Astro2020 Science White Paper

Partnering space and ground observatories - Synergies in cosmology from LSST and WFIRST

Thematic areas: 7. Cosmology and Fundamental Physics

Principal Author: Tim Eifler (University of Arizona)
email: timeifler@email.arizona.edu, phone: (520) 621-5448

Co-authors/Endorsers: M. Simet (UC Riverside), C. Hirata (OSU), C. Heinrich (JPL/Caltech), S. Hemmati (IPAC/Caltech), R. Mandelbaum (CMU), M. Jarvis (UPenn), E. Krause (U. of Arizona), O. Doré (JPL/Caltech), H. Miyatake (U. of Nagoya), B. Jain (UPenn), D. Spergel (Princeton), V. Miranda (U. of Arizona), X. Fang (U. of Arizona), A. von der Linden (Stony Brook), M. Takada (Kavli IPMU), N. Yoshida (U. of Tokyo/Kavli IPMU), M. Shirasaki (NAOJ), C. Heymans (U. of Edinburgh), R. Schuhmann (U. of Edinburgh), A. Pisani (Princeton), J. Zuntz (U. of Edinburgh), P. Melchior (Princeton), A. Choi (OSU), H. Wu (OSU), P. Capak (Caltech), D. Weinberg (OSU), Y. Wang (Caltech), N. MacCrann (OSU), E. Huff (JPL/Caltech), M. Troxel (Duke), J. Kruk (GSFC)
Endorsing Collaborations:
1) LSST Dark Energy Science Collaboration[1]
2) WFIRST Science Investigation Team on Cosmology with the High Latitude Survey

Abstract: We recommend the exploration of joint survey strategies that combine the two top-ranked survey endeavors of the 2010 Decadal Survey, the ground-based Large Synoptic Survey Telescope (LSST) and the space-based Wide Field Infrared Survey Telescope (WFIRST). By the time WFIRST launches, LSST will have been in survey mode for several years already and will have built up substantial survey depth and area. The science collaborations of LSST will know what limits the precision of their core science cases and what type of space observations are most valuable to overcome key systematic uncertainties. WFIRST, with its broad range of capabilities, will be an ideal partner observatory to LSST at exactly the right time.

In this white paper we outline two concepts for joint survey scenarios: The first is a 5-month, wide WFIRST survey in one band that would cover the full LSST survey area. This 5-month endeavor would provide high-resolution imaging for >95% of the LSST Year 10 weak lensing galaxy sample. The second scenario is a 1.5-year wide WFIRST survey in one band that would cover the full LSST survey area. For this second scenario we explore the joint LSST+WFIRST science return on cosmic acceleration from a joint weak lensing and galaxy clustering analysis.

The combination of space-based resolution, color information from the ground, and infrared coverage from space over 18,000 deg^2 would enable a new level of precision for the existing core science cases of both experiments. It is now timely for WFIRST and LSST to set up a joint survey optimization and systematics mitigation effort that maximizes the science return for the community from the next decade's flagship experiments in survey cosmology.

[1] LSST DESC is co-signing this white paper to endorse its content, having reviewed it following its internal management process for paper endorsement.

WFIRST Imaging Capabilities			
Telescope Aperture (2.4 meter)	Field of View (45′x23′; 0.28 sq deg)	Pixel Scale (0.11 arcsec)	Wavelength Range (0.5-2.0 μm)

Filters	R062	Z087	Y106	J129	H158	F184	W146
Wavelength (μm)	0.48-0.76	0.76-0.98	0.93-1.19	1.13-1.45	1.38-1.77	1.68-2.00	0.93-2.00
Sensitivity (5σ AB mag in 1 hr)	28.50	28.02	27.95	27.87	27.81	27.32	28.33

WFIRST Spectroscopic Capabilities				
	Field of View (sq deg)	Wavelength (μm)	Resolution	Sensitivity (10σ AB mag in 1000s)
Grism	0.28 sq deg	1.00-1.89	435-865	20.4 at 1.5 μm

Figure 1: Instrument capabilities of WFIRST. From `https://wfirst.gsfc.nasa.gov/science/WFIRSTScienceSheetFINAL.pdf`

Introduction

The Large Synoptic Survey Telescope (LSST) (LSST Science Collaboration et al., 2009), scheduled to be fully operational in the early 2020s, constitutes the ultimate imaging survey from the ground, covering 18,000 deg^2 every 3 nights in 6 visible bands and providing the community with ~20TB of imaging data nightly. Its science cases range from solar system studies to transients to Milky Way studies to galaxy evolution to dark matter and dark energy. LSST is of course limited by the atmosphere in terms of seeing and wavelength coverage. For dark energy and other science cases the issue of blended galaxies (Dawson et al., 2016) is a potential limiting systematic uncertainty for galaxy shape and photo-z measurements.

