Roman Core Community Survey White Papers

Optimizing the Roman HLWAS

Roman Core Community Survey: High Latitude Wide Area Survey (Imaging)

Scientific Categories: Large scale structure of the universe

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Abstract:

We outline possible survey strategies for the imaging component of the Nancy Grace Roman Space Telescope (Roman) High Latitude Wide Area Survey (HLWAS) that consider synergies with ground-based experiments, most prominently Rubin Observatory's Legacy Survey of Space and Time (LSST).

The *reference design* for the Roman HLWAS ensures excellent systematics control by covering 2000 deg^2 in 4 bands (and the grism). Alternatively, Roman could cover the LSST area of 18,000 deg^2 in the W-band (i.e. the F146 filter spanning 0.93-2.00μm). While the latter strategy significantly boosts the statistical constraining power of Roman, it is also more susceptible to systematic effects, e.g., shear calibration and photo-z estimation.

The most promising way to increase statistical constraining power while retaining systematics control is a two-tier HLWAS: to split the time between a "medium" tier, which resembles the reference survey but with a reduced area, and a "wide" tier in a single filter. We outline several options for the wide tier option that cover the trade space of systematics control vs statistical information content.

1 Introduction

Recent decades have seen great advances in cosmic surveys, motivated in large part by the remarkable discovery that the expansion of the Universe is accelerating [1, 2]. Today, the combination of the cosmic microwave background (CMB) and low-redshift measurements from supernovae and photometric and spectroscopic galaxy surveys has tightly constrained the parameters of the base cosmological constant + cold dark matter (ΛCDM) model as well as some possible extensions. However, there are also some tensions in the present data if interpreted within the ΛCDM model, including the discrepancy between early-Universe and local measurements of the Hubble constant H_0 [e.g. 3, 4], and the tension between the amplitude of perturbations measured at low redshift (usually parameterized by S_8) [e.g. 5–9] and the prediction from evolving the amplitude measured in the CMB forward in time. It is not currently known whether these tensions are due to observational systematics, missing ingredients in astrophysical modeling, the first sign of new fundamental physics beyond the ΛCDM model, or some combination of these possibilities. A key goal of the next generation of cosmic surveys is to investigate these possibilities.

Shedding light on the S_8 tension requires a new generation of weak lensing surveys, with a major leap in statistical constraining power, improvements in control of observational systematic errors, and a broader range of astrophysical information relating to large scale structure. This is best done with a combination of space- and ground-based facilities. The Nancy Grace Roman Space Telescope [10], with its high angular resolution and stable point spread function (PSF), and ability to carry out redundant survey strategies with rolls and multiple passes, will provide exquisite-quality shape measurements. Furthermore, its near infrared coverage will improve photometric redshifts at $z \gtrsim 1.2$, where the Balmer and 4000Å features redshift into the infrared. However, multi-band highly dithered surveys at space resolution are time-consuming and there are many other programs within Roman's 5-year primary mission, so Roman's Reference survey covers only 2000 deg^2. The Vera Rubin Observatory will be a dedicated optical survey telescope, with the largest CCD mosaic focal plane ever built for astronomy [11]. Although its angular resolution is limited by the Earth's atmosphere, its enormous étendue and low overheads mean that it can carry out a highly redundant survey in 6 bands of essentially the entire sky available from its observing site. The filter sets of the two observatories together span roughly a factor of 7 in wavelength, bracketing the Balmer and 4000Å features, the Lyman break, or both across the whole range of redshifts used for galaxy surveys (see Fig. 1).[1] Both Roman and Rubin photo-zs will benefit from calibration with the new highly multiplexed spectroscopic facilities such as DESI [12] and Subaru/PFS [13].

The CCS definition process is the right opportunity at the right time to reconsider the synergies between Roman and Rubin. In the decade since the $\sim$ 2000 deg^2 Reference survey concept was first proposed [14], there have been great advances in all aspects of weak lensing methodology, including shape measurements, photometric redshifts, and cosmological infrerence. The Vera Rubin Observatory's Legacy Survey of Space and Time (LSST) is scheduled to begin operations in 2024. Roman's design has been finalized and much of the hardware has been built and integrated. And we now have advanced, compatible simulation tools for both observatories [15–17].

