for relatively bright individual objects from the ground, as it requires IFU spectroscopy with laser guide stars. • *Completeness:* 3D-HST will provide spectra for all objects in the survey area, including galaxies dominated by emission lines (such as Ly-α emitters at $z > 7.8$) and close pairs. In contrast, multi-slit spectroscopy imposes severe geometrical restrictions on the target selection. Furthermore, ground-based emission line work (at $R = 5000$) is not possible in $\sim 2/3$ of the spectral range covered by the G141 grism, due to sky emission and absorption features. Hence key emission features in the majority of galaxies simply cannot be accessed from the ground.



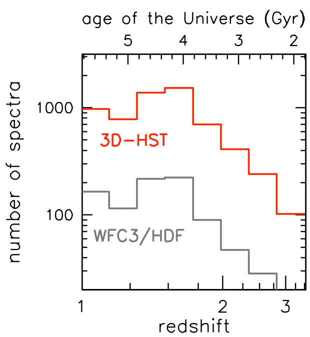


Fig. 1: What the survey will provide.
We propose to obtain WFC3 G141 grism spectroscopy over areas that will be observed in the Faber/Ferguson MCT imaging program. The MCT program will provide WFC3 J_{125} and H_{160} imaging along with parallel ACS V_{606} and I_{814} images. 3D-HST will provide crucial redshift information and spectral diagnostics for $\sim 10^4$ galaxies at $z > 1$ in these fields. The program will cover $\sim 5\times$ more area than the Cycle 17 GOODS-North program, increasing the spectroscopic coverage of the MCT area from 14 % to 75 %.

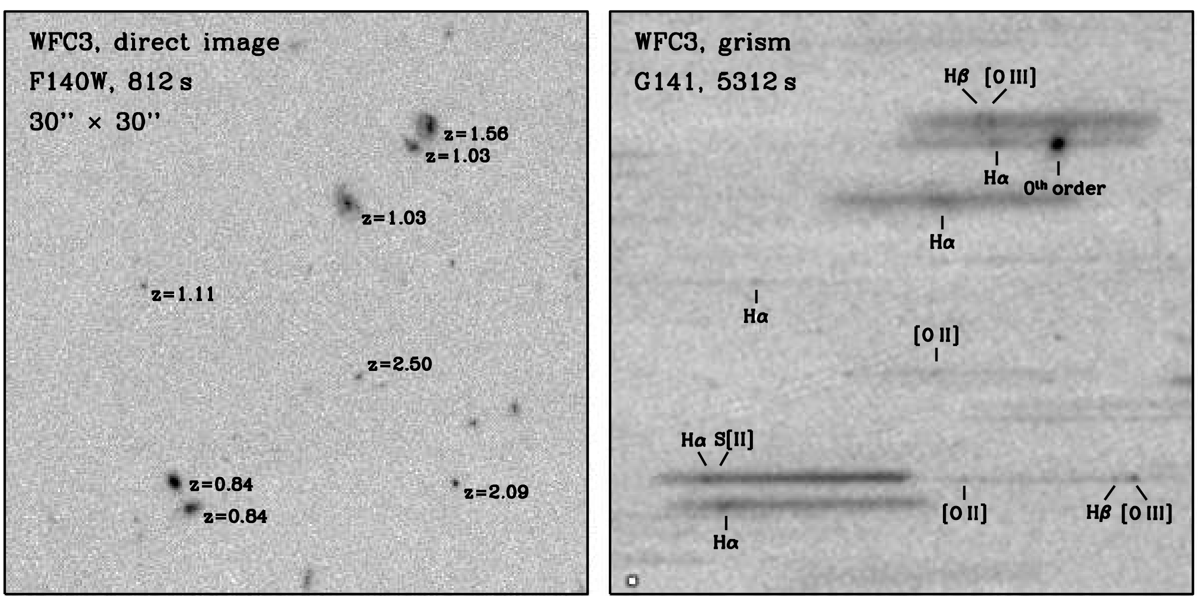


Fig. 2: 1/2000$^{\text{th}}$ of the proposed survey.
A direct WFC3 image on the left is compared to a 2-orbit G141 grism image on the right. The data are from the Cycle 17 program GO-11600 in HDF-N. The grism spectra cover the wavelength range 1.1 μm – 1.7 μm and are of remarkable quality. Thanks to the fact that rest-frame optical emission and absorption features fall in this wavelength range for $0.7 < z < 3.5$, the grism data give redshifts, along with approximate sizes of the line-emitting regions, for most of the easily visible galaxies in this field. The full survey area is 2000× larger than the area displayed here.