The Wide Field Infrared Survey Telescope (WFIRST), scheduled to start mid 2020s, is an extremely versatile space-based observatory, covering science cases from exoplanets to galaxy evolution to fundamental physics (Akeson et al., 2019). WFIRST's High Latitude Survey (HLS) is designed to constrain dark energy evolution and deviations from GR with exquisite control of systematics. The envisioned survey area of 2000 deg^2, which WFIRST covers in 1.6 years, translates into less statistical constraining power compared to LSST's 18,000 deg^2; it is however important to note that systematics control will be critical for cosmological constraints from large-scale structure surveys in the coming decade. The WFIRST HLS survey ensures excellent systematics control via space-quality imaging, photometry across 4 bands in the NIR, a 0.28 deg^2 field of view with a 0.11 arcsec pixel scale, and a ~600 resolution grism enabling deep spectroscopic galaxy redshift measurements over the same survey area as the imaging survey.

WFIRST and LSST were the top-ranked science endeavors in the 2010 decadal survey and they both pose extremely interesting standalone experiments. This white paper however focuses on synergies of both LSST and WFIRST for the science case of cosmology. Rather than considering WFIRST's HLS in its current form [2], we consider instead the versatile capabilities of the WFIRST observatory (cf. Fig. 1), and outline alternative scenarios (to be explored beyond the

[2] see white paper "WFIRST: The Essential Cosmology Space Observatory for the Coming Decade" for details

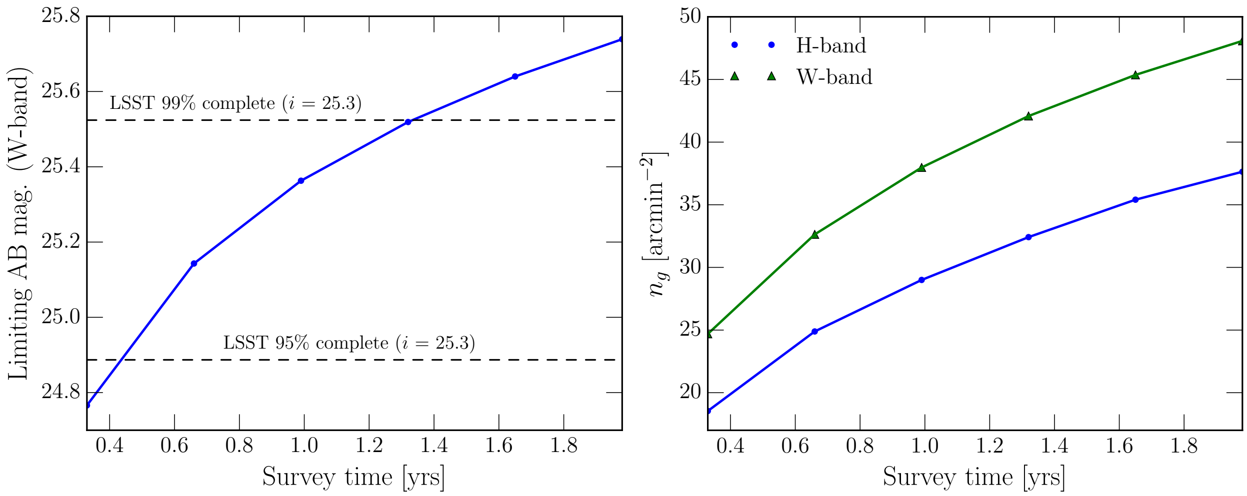

Figure 2: *Left:* Limiting magnitude of a 18,000 deg^2 WFIRST W-band survey as a function of survey time. We also show the LSST weak lensing samples 95% and 99% completeness thresholds as dashed lines. *Right:* The number density of a weak lensing galaxy sample for a 18,000 deg^2 WFIRST survey when conducted in W or H-band, respectively, again as a function of survey time.

already-planned surveys) that make the best use of WFIRST capabilities in partnership with LSST.