This white paper describes a space of alternative designs for the imaging component of the Roman High Latitude Wide Area Survey (HLWAS) that aim to optimize the synergies with Rubin by going wider. Even a single band of Roman data would be of benefit for providing space-based shape measurement, high-resolution data to inform blending, and observer-frame NIR photometry and morphology. Moreover, recent studies have shown that there is a potential improvement in dark energy constraining power from going wider [18]. The systematic error budgeting for the different possible designs is a work in progress: thus we present the range of options that we are studying (ranging from the most conservative Option 1 to the most aggressive Option 3)

[1] These curves are available on the Project website for Roman and the GitHub site (https://github.com/lsst/throughputs/tree/main/baseline) for Rubin.

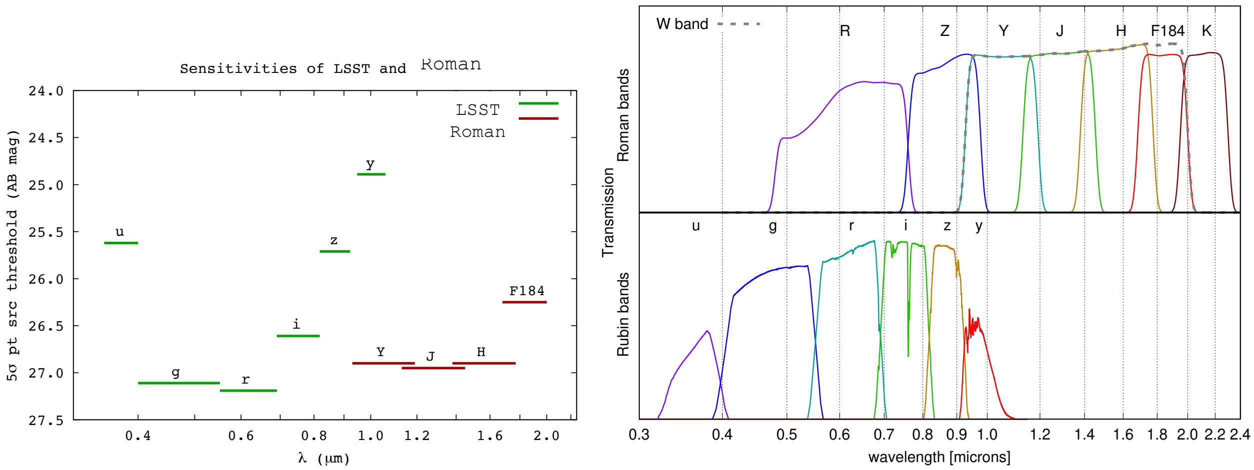

Figure 1: *Left:* Wavelength coverage and sensitivity of the 4 Roman NIR bands that are part of the reference survey and the 6 LSST optical bands. *Right:* Wavelength coverage of the imaging bands on Roman (top part of plot) and Rubin (bottom part of plot). The wide survey concept described in Eifler et al. [18] assumes the W-band (aka the F146 filter spanning 0.93-2.00μm, shown as a dashed line in the upper right) in addition to the 6 LSST bands.

rather than advocating a single design.

2 Motivation: The potential information in a wide survey

In Eifler et al. [18], we explore two different scenarios for the HLWAS imaging survey that bracket the design space considered in this white paper.

The first scenario is the well-known *HLS reference survey*, which ensures excellent systematics control via space-quality imaging and photometry across 4 bands in the NIR. This Roman coverage is complemented by 6 bands in the optical from Rubin Observatory's Legacy Survey of Space and Time (LSST) at similar depth (see Fig. 1, left panel). This reference survey would cover 2000 deg^2 and take $\approx$1 year for the imaging component.

