Roman CCS White Paper

Cosmology with HLWAS Imaging and Rubin Observatory: Advantages of a Balanced Strategy

Roman Core Community Survey: *High Latitude Wide Area Survey*

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Submitting Author:
Name: Jeffrey A. Newman
Affiliation: U. Pittsburgh
Email: janewman@pitt.edu

List of contributing authors (including affiliation and email):

Brett H. Andrews, U. Pittsburgh, andrewsb@pitt.edu
Humna Awan, UMichigan, hawan@umich.edu
Chihway Chang, U of Chicago/KICP, chihway@kicp.uchicago.edu
Eric Gawiser, Rutgers, gawiser@rutgers.edu
Melissa Graham, U. Washington, mlg3k@uw.edu
Arun Kannawadi, Princeton University, arunkannawadi@astro.princeton.edu
Anja von der Linden, Stony Brook, anja.vonderlinden@stonybrook.edu
Alex I. Malz, Carnegie Mellon U., aimalz@nyu.edu
Jeffrey A. Newman, U. Pittsburgh, janewman@pitt.edu
Andrina Nicola, AIfA Bonn, anicola@uni-bonn.de
Marina Ricci, APC/CNRS, ricci@apc.in2p3.fr
Javier Sanchez, STScI, jsanchez@stsci.edu
Samuel Schmidt, UC Davis, samschmidt@ucdavis.edu
Bryan Scott, Northwestern U., bryan.scott@northwestern.edu
Robert Sorba, Mt. Allison U., rsorba@mta.ca

(for the LSST Dark Energy Science Collaboration)

Abstract: In this white paper, we investigate how overlap of Roman data with LSST can both enhance the science gain from Roman and Rubin/LSST and greatly enhance the legacy value of these facilities. We outline three example scenarios covering the range from deep and relatively small-area imaging and spectroscopy to intermediate-area multiband imaging to single band, shallow and wide imaging. Each of these types of data enhances the cosmological measurements that can be obtained from the combination of Roman and Rubin/LSST in different ways. A balanced strategy combining elements of all three scenarios would optimize the ultimate science output.

Introduction

The combination of imaging data from the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) and the Nancy Grace Roman Space Telescope (Roman) will be extremely powerful for advancing our understanding of cosmology and galaxy evolution. However, the Roman High Latitude Wide Area Survey (HLWAS) will begin at a time when only the earliest years of data from the Vera C. Rubin Observatory will be available. As a result, it will still be difficult to anticipate how far the state of the art in systematics control will advance before the complete (ten-year) LSST dataset is available in 2035.

It will therefore be valuable to adopt a strategy which opens up the possibility of maximal scientific impact for the combined LSST+Roman dataset if we are not systematics-limited, but still delivers a powerful and unprecedented dataset if systematics prevent us from reaching the full potential of this complicated data. This can be achieved by obtaining both deeper, multi-band data over a smaller (but still sizable) area as well as shallower data with a wide-passband filter over as much of the LSST footprint as possible. In the scenario where systematic effects prove problematic and the single-band Roman-led weak lensing analyses become limiting, the wide-passband data would still greatly enhance LSST cosmological measurements by markedly improving deblending and star-galaxy separation, as well as modestly improving photometric redshifts. Conversely, if the single-band Roman-led weak lensing analyses are not systematics-limited, areas with deep multi-band imaging would still provide much more accurate photometric redshifts in the smaller sky area than would be possible from the wide-band data, greatly enhancing the range of studies of both cosmology and astrophysics.

In this white paper, we focus in particular on the impact that datasets of each of these types would have on cosmological measurements that principally rely on data from Rubin LSST, augmented by information from Roman, with a focus on the analyses planned by the LSST Dark Energy Science Collaboration (LSST DESC). We anticipate that other white papers will detail the benefits of such data for Roman-led analyses and other science cases.

Example scenarios

Below we summarize three illustrative examples, S1-S3, that span the range of surveys of interest here. We advocate that Roman consider adopting some element from each of these scenarios, as they each provide unique and significant gain to cosmology with LSST.

