Astro2020 Science White Paper

Ultra Deep Field Science with WFIRST

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics

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Abstract:

Studying the formation and evolution of galaxies at the earliest cosmic times, and their role in reionization, requires the deepest imaging possible. Ultra-deep surveys like the HUDF and HFF have pushed to magnitude ~ 30, revealing galaxies at the faint end of the LF to $z \sim 10-11$ and constraining their role in reionization. However, a key limitation of these fields is their size, only a few arcminutes (less than a Mpc at these redshifts), too small to probe large-scale environments or clustering properties of these galaxies, crucial for advancing our understanding of reionization. Achieving HUDF-quality depth over areas $\sim$100 times larger becomes possible with a mission like the Wide Field Infrared Survey Telescope (WFIRST), a 2.4-m telescope with similar optical properties to HST, with a field of view of $\sim$1000 arcmin^2, $\sim$100× the area of the HST/ACS HUDF.

This whitepaper motivates an Ultra-Deep Field survey with WFIRST, covering at least $\sim$100× the area of the HUDF, or up to $\sim$1 degree^2, to magnitude ~ 30, potentially revealing thousands of galaxies and AGN at the faint end of the LF, at or beyond $z \sim 10$ in the epoch of reionization, and tracing their LSS environments, dramatically increasing the discovery potential at these redshifts.

1 Introduction and Science Motivation

Probing the formation and evolution of galaxies up to redshifts $\sim$10 and beyond, into the epoch of reionization, requires deep imaging to magnitudes $\gtrsim 29.5 - 30$ at optical to near-IR wavelengths, with spatial resolution of $\sim 0\farcs1$ or better, to resolve the kpc-scale (or smaller) star-forming clumps at these redshifts. Achieving these depths is crucial for reaching sub-$L^{\star}$ galaxies (faint end of the galaxy luminosity function, hereafter 'LF') at $z \sim 10$, to explore their role in reionization and trace their assembly into more massive galaxies over cosmic time [1, 2, 3]. To date, the deepest fields have been obtained with HST, reaching these depths in the Hubble Ultra Deep Field (HUDF) initially in 2004 with ACS at optical wavelengths [4, 5], subsequently in 2009 – 2012 with WFC3 at near-IR wavelengths [6, 7, 8, 9] and in 2013 at UV wavelengths [10, 11], revealing a wealth of detail about the evolution of the faint end of the LF and size evolution of galaxies, as well as measuring the escape fraction of ionizing photons at high redshift and the role played by faint galaxies in reionization [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28]. With the HUDF having essentially reached the maximum observational depth practically achievable for HST (totalling several Msec of observing time), the Hubble Frontier Fields program (HFF) [29] was subsequently carried out, making use of gravitational lensing in six cluster fields to push up to an order of magnitude deeper into the LF at $z \sim 8 - 11$, see also [30, 31, 32, 33, 34], although the relatively small lensing area result in much smaller volumes probed at high redshift.

A key limitation of existing fields like the HUDF concerns its size, being only $\sim 2 - 3$ arcmin across, corresponding to $\sim$0.5 – 0.7 Mpc at $z \sim 10$. This volume of space probed is too small to enable significant studies about the large-scale environment or clustering properties of galaxies at the faint end of the luminosity function, yet these questions are crucial to address in order to further advance our understanding of reionization. JWST will probe deeper, but likely over similar sized survey areas, as already envisioned by current ERS and GTO programs, e.g., 'The NIRCam GTO Deep Field (PI: M. Rieke), 'The Cosmic Evolution Early Release Science (CEERS) Survey' (PI: S. Finkelstein), and 'The JWST-NEP TDF' (PI: R. Windhorst, [35]). While larger surveys with HST have been carried out, these typically trade depth for area due to the constraints of observing time; for example the combined GOODS [36] and CANDELS [37, 38] surveys cover $\sim$780 arcmin^2 to depths of $\sim$28.5 in up to ten bandpasses, while the COSMOS survey [39, 40] covers $\sim$1.6 deg^2 to $\sim$27.5 in a single bandpass (ACS F814W). These surveys have greatly enabled studies of galaxy formation at intermediate redshifts (eg, 'cosmic noon' at $z \sim 2 - 3$, as well as the brighter end of the LF up to $z \sim 6 - 8$, with many of these results also being reported in papers [12] – [28] above), and with COSMOS furthermore enabling the first large-scale-structure dark matter maps obtained from weak lensing measurements [41]. However, since these surveys are unable to probe down to the magnitude limits of $\sim$30 required to detect faint galaxies at $z \sim 10$, the science is restricted to either the extremely bright end of the LF at these redshifts, or galaxy evolution at more moderate redshifts. ***To significantly advance knowledge of the faint end of the galaxy LF at reionization, it is necessary to obtain HUDF-quality imaging and depth (AB $\sim$ 30 mag) over $\sim$100× larger area than existing ultra-deep surveys, which can be done with WFIRST.***