The second scenario, estimated to take $\sim$1.5 years, is based on the idea to cover the entire LSST area (assumed to be 18,000 deg^2) with the W-band only (see F146 band right panel of Fig. 1). This *HLS wide survey* concept boosts the statistical constraining power significantly, but it degrades systematics control compared to the reference design. Of particular concern are photo-z uncertainties, due to the limited information on the spectral energy distributions (SEDs) at $> 1\,\mu$m, and shape measurement uncertainties, due to the reduced dithering and the wavelength dependence of the PSF.

Cosmological forecasts: Figure 2 shows the constraining power on dark energy equation of state parameters for a joint analysis of weak lensing and galaxy clustering (so-called 3x2pt) measured for 3 different datasets: the LSST Y10 dataset, the *HLS reference design*, and the *HLS wide design*.

Our forecasting machinery that predicts area coverage, depth, redshift distribution of source and lens galaxies as well as priors on systematics is based on the Roman exposure time calculator [19], the CANDELS catalog as processed in [20], and the CosmoLike code [21] informed by the LSST-Dark Energy Science Collaboration Requirement document [22]. We refer the reader to Ref. [18] for details; the parameters derived from this machinery that enter the likelihood analysis in Fig. 2 are detailed in Table 1. Altogether our likelihood analyses span 56 dimensions, 7 of which relate to cosmological parameters and the remaining 49 describe uncertainties in modeling observational (shear calibration, lens and source photo-z uncertainties) and astrophysical systematics (galaxy bias, intrinsic alignment, baryonic physics). We assume more degraded shear calibration performance

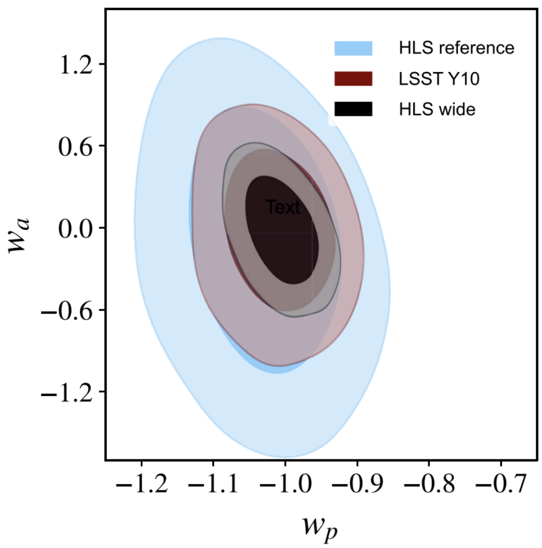

Figure 2: Constraining power on dark energy parameters w_p (where p is a pivot redshift, chosen such that the two parameters are somewhat decorrelated) and w_a, marginalized over 5 other cosmological parameters and 49 nuisance parameters describing observational and astrophysical systematics. We show results for the 18,000 deg^2 LSST Year 10 data set in *red*, for the 2000 deg^2 HLS reference survey in *blue*, and for the HLS wide survey (*black*). Both HLS scenarios assume LSST multi-band photometry over the corresponding area. We show the 68% and 95% contours.

Table 1: Parameters that enter the simulated likelihood analyses of Fig. 2 and corresponding DETF-FoM results. HLS reference and HLS wide assume coverage with LSST bands. Different priors for systematics are assumed for the different analyses in order to mimic the change in systematic effects.

Case	Bands	Area [deg^2]	$\mathrm{n_{source}}$ [1/arcm^2]	$\mathrm{n_{lens}}$ [1/arcm^2]	DETF FoM
LSST Y10	ugrizy	18,000	27	48	-
HLS reference	ugrizy YJH F184	2,000	51	66	0.44 $\mathrm{FoM_{LSST}}$
HLS wide	ugrizy W	18,000	43	50	2.4 $\mathrm{FoM_{LSST}}$

for the LSST Y10 analysis (ground -based shapes) compared to the HLS scenarios, and we assume degraded photo-z precision for the HLS wide compared to the HLS reference survey. We note however that a more detailed analysis on systematic effects is needed, in particular we need to derive these systematic effects directly from Roman+LSST image simulations.