[S1] Multi-band Roman imaging and deeper spectroscopy of LSST deep drilling fields (DDFs): LSST will observe six 9.6 square degree fields to 5-10x greater depth than other regions of the sky. These fields will enable the study of transients to fainter magnitudes and with more frequent cadence than in the broader LSST footprint, but the deeper imaging in these fields will also be important for characterizing photometric redshift distributions for Rubin cosmology studies. Roman data in at least four filters (F106, F129, F158, and F184) of comparable depth in these regions would enable better characterization of transient hosts and greatly improved photometric redshifts, enhancing photo-z characterization for both Roman and Rubin. Additionally, Roman grism spectroscopy in these fields would greatly enhance photometric redshift training and calibration at $z>1.5$, a regime which is poorly accessible from the ground; ideally, such spectroscopy would have both increased depth (to improve sensitivity to faint features) and broader wavelength coverage (to maximize the number of objects with secure, multiple-feature redshifts) than any existing data.

[S2] Multi-band Roman coverage of a subset of LSST area: A second scenario we consider is imaging that resembles the Design Reference Mission (DRM) HLWAS, with coverage of ~2000 sq. deg. in four filters (F106, F129, F158, and F184). We also evaluate the impact of more shallow imaging over a wider area by simulating photometric redshift performance if we assume one-fourth the exposure time, degrading the DRM depths by 0.375 mag (which we label as 8000 sq. deg. coverage, though in actuality the area covered would be less than this since overheads increase for wider surveys). We show how these different scenarios affect the photometric redshift quality in Figure 1. Grism spectroscopy over such a region could also enhance the calibration of Rubin-Roman photometric redshifts at z>1.5 via cross-correlation measurements [1].

[S3] Wide-band coverage of the full extragalactic LSST area: The final scenario we consider is imaging over the full LSST extragalactic area (defined as the low-extinction, depth-limited area with coverage in all 6 of LSST filters), comprising ~18,000 square degrees, using the wide F146 ("W") band which covers the wavelength range 0.93–2.00 µm. Because of its wide wavelength coverage, this band can reach a given depth up to 4 times faster than any of the broad bands in its wavelength range, at the cost of diminished spectral information and much greater shape measurement systematics (due to the wavelength dependence of the point spread function, or PSF).

Impacts of these datasets on Rubin Observatory cosmology analyses

[S1] Multi-band Roman imaging and deeper spectroscopy of LSST DDFs: Roman multi-band imaging covering the LSST DDF to a comparable depth to the final 10-year LSST imaging in the same areas would greatly enhance the legacy value of these fields for science spanning a wide range of astrophysical phenomena. For LSST cosmology studies in particular, the greatest value would be for enhancing our understanding of weak lensing systematics and photometric redshifts.

For weak lensing, deeper and higher-resolution images with a broader range of wavelengths would result in higher-accuracy inputs to the image simulations used for shear calibration. High-quality inputs have been shown to be essential for correctly capturing the selection effects and the coupling between shear measurements and photometric redshifts due to blending in the Dark Energy Survey (DES) [2]. In addition, using the deeper data as input to synthetic source injection simulations would improve characterization of magnification biases as shown by DES [3].

For photometric redshifts, both deep imaging data and spectroscopy from Roman in the LSST DDFs will be highly valuable. The deep photometry is essential in the multi-tiered self-organized map (SOM) approach employed by the DES photometric redshift analysis [4]. A SOM is trained on the deep subset with available deep redshift samples, enabling a detailed calibration of the color-redshift relation for each SOM cell. On the other hand, spectroscopy in these regions will be particularly valuable for the training and calibration of photometric redshifts. Such data would provide redshift measurements for objects that are difficult to obtain secure redshift measurements for from the ground, especially at $1.5 < z < 3$ for which few features are in the optical window. To maximize the probability of obtaining the highly secure redshifts needed for photo-z calibration in Stage IV surveys, spectroscopy should be covered over the broadest possible wavelength range with the highest feasible sensitivity [5]. At a minimum, this spectroscopy should be obtained within at least 15 widely-separated Roman pointings distributed sparsely within the DDFs in order to minimize the impact of sample/cosmic variance on redshift distributions [6].

