Enabling Cosmological Synergies between the LSST and WFIRST High Latitude Survey

Cosmology with the WFIRST High Latitude Survey Science Investigation Team

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Abstract

The High-Latitude Survey (HLS) will implement in a joint observing program two of the three dark energy probes that are defining objectives of the Wide-Field Infrared Survey Telescope (WFIRST). In its current design, the HLS imaging survey (4 filters spanning 0.93–2.00 μm) will measure accurate galaxy shapes for weak lensing while the HLS spectroscopic survey will measure galaxy redshifts using emission lines redshifted to > 1 μm. Both programs take advantage of WFIRST's wide field of view, its extreme optical stability, and the low NIR sky background available in space. Considering only the cosmological science enabled by the HLS, we discuss the remarkable science impact of the WFIRST HLS and LSST combination. It goes well beyond the science enabled by any of the data sets alone. In particular, this combination will be critical for photometric redshifts (object by object or in cross-correlation), source deblending, galaxy shape measument validation, and modeling in the nonlinear regime. The key requirement is for the LSST WFD to overlap with the WFIRST HLS and observe in at least $ugriz$. The needs from the WFIRST side are met by what the LSST WFD survey is currently planning to do. We are documenting it here primarily to ensure retention of the features that enable these powerful WFIRST HLS+LSST scientific synergies as the LSST observing strategy is adjusted.

1 White Paper Information

This white paper is submitted on behalf of the *Cosmology with the WFIRST High Latitude Survey (HLS)* Science Investigation Team (SIT)[1] by Olivier Doré (`olivier.p.dore@jpl.nasa.gov`), Tim Eifler (`timeifler@email.arizona.edu`), Shoubaneh Hemmati (`shemmati@ipac.caltech.edu`), Chris Hirata (`hirata.10@osu.edu`), Mike Jarvis (`mjarvis@physics.upenn.edu`), Elisabeth Krause (`krausee@email.arizona.edu`), Rachel Mandelbaum (`rmandelb@andrew.cmu.edu`), Michael Troxel (`michael.troxel@duke.edu`)

1. **Science Category:** This paper mostly addresses *the Nature of Dark Matter and Understanding Dark Energy.*
2. **Survey Type Category:** This paper focused on the *wide-fast-deep* survey. [Comment: Synergies between LSST deep drilling fields and WFIRST are covered in the companion white paper, "LSST Observations of WFIRST Deep Fields," led by Ryan Foley.]
3. **Observing Strategy Category:** A specific pointing or set of pointings that is (relatively) agnostic of the detailed observing strategy or cadence.

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[1] WFIRST High Latitude Survey SIT web site [Link].

2 Scientific motivation

The WFIRST High-Latitude Survey. The High-Latitude Survey (HLS) supports two of the three dark energy probes that are defining objectives of the Wide-Field Infrared Survey Telescope (WFIRST [14, 13]), as set forth in the 2010 Decadal Survey [2]. In its current design [4], the HLS imaging survey (4 filters spanning 0.93–2.00 μm) will measure accurate galaxy shapes for weak lensing using the high resolution and extraordinary optical stability available in space. The HLS spectroscopic survey will measure galaxy redshifts using emission lines at high redshift where they have been redshifted to > 1 μm, where highly multiplexed spectroscopy is difficult from the ground. Both programs take advantage of WFIRST's wide field of view and the low NIR sky background available in space. We expect the imaging to reach a depth of $J_{\rm AB} = 26.8$ (Fig. 2 left) and the spectroscopy to reach 7×10^{-17} erg cm^{-2} s^{-1} (both 5σ, point source, and at the optimal wavelength for spectroscopy). WFIRST is not optimized for maximum raw sensitivity but rather for control of systematic uncertainties and for having multiple techniques each with multiple internal cross-checks. The HLS design will be updated before launch to be most relevant in the science landscape of the 2020s. Survey configurations differing greatly from the current reference survey will be on the table.