We compare constraining power by computing the Dark Energy Task Force Figure of Merit, $\mathrm{FoM} = |\mathbf{C}^{-1}_{\mathrm{w_0,w_a}}|^{1/2}$. In other words, we obtain the FoM for a given scenario from the MCMC chains by computing the parameter covariance matrix, extracting the w_0, w_a submatrix, inverting it, and computing the square root of its determinant. For further details we refer the reader to Refs. [18, 23].

Survey speed vs. depth: In Eifler et al. [18] we discuss several ideas beyond the 3 specific scenarios for which we ran full likelihood analyses in Fig. 2. In Fig. 3, we consider the survey yields as a function of time for both a W-band survey and a standard-width filter (H-band being the highest-performance choice). The left panel shows the number density of galaxies suitable for shape measurements from a HLS 18,000 deg^2 survey as a function of survey time, the right panel shows the corresponding fraction of galaxies for which good photo-z information from LSST (5σ detection in the LSST bands, except for u-band) can be obtained.

Systematics: The fast W-band survey mode raise several potential systematics concerns for weak lensing shape measurement, in particular sampling (with a survey strategy that has fewer dithers than the Reference strategy) and PSF chromaticity (for the wide 0.93–2.00 μm bandpass). Recent simulations of image combination [24, 25] have shown promising results for sampling-induced systematics in the Roman Reference survey even in bands as blue as Y with typically 5–6 dithers, but recovery of a fully sampled coadded image fails with only 3 dithers, and current shear calibration algorithms [26, 27] suffer biases when run without full sampling [28, 29] (see also Appendix C of Ref. [24]). At present, the most robust approach to shear calibration in a wide survey mode would be to use a subregion observed with a Reference-like strategy as an "anchor."

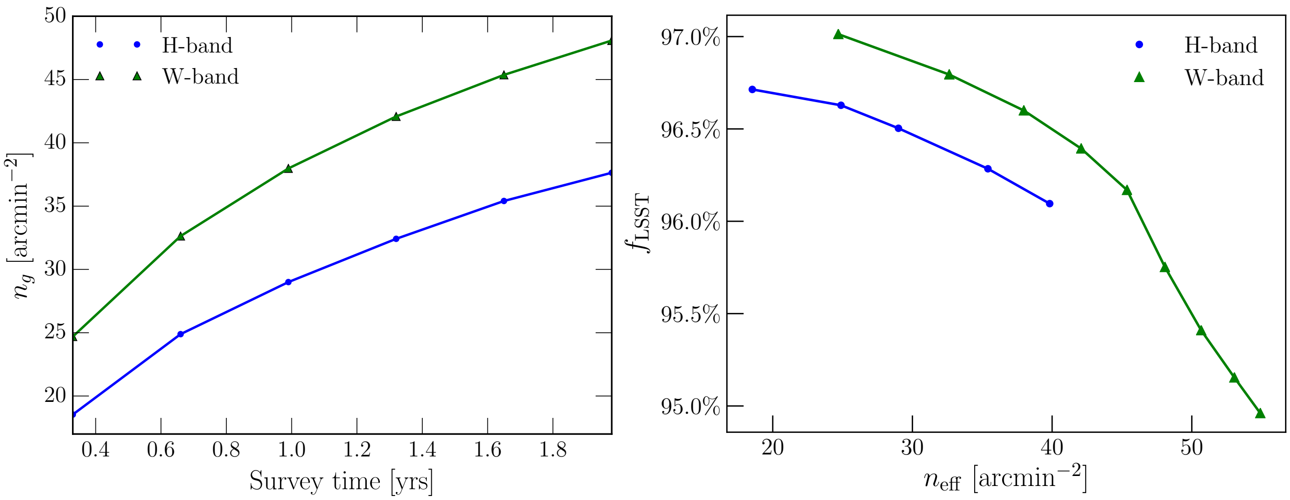

Figure 3: *Left:* The number density of a HLS wide weak lensing galaxy sample for a 18,000 deg^2 survey when conducted in W or H-band, respectively as a function of survey time. *Right:* Fraction of LSST galaxies with acceptable multi-band photometry as a function of number density of a HLS weak lensing sample, based on the CANDELS catalog.