[S2] Multi-band Roman coverage of a subset of LSST area: Having multi-band, high-resolution Roman imaging, accompanied by spectra, that covers a subset of the LSST wide area (~2000 sq. deg.) provides a different way to improve cosmology from LSST compared to the previous scenario in that the much wider coverage allows us to meaningfully characterize effects in the images with less concern about sample variance. The multi-band imaging should play a critical role in characterizing and controlling systematic effects for both Roman and Rubin studies; it is likely that without such data, analyses of the wide-band dataset could never reach their full potential. There are several important aspects to such a dataset.

First, the dataset will be extremely valuable for understanding how well we have corrected for the PSFs in our shear estimations. We can do so by comparing the shear estimates from the same galaxies as imaged by Roman and Rubin. The high resolution of space-based imaging will also enable greatly improved object classification for faint objects, which are important for PSF modeling. The data can be sliced and diced in many ways given the large number of exposures planned for LSST, which will allow us to perform a systematic study of how the PSFs are modeled given different observing conditions, etc. The 2000 sq. deg. area also allows for this study to be statistically meaningful.

Second, this dataset will be extremely useful for studies of blending/deblending and its impact on shear measurement and photometric redshifts [7]. At the same depth, Roman images will be significantly less blended due to the space-based PSF. As a result, it will provide an excellent training set for evaluating the performance of the LSST deblender and coming up with uncertainties associated with imperfect deblending. With 2000 sq. deg., we can come up with robust priors for the entire LSST footprint. As an example, [8] found that around 62% of all sources detected in full-depth LSST images contain at least 1% of flux from overlapping sources. In addition, as much as 15% of all LSST sources are expected to be unrecognized blends [9]. Therefore, accurate deblending is of prime importance for the success of LSST.

Third, having a dataset of galaxies with fluxes measured in optical and near-infrared wavelengths significantly improves the accuracy of individual photometric redshift estimates, allowing for easier and better calibration of their distribution for weak lensing analyses. Figure 1 shows the results of simulations of combined LSST and Roman data sets applying the methodology of [10]. The constraining power from combining photometry from optical and infrared instruments has been shown in [11] and in subsequent works by the Kilo-Degree Survey team. Along with the improved object detection, this would enhance the scientific quality of the combined dataset significantly.

Finally, the modest-depth grism spectroscopy that would be obtained over the same area as this imaging in the DRM would provide cross-correlation samples for objects at redshift $1.5 < z < 3$. These cross-correlation measurements can be used directly for cosmology, but also will provide valuable tests of the calibration of photometric redshifts [1]. The multi-band imaging would likely be important to the success of any Roman grism survey in the first place, as photometric redshift information can alleviate ambiguities in grism redshifts [12].

It is also worth noting that with better object classification, photometry and shape measurements that come with the Roman data, there is a large gain in the study of galaxy clusters, which live in intrinsically more blended fields [13]. The gain is especially large for high redshift clusters, where the cosmological power is the largest [14]. Adding an infrared band would help discriminate cluster galaxies from background source galaxies, thus helping cluster identification and reducing contamination and dilution of the cluster weak leasing profiles [15].

[S3] Wide-band coverage of the full extragalactic LSST area: Similar to the multi-band scenario above, Roman data will help here in the study of PSF systematics, blending/deblending, and object classification. In this scenario we will have full coverage of the LSST area with only one filter band.

Several studies have shown that even with one filter band, Roman data can already help with deblending Rubin data. For example, [16] finds that a wide-band Roman survey lasting approximately 5 months could already obtain high-resolution space imaging for around 95% of the LSST gold weak lensing sample, thus detecting a large fraction of unidentified blends. Similarly, object classification and PSF studies could be done to some extent with single-band data as well.