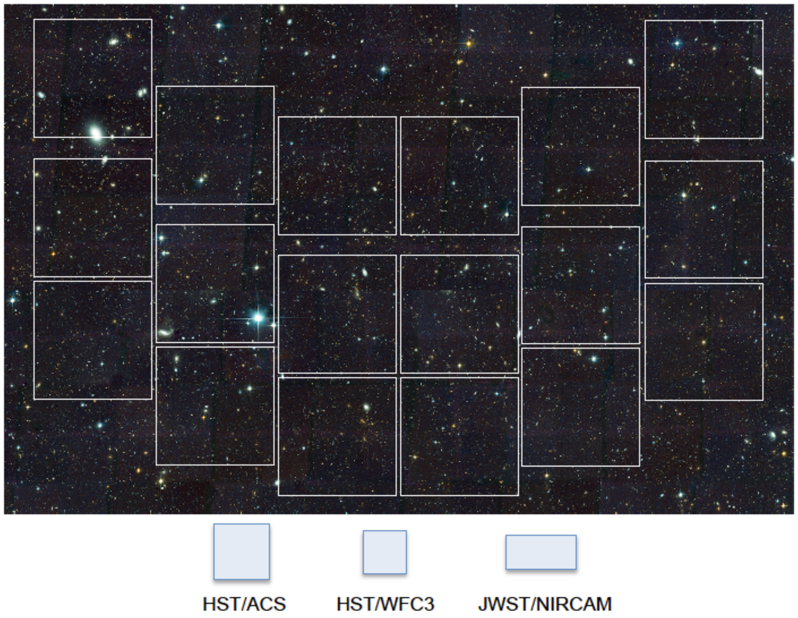


Figure 1: Field of view of the WFIRST Wide Field Instrument (WFI), compared with instruments from HST and JWST. Each of the18 WFI detectors is a 4k x 4k HgCdTe array with $0.11''$ per pixel. The field of view of $\sim$1000 square arcminutes is about 100 times the area of the HST/ACS HUDF.