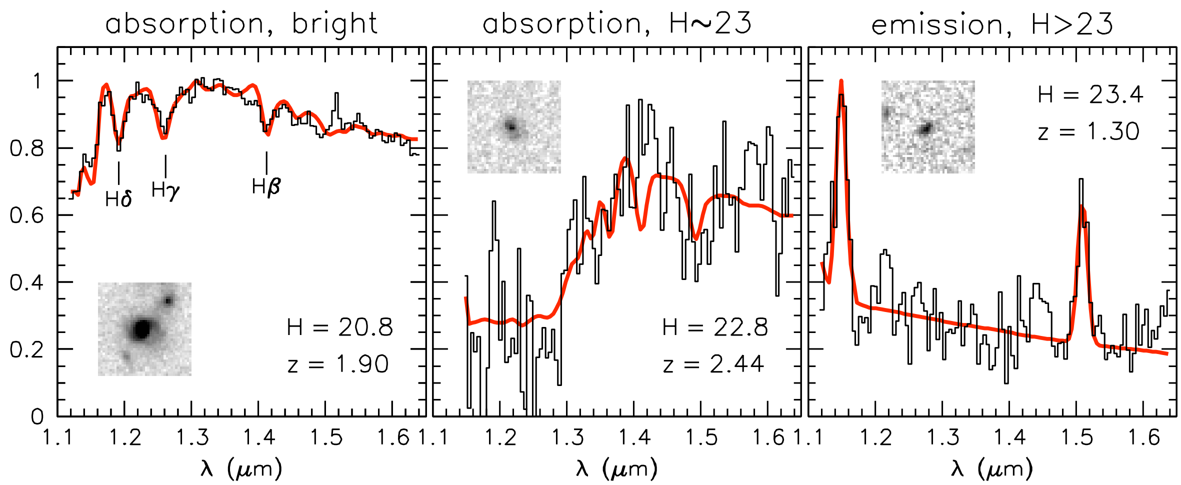


Fig. 3: Example grism spectra from Cycle 17.
Three examples of 2-orbit WFC3/G141 grism spectra in the Cycle 17 GOODS data, with data in black and template fits in red: a bright absorption line galaxy at $z = 1.90$, an absorption line galaxy at $z = 2.44$ near the completeness limit of 3D-HST of $H \approx 23$, and a galaxy fainter than this limit with emission lines. *These spectra are of absolutely spectacular quality* given the magnitudes and redshifts of these objects. The $z = 1.9$ spectrum has much higher S/N than any previous rest-frame optical spectrum at $z > 1.5$, and the $z = 2.45$ galaxy is several magnitudes fainter than all previously spectroscopically confirmed passive galaxies at high redshift.

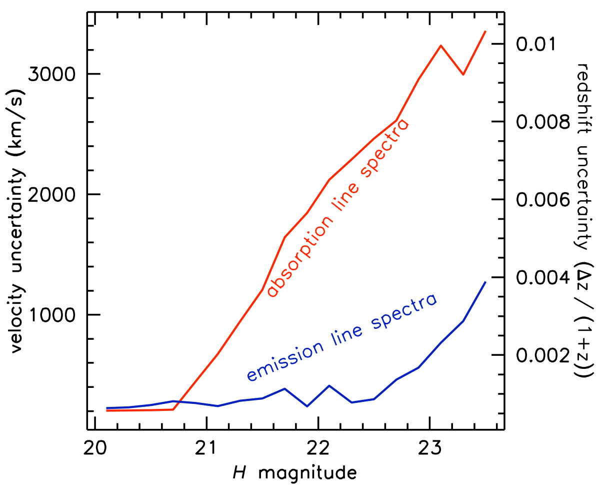


Fig. 4: Redshift error versus depth. Relation between redshift/velocity uncertainty and H-band magnitude, determined from simulations based on extracted grism spectra of bright galaxies at $z \sim 2$. For $H \leq 23$ the error in $\Delta z/(1+z)$ is $< 1\,\%$ even for galaxies lacking emission lines. For galaxies with emission lines the errors are even smaller.