The chromatic astrometric + PSF effects in the wide filter are an additional concern. While always present, they are of special concern for near-diffraction-limited space imagers with wide bandpasses such as Euclid/VIS or Roman W-band. The two largest chromatic effects for Roman are the dependence of diffraction on wavelength (λ/D varies from 0.081–0.174 arcsec in the W band), and the dispersion effect due to the wavelength dependence of the index of refraction of the fused silica filter substrate (a point source is smeared into a radial "rainbow", whose full length varies from 0 at the field center to $\approx$ 1.3 pixels in the field corners).[2] Several methods [30–32] have been proposed to control chromatic PSF uncertainties through a combination of improved galaxy SED templates or PSF measurements based on stars that span the same color range as the galaxies. There are challenges to implementing these for the Roman W-band (e.g., the star SEDs are very different from galaxy SEDs over such a wide band) and so the most promising approach to shear calibration is again to use a Reference survey-like region as an anchor.

Looking at the shape measurement problem from the perspective of LSST, blending represents a critical source of systematic uncertainty [e.g. 33, 34], and one of the least well understood. If this continues to be a challenge in the LSST era, then a wider layer of higher-resolution Roman data, even in one infrared band, would identify many of the blends (see, e.g., §5.4 of Troxel et al. [17], for the statistics in the current Roman+Rubin simulations). Initial results from Ref [18] show that a 5 month W-band survey would be able to provide space-based imaging for 95% of the LSST Y10 weak lensing galaxy sample, which would significantly mitigate LSST blending problems.

In summary, while the HLS wide scenario significantly increases statistical power of the Roman survey, as a stand-alone concept it is not sufficiently robust. Rather we advocate that a wide component should be part of a HLWAS two-tier strategy that combines exquisite systematics control using multi-band coverage over a

[2] While diffraction is common to both the Euclid and Roman missions, there are several technical differences that cause the physics of chromatic effects to be different. Most notably, Roman's bandpass filters are in transmission whereas Euclid/VIS is in reflection. A transmission coefficient through a multilayer filter as a function of frequency has no zeros in the upper half complex plane (Im $\omega > 0$) and so obeys a Bayard-Bode relation: the transmitted phase ripple is related to the transmitted power ripple and thus is constrained by the bandpass filter requirements. The light does pass through the filter substrate and thus suffers differential chromatic refraction, although for a clear substrate this is necessarily a smooth function of frequency. A reflection coefficient from a multilayer filter generically has zeros in the upper half plane and thus there is frequency dependence in the reflection phase that cannot be inferred from the reflection power. But in this case, the reflected light does not need to pass through the substrate.

smaller area with a Roman wide concept. In the next section we consider such two-tier scenarios.

3 Design space for a two-tier HLWAS survey

The Reference design for the Roman HLWAS covers 2000 deg^2 in 4 bands + the grism. Although there is a strong benefit in statistical errors to going wider (the usual $\propto \text{Area}^{-1/2}$ law), attempts to make the Reference design wider run into the basic challenge that with an appropriate dithering pattern to achieve full sampling in 4 bands and with the read noise and slew-settle overheads of an infrared focal plane on a large observatory, faster surveys become inefficient (the sensitivity degrades much faster than the square root of survey speed). Furthermore, although there is strong interest in the recently-added K band for extragalactic survey science cases (see §8 of Stauffer et al. [35] for an overview), adding a 5th band would make the survey speed challenge even more difficult. **The most promising way to break free of this limitation is a two-tier HLWAS: to split the time between a "medium" tier, which resembles the Reference Survey but with a reduced area, and a "wide" tier in a single filter.** The highly redundant medium tier would be used as an "anchor" for calibrating shear and photo-z systematics in the wide tier.

Notionally, one might consider an imaging program for the medium tier with $\sim$ 1000 deg^2 in 4 bands (or $\sim$ 800 deg^2 in 5 bands if K band is added). The spectroscopic element of the HLWAS might choose to go deeper on this footprint or not: discussion of the grism survey trade space is outside the scope of this white paper.