We focus here on the cosmological science enabled by WFIRST large-scale imaging and spectroscopic surveys (though a broad range of other astrophysical investigations will use the same data). The SN Ia program requires many revisits over a smaller area, and is a separate survey. The combination of data from WFIRST HLS and LSST goes well beyond the science enabled by any of the data sets alone: *the whole is greater than the sum of the parts* [7]. Considered jointly, the range in wavelength, angular resolution, and redshift covered by these two surveys is remarkable and unprecedented.

Photometric redshifts. Photo-zs play a central role in weak lensing cosmology. Since the WFIRST HLS will rely on only 4 bands covering 0.93–2.00 μm, it does not cover the Balmer/4000Å break at the low redshifts. Optical data (through z band) are needed for full redshift coverage. By far the most promising source for this optical data is the LSST WFD survey (DECam and Subaru/HSC would be the logical backup options, but neither realistically approaches the $A\Omega t$ available for LSST WFD) [5]. Fig. 1 visualizes 2D projections of the multi-dimensional color-space of WFIRST alone as well as the combination of LSST and WFIRST with Self Organizing Maps (SOMs). The color-redshift relation can only be learned and used when deep optical and NIR data are combined [11]. Data-driven simulations of redshift performance showed improved scatter and outlier rates when LSST and NIR data are combined [12]. Besides, high resolution space-based photometry is also crucial to reduce catastrophic redshift failures due to blending in ground-based data.

Cross-correlations. The WFIRST spectroscopic survey provides an opportunity to calibrate photo-zs using the clustering-based method, especially at $z \geq 1.5$ where the ground-based ELG samples tail off. Since the cleanliness of the sample is important, we focus on the sample where WFIRST detects the weaker member of [O III] 4959+5007Å at $> 3\sigma$, which contains 379 gal/deg^2 over $1.02 < z < 2.85$. Due to its high density (2.55× the DESI quasars [3] at $z > 1.5$), this will be the main cross-correlation sample for WFIRST photo-zs, with a statistical error on an overall shift of $\sigma_{\Delta z}/(1+z) = 0.0008, 0.0009, 0.0016$ in $\Delta z = 0.05$ bins at $z = 1.5, 2.0, 2.5$. This will also serve as a cross-check on the LSST redshift distribution.

Deblending. Source blending is an important challenge for weak lensing – most objects observed at full 10 year LSST depth will be blended at some level with other sources (58% of the galaxies in the shallower HSC Wide survey are blended [1]) – but proper mitigation remains one of the less well understood issues. High-resolution imaging from WFIRST opens up new strategies to deal with blending, including identifying potential blended sources and forced/joint deblending for improvement of photo-zs and shapes for LSST. This will also help the portion of the LSST footprint that does not overlap with WFIRST, through quantification of the systematic biases resulting from blending uncertainties. While our emphasis is on cosmology, blending will affect centroids, morphologies, photo-zs, and even raw source counts of galaxies, so this joint analysis program will positively impact the majority of the major science products from LSST.

Shape measurement validation. Parallel WFIRST observations will help LSST science through calibration of the weak lensing shear estimates, in particular PSF correction. WFIRST will have a much smaller PSF than ground-based observations (an order of magnitude smaller as measured by the area or 2nd moment), and moreover will have exquisite knowledge of the PSF thanks to the nm-level wavefront stability available in space and the extensive calibration program planned for detector effects (e.g., cross-talk, reciprocity failure). Comparison of mean ensemble shears for the same set of galaxies by LSST and WFIRST can provide an estimate of the overall shear calibration error due to imperfect PSF corrections. Therefore, LSST weak lensing science will benefit from having a significant overlap with the WFIRST HLS to enable this calibration.

The WFIRST shape measurements will be carried out mainly in the NIR bands. WFIRST will fly two optical filters ("wide R" and "wide Z"), and a key question for WFIRST planning is how useful heavily dithered observations of the deep fields in these bands – which more closely resemble LSST shape-measurement bands – would be for LSST. This is not part of the baseline survey, but coverage could be done in these two filters to LSST WFD surface brightness sensitivity at a rate of 1.8 deg^2/day.