• Bahcall 03, ApJ, 585, 182 • Bouwens 09, ApJ, subm. • Brammer 09, ApJ, 706 173 • Cox 06, MNRAS, 373, 1013 • Croton 2006, MNRAS, 365, 11 • Dressler 1980, ApJ, 236, 351 • Guo, White 08, MNRAS, 384, 2 • Kauffmann 03, MNRAS, 341, 33 • Kitzbichler 08, MNRAS, 391, 1489 • Kriek 06, ApJ, 649, 71 • Marchesini 07, ApJ, 656, 42 • Moster 10, ApJ, in press • Ota 08 ApJ, 677, 12 • Pasquali 06, ApJ, 636, 115 • Quadri 08, ApJL, 685, 1 • Somerville 08, MNRAS, 391, 481 • Steidel 99, ApJ, 519, 1 • Steidel 03, ApJ, 592, 728 • Tinker 09, ApJ, 691, 633 • van Dokkum 06, ApJ, 638, L59 • van Dokkum 08, ApJ, 677, 5

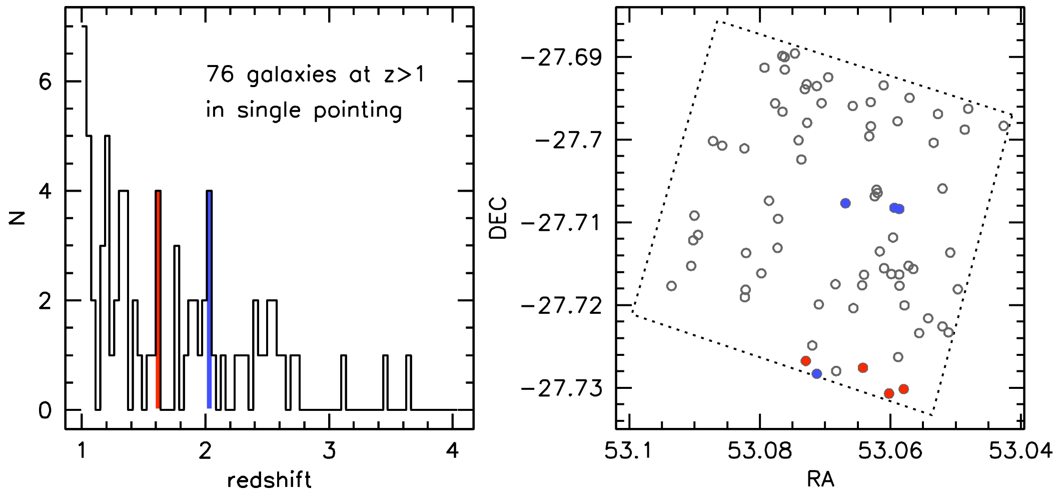


Fig. 5: Redshift distribution in a single pointing.
A single 2-orbit G141 grism pointing was included in the ERS observations in GOODS-South. We successfully measured redshifts for 245 galaxies in this field, 76 of which are at $z > 1$. The two highlighted redshift spikes demonstrate that we can unambiguously measure the environment of galaxies and determine group membership. The two groups are remarkably compact: in each of the groups the galaxies are likely part of a single halo and may merge. 3D-HST will observe 122 pointings, yielding $\sim 10^4$ redshifts and several hundred galaxy groups at $1 < z < 3.5$.