Observing strategies for the wide tier: There is a range of choices for the wide single-filter tier. The possibilities, ranging from most conservative to most ambitious in terms of speed, are:

Option 1: A wide layer done in the H band with the 2-pass Reference survey strategy. The H band would be chosen because it avoids the thermal background of F184, but has better sampling properties than Y and J. This choice is relatively conservative, in that it recovers full sampling using IMCOM [24] and enables übercalibration using the cross-linked survey strategy. It can use the same data processing tools with similar settings as the medium-tier survey, and would serve as 1 of the 4 bands if the decision were made to increase the area of the medium tier in an extended mission. There will be enhanced photo-z scatter due to the 1.06–1.38 μm gap in photometric coverage; the source redshift distributions in the wide layer would have to be calibrated from the medium layer using the mapping from the full color space to the lower-dimensionality $ugrizyH$. The principal disadvantage is that the 1-band survey speed is only $\sim 4\times$ faster than the medium tier 4-band survey speed.

Option 2: A variant is to do the wide layer in the H band with reduced dithers (one full pass, and only a sparse second pass for cross-linking) to save time. The disadvantage is that full sampling is not recovered, so in addition to calibrating the effect on photo-zs of having only some of the bands, we would also have to calibrate the undersampling effects.

Option 3: The fastest weak lensing survey possible with Roman is to use the W filter with shorter exposures. This opens the exciting possibility of observing the full extragalactic LSST footprint. However it also poses the greatest challenge for systematics: in addition to needing to calibrate $ugrizyW$ photo-zs and undersampling effects from the 4-band layer, we would need to calibrate the chromatic astrometric + PSF effects over the 0.93–2.00 μm bandpass.

A comparison of the survey yields for the Reference survey and these three options for the wide tier is shown in Table 2.

Footprints: The sky area available for Roman + Rubin synergistic surveys could in principle be expanded to include almost half the sky. However, although the Universe as a whole is isotropic, observing conditions

Table 2: The forecast survey yields of the Reference survey and the various wide options. Shape measurement cuts are defined with matched filter S/N>18; resolution factor >0.4; and ellipticity measurement error per component $\sigma_e < 0.2$ (in the Bernstein & Jarvis [36] convention). Combinations such as "J+H" denote a synthetic filter made by combining, e.g., the J and H band images. The zodiacal light brightness of $1.5\times$pole is $\sim$70th percentile in the Reference survey; the case of $2.5\times$pole is appropriate for regions near the Ecliptic in the wide survey options. Weak lensing source densities in parentheses correspond to cases where we would have to implement shear measurement without recovering full sampling and calibrate any resulting biases.

Case	band	Zodi brightness [pole=1]	source $n_{\rm eff}$ [arcmin^{-2}]	$z_{\rm med}$	5σ pt src depth [mag AB]
Reference Survey	F184	1.5	25	0.9	26.1
(2000 deg^2/yr)	H	1.5	36	1.0	26.7
	J	1.5	35	1.0	26.8
	Y	1.5	(28)	(0.8)	26.7
	J+H	1.5	46	1.0	27.1
Wide tier, Option 1	H	1.5	36	1.0	26.7
(8000 deg^2/yr)	H	2.5	32	1.0	26.5
Wide tier, Option 2	H	1.5	(29)	(0.9)	26.4
(13000 deg^2/yr)	H	2.5	(26)	(0.9)	26.2
Wide tier, Option 3	W	1.5	(44)	(1.0)	27.1
(13000 deg^2/yr)	W	2.5	(38)	(1.0)	26.9

make some of these regions more valuable than others. The "best" area for the optical data will likely be the regions that pass near zenith at the Rubin site (to minimize atmospheric dispersion and extinction effects) and have low Galactic dust column (to minimize reddening). There are 7010 deg^2 of sky that pass within 30° of zenith at Rubin and have $E(B-V)_{\rm SFD} < 0.05$ mag.[3] This region is split into 5780 deg^2 (South Galactic Cap) + 1230 deg^2 (North Galactic Cap).