Cosmological information in the nonlinear regime. Understanding astrophysical systematics, such as baryonic physics, galaxy intrinsic alignment, galaxy bias, and the cluster mass observable relation is critical to fully extract the cosmological information of future surveys. Overlapping multi-wavelength observations, especially from LSST and WFIRST deep imaging and spectroscopic NIR data, are the most promising avenue to improve our understanding and modeling of astrophysical systematics, especially on small nonlinear scales. In Figure 2, the right panel illustrates for LSST that these uncertainties are strongly constrained and can thus be self-calibrated through galaxy-galaxy lensing in a multi-probe analysis, if the photo-z accuracy is sufficiently high. Combining the high galaxy number density of the WFIRST weak lensing sample, and the enhanced photo-z quality from the joint LSST+WFIRST optical-NIR coverage will allow for tight constraints on the connection between galaxies and dark matter halos on small scales using galaxy-galaxy lensing (even in the presence of other observational and astrophysical systematics).

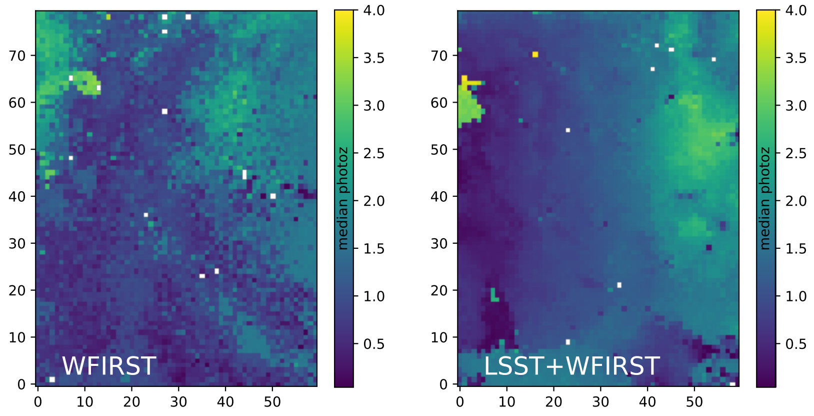

Figure 1: Self Organizing Maps (SOM) trained by simulated WFIRST and LSST+WFIRST colors are shown on left and right panels, respectively. Photometry in LSST and WFIRST filters are simulated based on CANDELS observations. The color coding represents the median of galaxy photo-z in each cell [5]. The smoothness of the right panel compared to left demonstrates the need for including optical colors in learning the color-redshift relation.

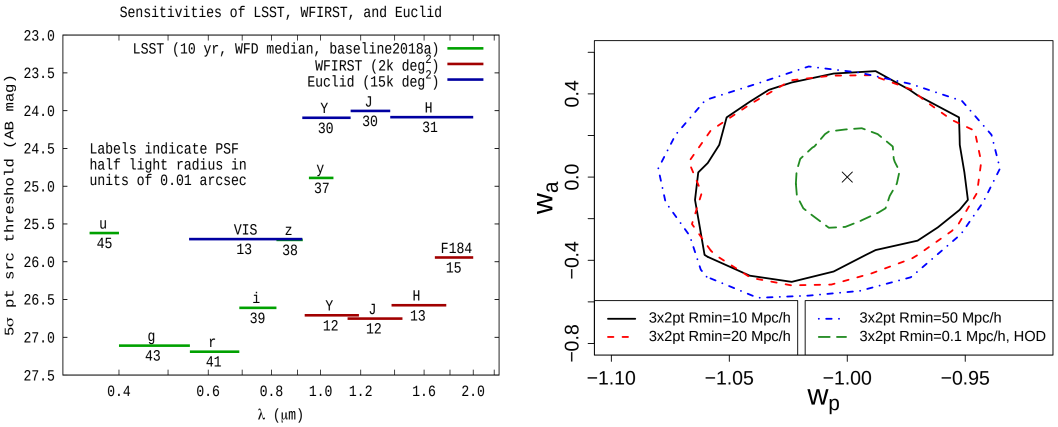

Figure 2: *Left:* Currently predicted WFIRST HLS (update from Ref. [13]), LSST [8], and Euclid [10] depth. *Right:* Gain in information on dark energy parameters w_a and w_p for the LSST 3x2pt analysis (cosmic shear, galaxy clustering, galaxy-galaxy lensing) when varying the minimum scales included in galaxy clustering and galaxy-galaxy lensing measurements. The most constraining analysis (green/dashed contours) will be difficult to achieve for LSST alone; overlapping WFIRST information will be highly beneficial on these nonlinear scales. Figure taken from [9] .