2 Future Deep, Wide, High-Res. Imaging from Space: WFIRST

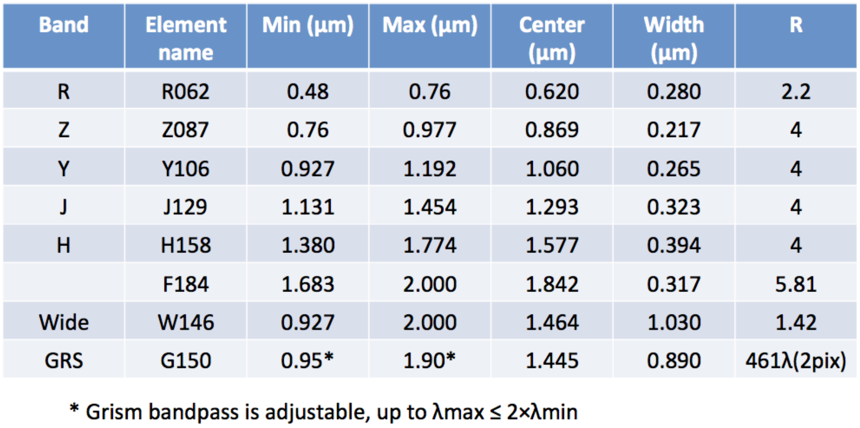
Achieving HUDF-quality depth over $\sim$100 times larger areas is *only* possible with a mission like the Wide Field Infrared Survey Telescope (WFIRST), which is the top-ranked space mission from New Worlds, New Horizons [42, 43]. The design consists of a 2.4-m telescope, offering a comparable resolution to HST, equipped with the Wide Field Instrument (WFI) that is made up of 18 HgCdTe detectors, each 4k$\times$4k with $0.11''$ pixels, providing a field of view over $\sim$1000 square arcminutes, or almost 100 times the field of view of HST/ACS (Figure 1). The currently planned configuration of the WFI includes seven broad-band filters ($RZYJHF$, and one ultra-wide) spanning $\sim$0.5 – 2.0 μm, an $R \approx 600$ grism (spanning 1.0 – 1.9 μm), and an $R \approx 100$ prism (spanning 0.6 – 1.8 μm), where the relative field of view is illustrated in Figure 1.

3 Survey Programs with WFIRST

The WFIRST design reference mission includes a nominal 5-year observing plan containing a guest observing program, and several large surveys that target galactic science themes, namely exoplanets and bulge microlensing, as well as large extragalactic programs consisting of a high-latitude survey and a supernova program.

3.1 The High Latitude Survey and Supernova Survey

The high latitude survey (HLS) is envisioned to cover $\sim$2000 square degrees at sparse time-sampling cadence to depths of $\sim$26 – 27 mag, and is thus at the opposite end of parameter space



Band	Element name	Min (μm)	Max (μm)	Center (μm)	Width (μm)	R
R	R062	0.48	0.76	0.620	0.280	2.2
Z	Z087	0.76	0.977	0.869	0.217	4
Y	Y106	0.927	1.192	1.060	0.265	4
J	J129	1.131	1.454	1.293	0.323	4
H	H158	1.380	1.774	1.577	0.394	4
	F184	1.683	2.000	1.842	0.317	5.81
Wide	W146	0.927	2.000	1.464	1.030	1.42
GRS	G150	0.95*	1.90*	1.445	0.890	461λ(2pix)

* Grism bandpass is adjustable, up to λmax ≤ 2×λmin

Figure 2: Planned filter set for WFI, from the WFIRST Reference Information documents at https://wfirst.gsfc.nasa.gov/science/WFIRST_Reference_Information.html

from that probed by ultra deep surveys, although it can be expected to yield significant numbers of rare high-luminosity sources in the epoch of reionization, along with measurements of large scale structure evolution on $\sim$ Gpc-scales up to high redshift.

The supernova survey will cover $\sim 20-50$ square degrees with more frequent time-sampling cadence, aiming to reach magnitudes $\sim 28-29$ in the final full-depth images, achieving comparable depths to the medium-depth HST surveys such as GOODS and CANDELS, over a $\sim 2-3$ orders of magnitude larger area. This survey is subject to further optimization, but one current working version envisions two tiers: wide and deep, targeting different redshift ranges. If compatibility with ground-based facilities were not an issue, each tier would be split into a few fields, reducing the impact of cosmic variance, and all fields would be in the WFIRST Continuous Viewing Zone (CVZ). It is also possible that the deep-tier fields will be embedded in the wide-tier fields, reducing the impact of edge effects in the deep tier. Good choices for SNe fields (low extinction, low zodiacal emission, and CVZ) exist in both the North and the South.