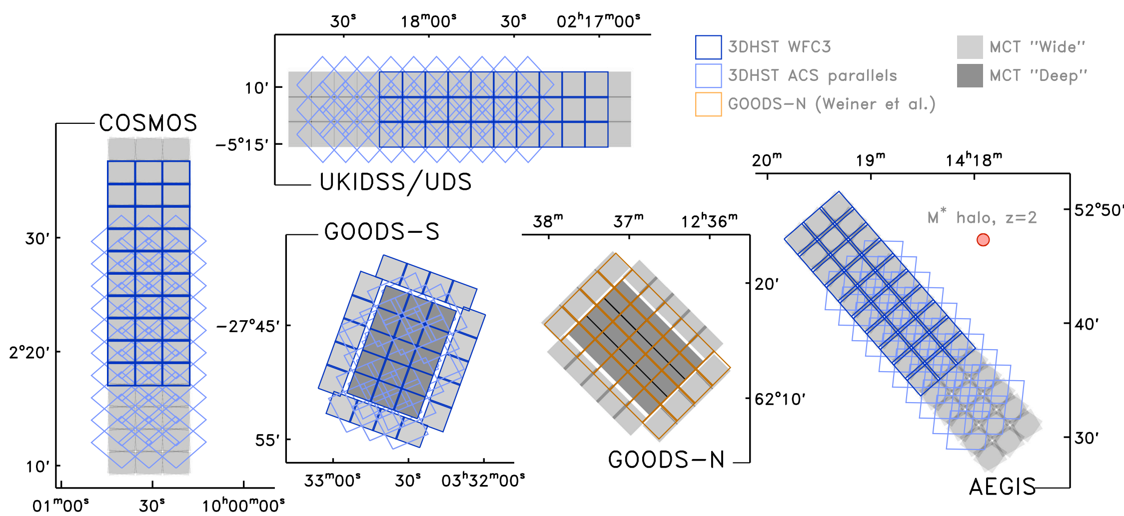


Fig. 6: 3D-HST will cover most of the Faber MCT area.
To overcome field-to-field variations (e.g., Moster et al. 2010) and to obtain sufficiently large samples we propose to cover a total area of 580 arcmin^2, spread over 4 fields: COSMOS, UKIDSS/UDS, GOODS-South, and AEGIS. The red circle indicates the virial radius of the halo of an $M \sim M_*$ galaxy at $z = 2$. The WFC3 pointings and ACS parallels will coincide with those of the Faber MCT imaging program in these fields. Adding the existing grism data in GOODS-North, 3D-HST will provide spectra and redshifts in all 5 MCT fields, covering 75 % of the total area, thus greatly enhancing the scientific returns from the 912-orbit MCT program.

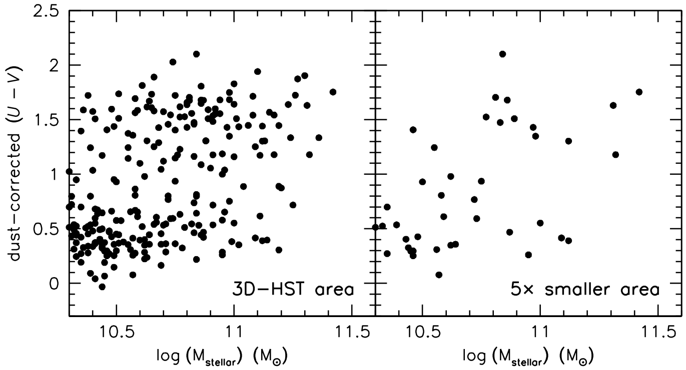


Fig. 7: Importance of area. Reddening-corrected color-mass relation in a redshift slice at $z = 2.25 \pm 0.25$, as determined from $H < 23$ galaxies in the Brammer et al. (2009) sample. The left panel shows the sample that we will obtain in the proposed area and the right panel shows the sample that we would get in a single GOODS-sized area.

Description of the Observations

Observing strategy and scheduling: 3D-HST complements the extensive imaging surveys that have been done with HST (in particular the MCT Faber program) with grism spectroscopy. As discussed above, a thorough investigation of the currently available grism data shows that 2 orbits are sufficient for continuum spectroscopy down to $H \sim 23$. The Faber fields are 3×15 pointing strips in COSMOS, AEGIS, and the UKIDSS UDS field, deep 3×5 pointing mosaics in each of the GOODS fields, and 18-pointing "borders" around the deep GOODS mosaics. As shown in Fig. 6 we will observe all three wide strips along with GOODS-South (including the border). A 28-pointing mosaic already exists in GOODS-North, which means that all of the MCT fields will be covered by grism observations. The total number of pointings that need to be observed is $2 \times 3 \times 15$ for the strips in COSMOS and AEGIS plus 32 in GOODS-South (as 1 pointing is already available from the ERS), or 122. With 2 orbits per pointing this implies an orbit total of 244. Additionally, we propose to add 4 orbits to the UDF in GOODS-South, as having 3 independent 2-orbit depth dispersed images of the same pointing will allow us to empirically verify our noise model. The total orbit request is therefore 248. We will follow the same pointing strategy as the Faber program (see Fig. 6). Parallel ACS grism observations will cover $\gtrsim 85\,\%$ of the WFC3 area. Scheduling of 3D-HST will be coordinated with the Faber program. Our program has fewer restrictions as it does not have a supernova component; nevertheless, we realize that it may be helpful or necessary to spread 3D-HST over 2 Cycles.