Photometry in the wide F146 filter would modestly benefit photometric redshift measurements across the full Rubin extragalactic footprint. However, due to the limited spectral information available given the breadth of the filter, the gains are much more modest than those provided by multi-band photometry, with a maximum improvement to individual-object photometric redshift errors of roughly 25% (occurring at redshift z~1.5), as illustrated in Figure 1.

It is worth noting that all of these gains would be realized even if systematic effects limit the constraining power of Roman-based weak lensing measurements based upon the wide-area F146 filter observations. In such a scenario, the definitive Roman lensing measurements would come from the smaller multi-band imaging area, but the definitive Rubin lensing measurements would be improved via the Roman imaging across the full LSST extragalactic footprint.

Example metrics for assessing Rubin LSST science impact

[S1] Multi-band Roman imaging and deeper spectroscopy of LSST DDFs: For the deep LSST fields, the first key metric is the amount of area that has DDF-like depth in Roman bands, as this will determine how large the samples are that can be used to test systematics. For photometric redshift training with grism data, the key metric is the number of Roman pointings with deep spectroscopy that are widely separated from each other; a minimum of 15 widely separated pointings are needed to suppress the effects of cosmic variance. This can be met if the pointings are sparsely distributed within at least four LSST DDFs but not fewer.

[S2] Multi-band Roman coverage of a subset of LSST area: For wider areas with multiband coverage, the key metrics are the area that will have that coverage; the fraction of LSST gold sample objects that will have deep enough Roman imaging to resolve blends; and the improvements in photometric redshift errors (both scatter and outlier rate) from the Roman imaging. Figure 1 shows examples of the impact of different Roman survey strategies on these photo-z metrics. An alternative approach for quantifying photometric redshift improvements is provided by ת (also known as TheLastMetric [17]), which quantifies the potentially recoverable redshift information content from a strategy; an example application of this metric is shown in Figure 2.

[S3] Wide-band Roman coverage of a subset of LSST area: For very wide area single-band coverage, the key metrics are the fraction of LSST extragalactic area covered and the fraction of LSST gold sample objects that will have deep enough Roman imaging to resolve blends.

All of the above direct metrics can then be propagated into e.g., the dark energy Figure of Merit (FoM) for LSST 3x2pt data vectors, where we can evaluate the gain in the FoM with improved priors in the photometric redshift bias, improved priors on residual PSF systematics, and the gain in effective galaxy number counts via better deblending.

Conclusions

In this white paper, we have outlined three example scenarios covering the range from deep and relatively small-area deep imaging and spectroscopy to intermediate-area multiband imaging to single band, shallow and wide imaging. Each of these types of data enhances the cosmological measurements that can be obtained from LSST in different ways. The combination of Rubin and Roman data will enhance measurements of photometric redshifts and weak lensing shears, enhance object classification, and greatly improve deblending, amongst many other benefits. Some of these gains will be more important in either high-systematics or lower-systematics scenarios; however it is impossible to predict which of these scenarios will apply by the mid-2030s. We therefore advocate for a balanced strategy that incorporates deep data over smaller regions; an intermediate layer with multiband imaging over substantial areas of sky; and shallow single band imaging over the full LSST extragalactic footprint. Such a strategy would greatly enhance the cosmological constraint from Rubin while also delivering an extremely valuable legacy data set from Roman with rich astrophysical applications.