Simulating WFIRST observations

We use the WFIRST exposure time calculator (ETC) in weak lensing mode (Hirata et al., 2012) to compute the results of Figs. 2 and 3. We fix the time per exposure and vary the number of exposures covering the sky area; total survey time for a given number of exposures includes a simple prescription for overheads and is correct to approximately 10%.

We closely follow Hemmati et al. (2018) in applying the ETC results to the CANDELS data set (Grogin et al., 2011). The ETC has a built-in option to obtain a weak lensing catalogue based on an input catalogue. We apply this feature to generate the WFIRST lensing sample from the CANDELS catalogue and look up the distribution of magnitudes in the LSST bands for the detected WFIRST galaxies. For LSST, our catalog cuts are based on the galaxy magnitudes and uncertainties in the LSST *i*-band, in particular we assume an LSST weak lensing galaxy sample that includes all galaxies with a 20σ point detection. After applying these cuts to the CANDELS galaxies we determine the *H*- and *W*-band magnitude distributions.

For the WFIRST clustering sample we select CANDELS galaxies with S/N>10 and again look at the LSST columns to determine whether a detected galaxy in WFIRST is detected at sufficient S/N in the LSST bands to enable ground-based photo-z.

Combining LSST and WFIRST - Example for a joint weak lensing and galaxy clustering analysis

The ETC calculations of the past section enable us to define galaxy samples for a joint LSST and WFIRST cosmology analysis. We first note that a ~5 month WFIRST W-band survey can obtain high-resolution space imaging for ~95% of the LSST weak lensing sample (see Fig. 2). If blending poses a systematics limitation to LSST weak lensing cosmology, such a dedicated 5 month WFIRST survey would identify almost all LSST blends and enable modeling of shapes and photo-z for said blends.

A 1.3 year WFIRST W-band survey will provide corresponding information for ~99% of the LSST weak lensing sample and of course also substantially increase the depth of the WFIRST imaging, which opens up the idea to use the deeper WFIRST imaging for shape measurements and combine these with the ground based LSST photometry. Figure 2 (right) shows the number density of galaxies suitable for shape measurements from a WFIRST 18,000 deg^2 as a function of survey time and Fig. 3 (left) shows the corresponding fraction of LSST galaxies for which good photo-z information (5σ detection in all LSST bands) can be obtained.

For the simulated likelihood analysis depicted in Fig. 3 (right) we assume a 1.5 year WFIRST wide survey in the W-band and the nominal LSST Y10 survey as detailed in The LSST Dark Energy Science Collaboration et al. (2018). We derive the lensing and clustering galaxy sample for WFIRST based on ETC calculations and cuts in the CANDELS catalog and obtain redshift distributions with 45 galaxies/arcmin^2 for the lensing and 68 galaxies/arcmin^2 for the clustering sample. We require good LSST photometry for our WFIRST galaxy sample, which reduces the number densities to 43 galaxies/arcmin^2 for the joint lensing and 50 galaxies/arcmin^2 for the joint clustering sample. In this scenario the shape information would come from WFIRST and the photometry information would come from WFIRST and LSST.

Based on these galaxy samples we conduct a joint weak lensing, galaxy-galaxy lensing, and galaxy clustering analysis (a so-called 3x2pt analysis). We employ the CosmoLike framework (Krause & Eifler, 2017), which is being used in the WFIRST HLS Science Investigation Team and was used to compute the "static probe" scenarios of LSST (joint weak lensing, galaxy clustering, and galaxy clusters in the DESC Science Requirement Document (The LSST Dark Energy Science Collaboration et al., 2018) and DESC white paper on the wide-fast-deep survey (Lochner et al., 2018).

The contours in Fig. 3 (right) reflect statistical uncertainties only and do not include systematic uncertainties. We assume conservative scale cuts to shield against astrophysical systematics ($l_{\rm max}$ = 3000 for LSST lensing, $l_{\rm max}$ = 4000 for WFIRST lensing, $R_{\rm min}$ = 21 Mpc/h for galaxy-galaxy lensing and for galaxy clustering in both surveys).