3.2 GO Programs and Ultra Deep Surveys with WFIRST

While the HLS and SNe survey programs will lay significant groundwork for extragalactic galaxy and AGN astrophysics, the broader WFIRST Guest Observer (GO) community will likely seek to complement these fields with additional Ultra Deep Fields, covering a single or few pointings to fainter sensitivities. The WFIRST GO opportunity will arrive after both JWST and Euclid have been operational for several years, and therefore both the motivation and science return of such UDF programs should be carefully considered.

Scientifically, UDF fields with WFIRST will provide several critical capabilities. Contiguous, deep ($m_{\rm AB} \sim 30$ mag per filter per pointing) areas of the sky at $1-2\,\mu$m with JWST will remain limited to a few hundred square arcminutes at most, even after years of operations, with deep JWST spectroscopy even more limited. Questions about the role of faint galaxies and AGN in cosmic reionization will depend on interpretations of disjoint fields with limited individual areas. While disjoint fields can help reduce cosmic variance for high-redshift samples, they cannot effectively connect the properties of galaxy populations to their surrounding environment.

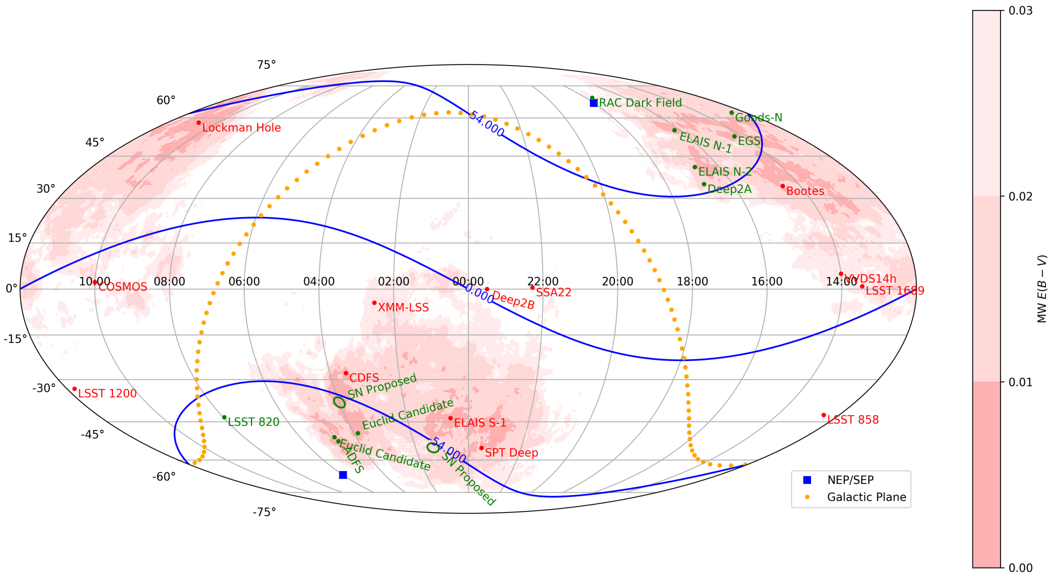


Figure 3: Equatorial map of the sky indicating potential deep fields for WFIRST (courtesy of D. Rubin, R. Foley). The red shading displays the Milky Way reddening (as indicated by the color bar on the right) with lower reddening values being darker. Ecliptic latitudes of $|54°|$, corresponding to the edge of the *WFIRST* continuous viewing zone (CVZ) are also displayed as blue lines. Several extragalactic fields are marked, those in green being in the *WFIRST* CVZ, while a representative set of other well-studied fields are in red, incl. CDFS, COSMOS, ELAIS-S1, SPT Deep, and other fields, all of which are collected in Table 1.