3 Technical Description

3.1 High-level description

The key requirement is for the LSST WFD to overlap with the WFIRST HLS and observe in at least *ugriz*. The needs from the WFIRST side are met by what the LSST WFD survey is currently planning to do (or by reasonable alternatives, such as the footprint that is proposed in the DESC Wide-Fast-Deep White Paper). We provide further details below.

3.2 Footprint – pointings, regions and/or constraints

The key requirement is for the LSST WFD footprint to be a superset of the WFIRST HLS footprint. This is enabled by the LSST baseline WFD survey, the modified footprint proposed in the DESC WFD White Paper, and most reasonable alternatives; we are documenting it here primarily so that this requirement is clearly understood in case of further changes.

The WFIRST HLS footprint is not finalized – indeed, *no* final decisions have been made yet on WFIRST observing programs or time allocation – but the key parameters of the baseline survey are that it should (1) have ≥ 2000 deg^2; (2) have a low dust column; and there are competing preferences for (3) avoiding the Ecliptic Plane (highest zodiacal background) and (4) having some of the footprint accessible from Northern Hemisphere facilities (especially Subaru at latitude 20°N). The current footprint has $> 90\%$ of the area at $E(B-V) < 0.035$ (we cannot ask for 100% since we always get a few dust filaments). The current arrangement balances competing demands (3) and (4) by stretching the HLS out in the latitude direction. The Southern end reaches Ecliptic latitude $\beta = -78^\circ$, while the Northern end reaches $\beta = -19^\circ$ (one tip reaches $\beta = -16^\circ$ to encompass the XMM-LSS field, which is also an LSST Deep Drilling Field). This achieves placement of 499 deg^2 of the HLS at declination $\delta > -20^\circ$, 778 deg^2 is at $\delta > -25^\circ$, and 1044 deg^2 is at $\delta > -30^\circ$. The entire declination range is at $-60.4^\circ < \delta < -3.0^\circ$. This may evolve in the future, partially in response to the final choice of LSST WFD footprint. The current WFIRST HLS footprint is shown in Fig. 3.

Significant changes of the WFIRST footprint relative to the baseline are possible between now and launch, if developments in the science landscape warrant this. We anticipate the WFIRST project will formalize the process to select the HLS design in the coming years. If the changes are "perturbative" (e.g., modest increase in the area), then there is room for the HLS footprint to grow westward, even with the baseline WFD survey ($-62^\circ < \delta < +2^\circ$) and allowing for avoidance of the Galactic Plane. More radical ideas for WFIRST have been suggested, like doing a wide/fast tier to get high-resolution NIR imaging in one band (either by reducing some of the other surveys, or in an extended mission) – however if this emerges as the best option for WFIRST, it could be optimized within any reasonable candidate for the LSST WFD footprint.