We note that of this ideal region 5300 deg^2 are $> 15°$ from the Ecliptic (hence with Euclid coverage). These regions farther from the Ecliptic have lower zodiacal background available from space, but they are also farther south and hence less accessible to Northern Hemisphere facilities. Because read noise is significant in the fastest Roman survey modes, the benefit of choosing high ecliptic latitude fields is not as strong as for Euclid/VIS: for example, in 5×140 s exposures in Roman H-band, we find the weak lensing source density $n_{\rm eff}$ varies from 38 arcmin^{-2} at the Ecliptic poles to 30 arcmin^{-2} in the Ecliptic at quadrature (only a 23% loss).

An example of a footprint for an Option 1 survey (the most conservative of our three options) is shown in Fig. 4. This should be thought of as a proof of concept, and the boundaries could be adjusted somewhat. This example covers 4775 deg^2 in the South Galactic Cap, of which 783 deg^2 is within 15° of the Ecliptic.

4 Summary: the Roman HLWAS imaging program in context

By the time Roman launches (October 2026), several Stage 4 cosmology surveys will be well underway. DESI will have just completed its 5-year survey, potentially DESI II will have commenced, and the Prime Focus Spectrograph survey on Subaru will have started. The Euclid satellite mission (launch 2023) will have covered $\sim$50% of its footprint, Rubin/LSST will have collected 30–40% of its data, and the SPHEREx mission will be close to completing its 2-year mission. Cosmic microwave background observations will also have advanced: the Simons Observatory (SO) will have completed several years of operations and be preparing for a major upgrade, and CMB-S4 (S4) will be under construction.

[3]This area varies continuously with the choice of boundaries, e.g., it is 11050 deg^2 at $E(B-V)_{\rm SFD} < 0.1$ mag.