A mission like WFIRST, providing contiguous, ultra-deep coverage over at least 1 deg^2, will directly probe clustering and other spatial correlations for faint galaxies and AGN at significant comoving distances at high-z, along with possible variations in the faint-end slope of the LF with environment at high-z. This will likely provide the first clustering constraints on the dark matter halo mass for galaxies that dominate the luminosity density of the universe at early times. Single WFIRST pointings are wide enough to capture several ionized bubbles in the IGM during the height of the reionization era, and will supply a chance to connect the properties of the dominant ionizing sources with the ionization state of the IGM that surrounds them. Such studies combining WFIRST imaging and grism observations could connect the Lyα emission statistics of faint galaxy populations directly with their environmental overdensity. While the WFIRST HLS and SNe Deep Fields will also prove tremendously fruitful for studies of the reionization era and throughout the high-redshift universe, the ability to provide sensitive imaging over a substantial area through GO UDFs will remain a unique WFIRST role for at least a decade after HST and JWST.

4 Potential Locations for Deep Fields with WFIRST

For any potential deep field programs, important considerations include the fraction of time that the field is accessible to WFIRST (i.e., location relative to the CVZ), as well as accessibility to ancillary telescopes that will be expected to play significant roles in observing the field (ie, whether the fields are exclusively accessible to ground-based telescopes in the northern or southern hemispheres, or both). In addition, the amount of galactic extinction $E(B-V)$ is an important consideration, in order to avoid introducing reddening-related effects in colour measurements of supernovae and galaxies. The amount of zodiacal emission is also important to consider in terms of the ultimate limiting magnitude that can be reached in a given location. The presence of deep X-ray, Herschel far-IR, and ALMA observations will also prove valuable given their unique probes of galaxy and AGN SEDs well outside the wavelength regime covered by WFIRST. Finally, connecting with 21cm surveys and submillimeter surveys, the HERA and SPT Deep fields are of particular interest for the placement of GO grism fields that could connect with ground-based intensity mapping experiments that directly probe the epoch of reionization in complementary ways.

Table 1: A Compilation of representative well-studied extragalactic fields

Field	R.A.	Dec.	Ecl. Lat.	Area (deg^2)	E(B-V)	Rel. Zodi	Days/yr
Polar fields $(< 36^\circ)$**:**							
IRAC Dark Field	17:40	+69:00	+87	0.2	0.043	1.0	365
Extended Groth Strip	14:17	+52:30	+60	0.2	0.009	1.2	365
GOODS-N	12:36	+62:13	+57	0.25	0.012	1.2	365
Deep2A	16:52	+34:55	+57	1	0.018	1.2	365
ELAIS N-2	16:46	+41:01	+63	5	0.014	1.1	365
ELAIS N-1	16:11	+55:00	+73	9	0.008	1.0	365
Akari Deep Field South	04:44	−52:20	−73	12	0.008	1.0	365
JWST-NEP-TDF	17:22	+65:49	+86	0.2	0.042	1.0	365
NEP-Spitzer	18:00	+66:33	+90	10	0.046	1.0	365
SEP-Spitzer	06:00	−66:33	−90	10	0.062	1.0	365
Equatorial fields:							
CDFS	03:32	−27:48	−45	0.3	0.008	1.4	229
Deep2B	23:30	+00:00	+3	1	0.044	19	146
SSA22	22:17	+00:24	+10	4	0.056	5.6	149
COSMOS	10:00	+02:12	−9	2	0.018	6.0	148
VVDS14h	14:00	+05:00	+16	4	0.026	3.6	153
ELAIS S-1	00:35	−43:40	−43	7	0.008	1.5	215
Bootes	14:32	+34:16	+46	9	0.016	1.4	236
Lockman Hole	10:45	+58:00	+45	11	0.011	1.4	229
XMM-LSS	02:31	−04:30	−18	11	0.024	3.2	155
SPT Deep	23:30	−55:00	−46	100	0.010	1.4	236
HERA	07:00	−30:43		1200			

5 Summary

In summary, this paper presents a recommendation for an Ultra Deep Field program with WFIRST, representing a major leap forward from existing ultra-deep surveys by increasing the area by at least a factor of 100×, covering $\sim$1 deg^2 to $m_{\rm AB} \sim 30$ mag, to study the impact and evolution of the faint galaxy population in the epoch of reionization to $z \sim$ 10–11 or beyond, dramatically increasing the discovery potential at these redshifts.

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