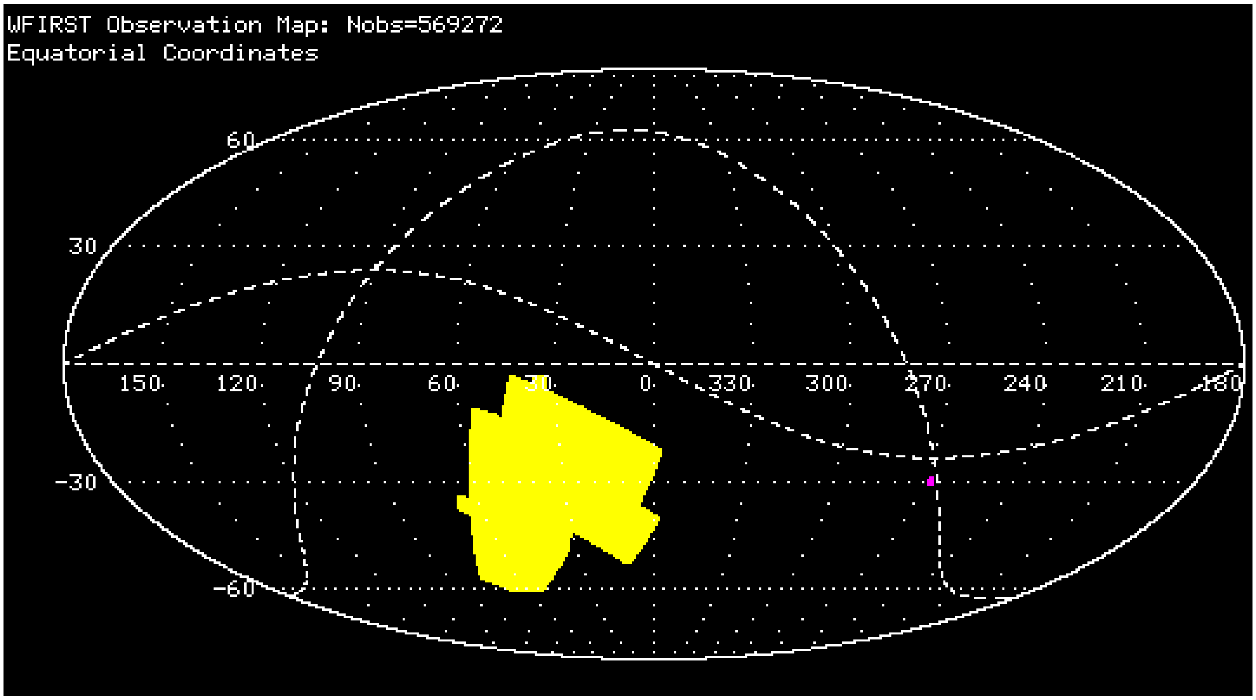

Figure 3: The footprint of the notional HLS (yellow) in Equatorial coordinates. For illustration purposes, the microlensing fields are shown in magenta.

3.3 Image quality

The main driver for LSST image quality is that blending in the lower-resolution optical photometry represents a potential systematic error for the photo-*z*s. Image quality in the *ugriz* bands is a driver (though not *y* since we will use deeper, higher-resolution WFIRST *Y*-band imaging). Our understanding of the blending problem is not yet sufficient to prioritize image quality in different filters (e.g., favoring *ri* in good seeing at the expense of *ugzy*, versus no such weighting).

3.4 Individual image depth and/or sky brightness

The main cosmology objectives for the wide HLS are static sky science, so *individual* image depth is not a driver.

3.5 Co-added image depth and/or total number of visits

Co-added image depth in *ugriz* is a key parameter for LSST+WFIRST photo-*z* performance. (WFIRST *Y* will be deeper than LSST *y* in the region with WFIRST coverage.)

We assumed idealized 10 years median depths [6] for the LSST simulation shown in Fig. 1 (i.e. 26.1, 27.4, 27.5, 26.8, 26.1 AB mag for *ugriz* 5σ). Simulations of redshift performance show more than 5 and 10 times improvement in scatter and outlier fraction respectively by substituting optical data from DES with that of LSST (i.e. ∼3 magnitudes deeper in i band; Laigle et al., in prep).

3.6 Number of visits within a night

The main cosmology objectives for the wide HLS are static sky science, so number of visits within a night is not a driver.

3.7 Distribution of visits over time

WFIRST is currently targeting a launch in 2025, which means that the 5-year primary mission will be complete in 2030. This means that a cosmology analysis with the WFIRST primary mission data set would likely use data through LSST Year 8. As long as the LSST visits in the WFIRST footprint are uniformly distributed across years (so that Year 8 depth is only ~ 0.12 mag shallower than Year 10 depth), the fine details of the cadence are not a major driver.