Data acquisition, analysis, and data products: Following a similar strategy as the ERS observations we will obtain 4 dithered grism exposures at each position, along with short ($4 \times 200\,$s) direct images in F140W which are necessary for wavelength calibration. We have demonstrated that we are able to extract high quality spectra from such data (see Fig. 3), using a combination of public software (aXe) and special-purpose scripts that improve sky subtraction and other aspects of the reduction. We will optimally extract 1D and 2D spectra, carefully deconvolving overlapping spectra (which affect $\sim 20\,\%$ of spectra). The extensive experience of the co-Is with HST and near-IR spectra will ensure that the delivered data and spectra are of very high quality. The survey products comprise: *i)* reduced, calibrated, and combined dispersed and undispersed images; *ii)* wavelength- and flux-calibrated WFC3/G141 and ACS/G800L 1-D and 2-D spectra; *iii)* redshifts and emission line fluxes;

iv) ancillary data in the 3D-HST fields from GALEX, Subaru, CFHT, ground-based near-IR imaging, and Spitzer IRAC and MIPS; *v)* photometry from these ancillary datasets on the same flux scale as the spectra; *vi)* best-fitting spectral synthesis models to the photometry and spectra and derived parameters such as masses, star formation rates, and metallicities; and *vii)* all the software and documentation needed to go from *i)* to *vi)*. We will include the existing data in GOODS-North in the analysis and data releases. We will release these products within 18 months of obtaining the data.

Team expertise: The members of the team have enormous experience with ground-based near-IR spectroscopy and also with the HST ACS and WFC3 grisms. Co-Is Steidel and Rix are (co-)PIs of the multi-object near-IR spectrographs MOSFIRE on Keck and LUCIFER on LBT, respectively. Co-Is McCarthy, Pasquali, and Brammer are experts on HST grism spectroscopy. Co-Is Kriek, Erb, Fan, Förster Schreiber, Franx, van Dokkum, and Kauffmann are world leaders in the analysis and science described in this proposal. We have successfully executed large projects of similar complexity (COMBO-17, GEMS, FIRES, HUDF-09, MUSYC, NMBS, etc). We have pushed ground-based telescopes to their limits, and are now ready to capitalize on the huge leap in capability that comes with the exciting WFC3 grism.

Special Requirements

Coordinated ACS parallels add spatially resolved rest-frame UV spectroscopy to the program, enhancing its legacy value and helping with the interpretation of the WFC3 spectra.

Coordinated Observations

Justify Duplications

None.

Past HST Usage and Current Commitments

Past HST programs led by the PI: The PI of this proposal was the PI of two previous HST programs: GO-10808 and GO-10809, both of which resulted in several published papers. A key paper from GO-10808 is "Confirmation of the Remarkable Compactness of Massive Quiescent Galaxies at $z \sim 2.3$: Early-Type Galaxies Did not Form in a Simple Monolithic Collapse", van Dokkum et al. 2008, ApJ, 677, L5. The PI and co-Is have been involved in numerous other HST programs, including the ACS GEMS survey in the E-CDFS (PI: Rix), the GRAPES ACS grism Treasury program (Pasquali), the WFC3 Early Release data (McCarthy), and the Cycle 17 WFC3 Treasury program in the UDF (PI: Illingworth).

Other commitments of key personnel: This will be the major research effort of van Dokkum, Rix, Kriek, Kauffmann, Erb, Franx, Labbé, Marchesini, and their research groups. The PI and the key co-Is have no other major commitments other than the usual duties related to teaching and administration.