We stress that systematics should be included in future studies of such a joint analysis to assess the gain in information, however such studies require a broader consensus in the community of how to parameterize systematics and which uncertainties (parameter values) to assign. It can be assumed that the improvement in constraining power is even more impressive when including systematics, since a joint analysis of LSST and WFIRST will reduce uncertainties in shear and photo-z information and it will enable improved modeling of astrophysical uncertainties (galaxy bias, intrinsic alignment, baryonic physics). Future studies should also include probes beyond the 3x2pt analysis presented here.

Figure 3 (right) shows the substantial increase in statistical precision when combining the LSST data set with a 1.5 year WFIRST wide W-band survey. This improvement stems from a combination of higher number density of galaxies (see Schuhmann et al., 2019, for a detailed study), deeper redshift distribution of source and especially lens galaxies. It would be interesting to explore the information gain for LSST as a function of WFIRST survey time as an extension of this study.

We again emphasize that this white paper does not recommend replacing the current 2000

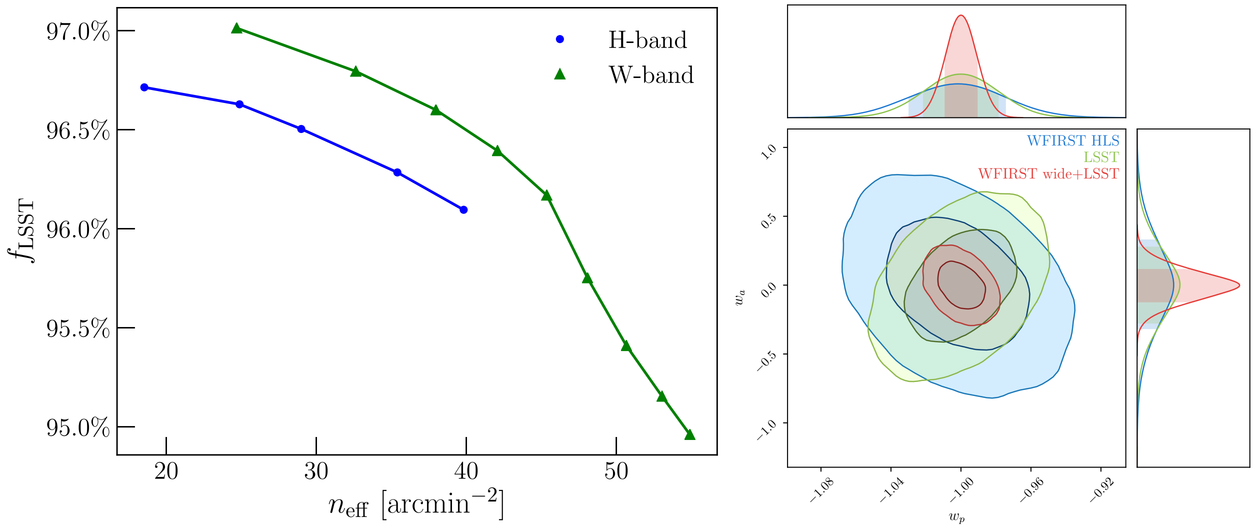

Figure 3: *Left:* Fraction of LSST galaxies with acceptable multi-band photometry as a function of number density of a WFIRST weak lensing sample, based on the CANDELS catalog. *Right:* Potential gain in constraining power on dark energy parameters w_p and w_a, marginalized over 5 other cosmological parameters (no systematics), for a joint data set of LSST multi-band photometry and deep W-band WFIRST imaging over the whole LSST area.

deg^2 HLS survey with a wide W-band survey of WFIRST. The current design of the HLS ensures exquisite systematics control and it is the consensus in the community that systematics control will be more important than maximizing statistical power. We instead recommend the exploration of the WFIRST wide survey strategies in combination with the HLS approach, specifically we envision that a wide WFIRST survey component would use the reference HLS to anchor shear and photo-z calibration.

Summary - The Big Picture:

By the time WFIRST launches, LSST will have been in survey mode for several years already and will have built up substantial survey depth and area. The science collaborations of LSST will know precisely what limits the precision of their core science cases and what type of observations are neccessary/most interesting. WFIRST with its broad range of capabilities will be an ideal partner observatory to LSST at exactly the right time.