3.8 Filter choice

Since WFIRST HLS observations will cover the 0.93–2.00 μm range, the need for overlapping optical observations spans LSST $ugriz$ (but not y). The Wide-Fast-Deep survey should include these filters as a minimum. (We note that WFD coverage in these filters + y is already an LSST requirement, so this is not a *new* driver.)

3.9 Exposure constraints

The main cosmology objectives for the wide HLS are for faint objects, so minimum and maximum exposure times or saturation limits are not a direct major driver for us. (They may enter indirectly if they affect other aspects of LSST data quality or calibration, or overall survey efficiency.)

3.10 Other constraints

No other constraints were identified.

3.11 Estimated time requirement

We anticipate using data from the LSST WFD survey for synergies with the WFIRST HLS. This does not require additional time, rather it is a consideration in trading options for LSST WFD.

Properties	Importance
Image quality	1
Sky brightness	3
Individual image depth	3
Co-added image depth	1
Number of exposures in a visit	3
Number of visits (in a night)	3
Total number of visits	3
Time between visits (in a night)	3
Time between visits (between nights)	3
Long-term gaps between visits	2
Other (please add other constraints as needed)	N/A

Table 1: **Constraint Rankings:** Summary of the relative importance of various survey strategy constraints, where 1=very important, 2=somewhat important, 3=not important.

3.12 Technical trades

We see no further trade-offs to consider.

4 Performance Evaluation

The key issues for evaluation of the data quality will be depth, image quality, and dust extinction; and we also care about overlap with the WFIRST HLS.

The primary metrics that go into photo-z performance (i.e., that are required as inputs to photo-z simulations) are:

1: Median co-added depth in LSST WFD u, g, r, i, and z (5σ point source).

2: Median effective seeing in LSST WFD u, g, r, i, and z. (The seeing is needed to evaluate the loss of S/N for an extended source. It will also feed into de-blending studies.)

We have developed two primary metrics for the footprint, one focused on being able to implement the baseline HLS in a contiguous region; and one for a potential WFIRST wide/fast extragalactic survey.

3: The area in the WFD survey at $E(B-V) < 0.05$, in the Southern galactic cap ($b < 0°$), and Ecliptic latitude $\beta < -15°$. [This has a maximum possible value of 5390 deg^2. Ideal would be > 4000 deg^2, as this would allow not just the currently planned WFIRST HLS but a continuation in an extended mission. There would be a "pain threshold" if this were to fall below 2500 deg^2, but we do not consider this likely.]

4: The area in the WFD survey at $E(B-V) < 0.2$ and away from the Ecliptic plane, i.e., at Ecliptic latitude $|\beta| > 15°$. [This has a maximum of 15940 $\deg^2$ if a Northern limit $\delta < 30°$ is imposed. Since a wide layer of the WFIRST survey is only being discussed at this time, and it is not part of the present baseline or requirements, we are not specifying a threshold.]

5 Special Data Processing

As demonstrated above, joint analysis of LSST and WFIRST data will provide significant benefits [7]. These will be made possible by linking the data from the different surveys and providing a common access point for interrogating the data in a user-friendly way with the appropriate tools. For much of the science, we will need to combine the photometry across multiple wavelengths with varying spectral and spatial resolution – a technical challenge. The joint analysis can be carried out in ways that have different computational demands. The most technically demanding joint analysis is to work with pixel level data of the entire area of overlap between the surveys. Many of the goals of a joint analysis require such a pixel-level analysis. If pixel-level joint analysis is not feasible, catalog-level analysis can still be beneficial, say to obtain calibrations of the lensing shear or the redshift distribution of galaxies. Hybrid efforts are also potentially useful, for example using catalog level information from space for deblending LSST galaxies, or using only a mutually agreed subset of the data for calibration purposes. However the full benefits of jointly analyzing any two of the surveys can be reaped only through pixel-level analysis. Joint cosmological and instrument and pipeline simulations will also be needed to fully analyze these data and such efforts are already on-going within the DESC's DC2 effort. The TAG (Tri-Agency Group: DOE/NASA/NSF) commissioned an on-going report on how joint pixel-level data processing could be done in the US and what work is needed to make that happen.

6 Acknowledgements

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