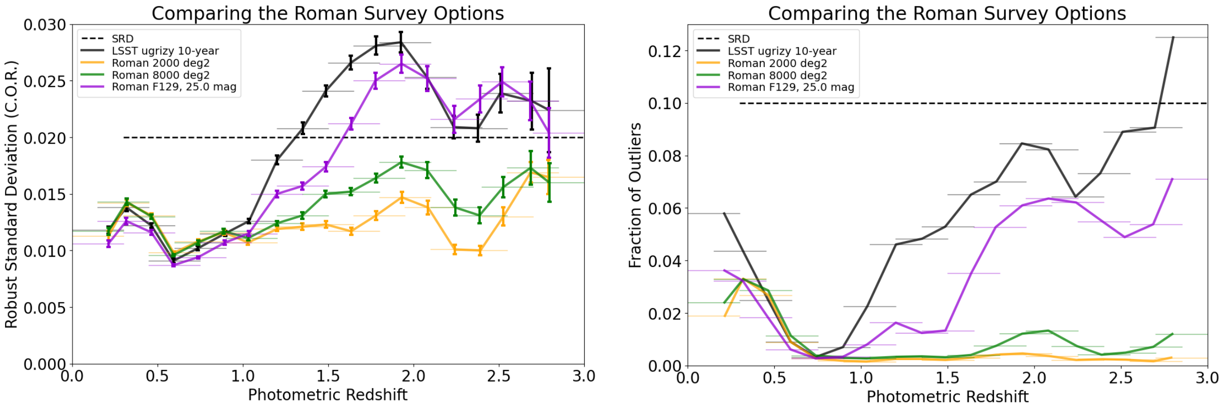

Figure 1. Robust Standard Deviation (left) and Fraction of Outliers (right) as a function of redshift resulting from combinations of Rubin Observatory imaging with a variety of potential datasets from Roman, from simulations by Melissa Graham (see [10]). The 2000 sq. deg. scenario corresponds to the Roman Design Reference Mission (DRM); the 8000 sq. deg. scenario assumes 1/4 of the exposure time per pointing enabling wider sky coverage (though less area than 8000 sq. deg. would be covered due to increases in overheads, which are quite substantial); and the F126 scenario assumes only single band coverage. Single-band Imaging provides only modest improvements, but even the shallower multiband imaging greatly improves photometric redshift errors.

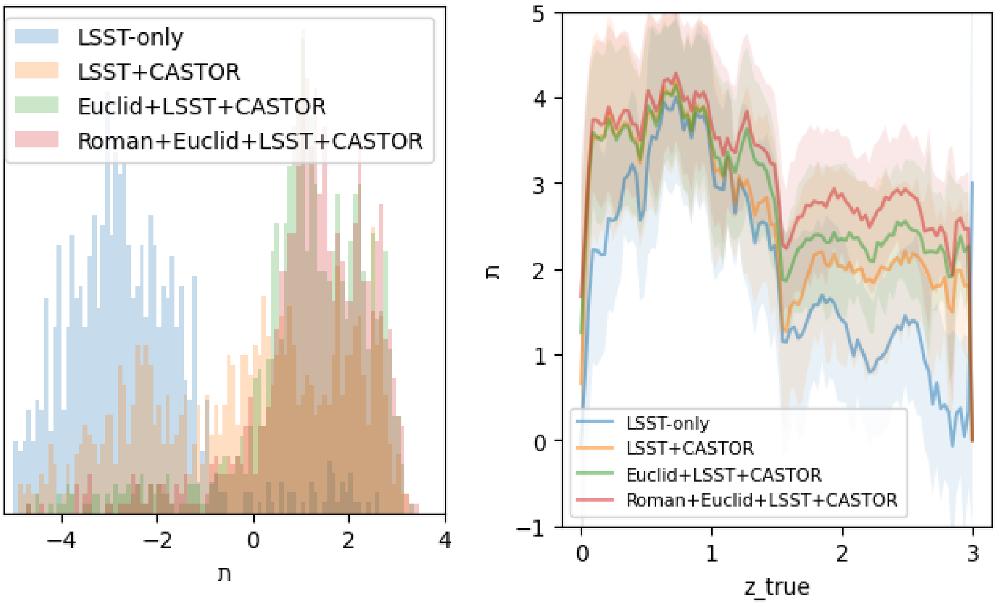

Figure 2. Distribution of TheLastMetric [17], ת (left) and ת as a function of true redshift (right) for mock catalogs with photometric data from the indicated surveys. Figure by Alex Malz, Bryan Scott, and Bobby Sorba. Overall, the figures show that overlapping data from Roman can make a significant difference in the potentially recoverable redshift information content, i.e. the best case for any hypothetical estimator, for LSST's galaxy sample.

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