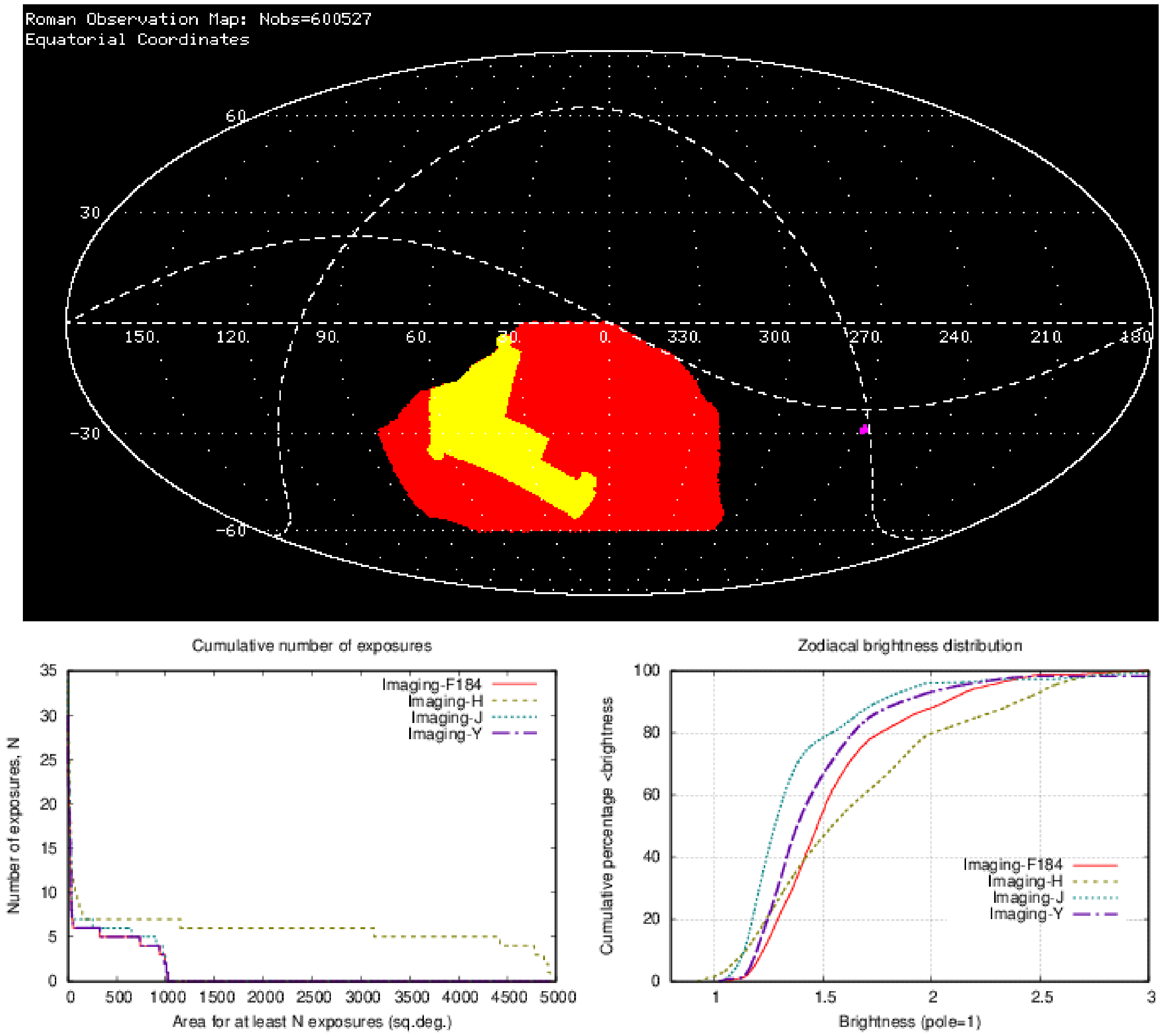

Figure 4: A worked example of an Option 1 survey. This survey requires 1.01 years for HLWAS imaging (including the deep fields). The coverage at ≥ 4 exposures is 4775 deg^2 in H band (mean coverage = 6.0 exposures). *Top panel*: The simulated survey footprint in Equatorial coordinates. The yellow region shows the medium tier (+ deep fields) and the red region shows the wide tier. *Bottom panel*: The cumulative coverage and zodiacal light brightness in each band.

This opens up unique opportunities for Roman to design an HLWAS survey that is not just an exciting dataset in itself but highly synergistic to the contemporary datasets. In this white paper we focused on the Roman HLWAS imaging component and primarily consider synergies with LSST. These two datasets have excellent complementarity in terms of wavelength coverage, they can reach similar depth in their observations, and they can observe the same footprint. The Euclid mission also has excellent synergies with LSST, but it does not reach LSST depth and its overlap with LSST is approximately 8200 deg^2. Also, access to the Euclid dataset/tools will be significantly delayed for the large majority of the US and international astronomy community (those outside of the Euclid collaboration), whereas the Roman dataset will be available immediately. Regions that do have Euclid + Roman wide tier coverage will have two bands of space-resolution morphological information — and at $z \sim 1$, near the median of the weak lensing sample, this includes one (Euclid/VIS) that highlights younger stars and one (Roman H or W) more sensitive to the old component.

In this white paper we have outlined several two-tier survey scenarios for the HLWAS imaging component that have a wide imaging survey component to improve the cosmological constraining power, and a smaller area covered in multi-band photometry to anchor our understanding of the systematics. Option 1 represents a conservative choice, building on the data processing and shape measurement strategies that have been extensively simulated thus far [17, 24, 25]. Options 2 and 3 cover even more area and could potentially cover all of LSST's extragalactic sky to LSST depth. However, they will require additional simulations to develop a complete shear and photo-z systematics budget and to connect this with the forecasting machinery.

Such a Roman wide survey component that overlaps with LSST would not just enhance cosmology science based on weak lensing and photometric galaxy clustering, it would also significantly enhance cross-correlation based science e.g., galaxy-galaxy lensing between SPHEREx/DESI and Roman, and CMB lensing cross-correlation measurements with SO/S4. Beyond correlation function measurements, galaxy cluster cosmology (optical cluster selection and weak lensing based cluster mass estimation) will also benefit from the increased statistics of a Roman wide survey component, as will trough and void cosmology.

For cosmology and many other science cases a fast, perhaps slightly shallower survey early in the mission with the Roman H- or W-band that covers (a large fraction of) the LSST footprint and that is made available to the public immediately would be a unique dataset to explore.

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