For cosmology and dark energy science from LSST it is not unlikely that blending of source galaxies will be a limiting systematic for LSST shape and photo-z measurements. It is also possible that the lack of deep training data (spectra) for photo-z, or the lack of multi-band IR coverage will limit LSST photo-z accuracy. If blending proves to be a limiting issue, the 5-month WFIRST wide survey is an important idea to study further. If the lack of spectroscopic information is limiting, exploring the idea of extended WFIRST grism observations is interesting. If narrow band IR information is useful, a WFIRST wide survey with the H-band is interesting to study.

In terms of how to fit the wide survey into the WFIRST mission, several options arise: one is an extended mission, which is well-matched in terms of timescale to LSST Y10. A second option is to get the wide survey data earlier and to reduce the 2000 deg^2 of HLS in the primary mission. A third option would be to do a subset of the 18,000 deg^2 in the WFIRST primary mission, e.g. one could survey 10,400 deg^2 with E(B-V)<0.08 that pass within 32 degrees of zenith at LSST. This will likely be the best part of the LSST footprint for extragalactic studies, and it can be surveyed in 58% of the time indicated by the x-axes of Fig. 2. In this context we note that the WFIRST observing time, including the survey design of the HLS, has not been allocated to date, and that corresponding decisions will depend on the science landscape in ~5 years.

A WFIRST wide survey in one band as described above opens numerous science applications in cosmology beyond the joint weak lensing and galaxy clustering dark energy science depicted in Fig. 3:

- **Galaxy cluster science:** An 18,000 deg^2 W-band survey would substantially enhance the weak-lensing mass calibration of clusters, a key ingredient for cluster cosmology. Both the increased spatial resolution and the broader wavelength coverage will help to decrease systematic uncertainties due to blending and photo-z misclassification, which are amplified in overdense cluster fields. An important aspect is that the W-band addition would enable precise mass calibration to higher redshift clusters than LSST alone.

- **CMB cross correlations:** The increased number density of galaxies and precision in shape measurements from space-based imaging over the full LSST area would enable a new level of cross-correlation measurements with contemporary CMB experiments (e.g., Simons Observatory, CMB-S4). This would apply to cross-correlations of galaxy clustering and CMB lensing, and galaxy shapes and CMB lensing. Similarly, tSZ observations from CMB surveys will detect a wealth of clusters, all of which benefit strongly from cluster mass calibration through high-precision weak lensing.

- **Trough cosmology:** Cosmic underdensities have emerged as a powerful probe of structure formation and hence dark energy and modified gravity; potentially corresponding observables are easier to model compared to probes that rely on higher-density environments. Trough cosmology, and especially trough lensing, would benefit from the 18,000 deg^2 wide WFIRST survey scenario because of the higher density of source galaxies (for trough lensing) and the higher density of detected galaxies that signify the trough boundaries.

- **Strong Lensing:** LSST will find an enormous number of strong lenses. Color and more importantly shape information from overlapping space observations will allow for substantially improved constraints on cosmology, simply because of the enhanced control of lens profile modeling uncertainties.

Many of the WFIRST science cases will build on the existing LSST data set. Especially for cosmology, where the existing LSST data are highly complementary to the planned WFIRST science, this will be the case. It is however important to note that this partnership is mutually beneficial and that exploring optimal joint science strategies for WFIRST and LSST deserves serious consideration, calculations, and meaningful metrics. We recommend the exploration of WFIRST survey strategies as a function of potential results and possible limitations from LSST data (taking into account DESI, PFS, SPHEREx, Euclid) and development of optimal joint systematics mitigation concepts that allow WFIRST and LSST to create the legacy data set that will shape cosmology well into the 2030s.

References

Akeson R., et al., 2019, arXiv:1902.05569,

Dawson W. A., Schneider M. D., Tyson J. A., Jee M. J., 2016, ApJ, 816, 11

Grogin N. A., et al., 2011, The Astrophysical Journal Supplement Series, 197, 35

Hemmati S., et al., 2018, arXiv:1808.10458,

Hirata C. M., Gehrels N., Kneib J.-P., Kruk J., Rhodes J., Wang Y., Zoubian J., 2012, arXiv:1204.5151,

Krause E., Eifler T., 2017, MNRAS, 470, 2100

LSST Science Collaboration et al., 2009, arXiv e-prints, p. arXiv:0912.0201

Lochner M., et al., 2018, arXiv:1812.00515,

Schuhmann R. L., Heymans C., Zuntz J., 2019, arXiv:1901.08586,

The LSST Dark Energy Science Collaboration et al., 2018, arXiv:1809.01669,