Astro2020 Science White Paper: Cosmological Synergies Enabled by Joint Analysis of Multi-probe data from WFIRST, Euclid, and LSST

Thematic Areas: ☒ Cosmology and Fundamental Physics

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Abstract: NASA, NSF, and DOE will collectively spend well over $4B this decade and the next on missions and surveys that have dark energy cosmology as one of their primary drivers. WFIRST, Euclid, and LSST are all missions designed to perform dedicated surveys that offer unprecedented statistical constraining power and control of systematic uncertainties. However, there is a growing realization that these missions will be significantly more powerful when the data are processed and analyzed in unison. This will require coordinated cross-survey and inter-agency effort. With proper attention to how data are jointly processed and analyzed, the combination of these missions will provide constraints and systematics control that is *better than the sum of their individual parts*, as stated in the title of Jain, et al. (2015). We advocate for the three relevant US agencies to work together with our international partners to ensure that the synergy from these multi-probe missions is fully realized.

A Tri-Agency Effort: In recommending both LSST and WFIRST as its highest priority large class missions, the Astro2010 Decadal Survey noted the unique synergy between these two telescopes. Deep, multi-epoch optical photometry from the ground combined with high-resolution NIR photometry and grism spectroscopy from space opened up a myriad of science possibilities. In both cases, the use of multiple probes to study dark energy cosmology was a primary scientific driver and helped to set implementation requirements. Likewise, ESA's 2011 selection of the Euclid mission signaled that a multi-probe space mission to study the properties of dark energy was a primary science goal of the European community. A growing realization since 2010 has been that these three missions allow for deeper synergy than was envisioned a decade ago, but will require attention to how their respective data are jointly processed (down to the pixel level, in some cases) and analyzed in order to fully unlock those synergies (see the white paper submitted by Chary for more specifics about joint processing).

Over the past 5 years, the worldwide scientific community has begun to more fully explore these synergies and the three relevant agencies (NASA, NSF, and DOE) have set up an informal Tri Agency Group (TAG) to discuss how to coordinate the relevant efforts on the US side. The TAG has asked the projects to spin up task forces on (1) joint pixel-level processing, (2) survey coordination, e.g. cadence and overlap, and (3) coordination of cosmological simulations using high performance computing. In all three cases, there has been progress toward a definition of the required levels of coordination for various science cases and the plans to implement that coordination. At the same time, the scientific community has begun to explore in detail the synergies unlocked by combining data from multiple cosmological probes, e.g. photometric weak lensing and spectroscopic galaxy clustering surveys over the same areas of sky. We detail some of these initial steps here and advocate for further coordination and effort in order to maximize cosmological constraints and mitigate systematic uncertainties.

Pairwise synergies: Many of the synergies arising from joint processing and analysis, a few of which we describe below, are pairwise between the space missions (Euclid and WFIRST) and LSST from the ground. The timing is such that both Euclid and LSST are expected to start survey operations in 2022. Euclid will gather high-resolution optical imaging, lower resolution NIR imaging, and NIR grism spectroscopy over about 2500 square degrees per year. At the same time, LSST will be covering its ~18,000 square degree survey to ever increasing depth. Early LSST depths will be well matched to the depth of Euclid imaging. In ~2026, WFIRST high-resolution NIR imaging and NIR grism spectroscopy will start to be available. The WFIRST and full LSST imaging depths will be well-matched in the latter part of the 2020s. Thus, initial joint processing and analysis efforts aimed at the combination of LSST and Euclid will pave the way for deeper WFIRST/LSST data using the same techniques.

Synergistic Measurements: We describe below some of the areas of synergistic measurements and inter-project coordination that will allow for greater statistical constraining power, more complete control of systematic uncertainties, and most efficient use of resources.

1. **Object Detection and Deblending**

   A growing concern for deep ground-based surveys is blending, i.e. the overlap of multiple sources. In its more benign form, adjacent sources can still be recognized as distinct, but measurements of position, flux, or morphology will be affected by the proximity to other sources. At the 10-year depth of LSST, approximately 50% of all sources will experience blending at that level (Bosch et al. 2018). The resulting biases are at the several per-cent level for weak-lensing shear estimates (Samuroff et al. 2018) and likely at the same level for photo-z (an ongoing area of research), but can be substantially reduced by simultaneous modeling of all sources in the scene (Drlica-Wagner et al. 2018; Melchior et al. 2018). Adding high-resolution space-based images into the pipeline reduces the degeneracies in the joint-fitting solutions because they reveal how much of the apparent overlap is caused by the convolution with ground-based seeing.

In addition, at the full depth of LSST approximately 15% of all sources will experience blending that is not even recognized as such (Dawson et al. 2016), namely when multiple sources are so close to each other that they appear as one for LSST. While the consequences of unrecognized blending for cosmological probes are still being investigated, mitigation techniques from ground-based imaging alone will likely be limited to statistical calibrations. In contrast, simulations suggest that performing detection and joint modeling with high-resolution space-based images should resolve more than 90% of the unrecognized blends (Melchior et al., 2019). Combination with the Euclid imaging will be effective for the LSST “Gold” sample ($i < 25.3$), while the combination with WFIRST can push the same technique to the detection limit of LSST.

2. Photometric Redshift Measurement and Calibration

Precision cosmology experiments require very accurate characterization of redshifts for statistical samples of galaxies. Spectroscopy offers the redshift precision needed for the upcoming stage IV dark energy experiments aimed for the 2020s (Albrecht et al. 2006) and is used in supernova (SN) and baryon acoustic oscillations (BAO) programs. However, obtaining spectroscopic redshifts for hundreds of millions to billions of faint galaxies for weak lensing analysis is not practical. Instead, photometric redshifts calibrated by a spectroscopic subsample are used to infer distances. A joint analysis of optical LSST and near infrared WFIRST/Euclid data results in a more accurate measurement as well as a more optimized calibration strategy of photometric redshifts (c.f. Hemmati et al., 2019).

Photometric redshift fitting codes use the information encoded in the galaxy broad-band SED to infer distances. To first order, a joint effort is needed to ensure a consistent and high-S/N photometry measurement across all optical and infrared bands (i.e., consistent source selection, similar treatment of the PSF, etc.) to reduce the leaking of uncertainties in the photometry to the photometric redshifts. Additionally, combining LSST optical and WFIRST and Euclid NIR data ensures the coverage of the most prominent features in the galaxy SED shape (i.e. the Lyman and 4000Å break) at a wider redshift range. This combination increases the precision of photometric redshifts and reduces the redshift outlier fractions compared to when only optical or infrared data are used (see e.g., Rhodes et al. 2017). Finally, due to the chromaticity of the PSF,color gradient information for galaxies is needed to make accurate shape measurements, especially in the very wide Euclid VIS band. Such information will be encoded in LSST data to some extent, but may not be derived naturally without joint processing of the combined data sets.

Spectroscopic calibration of photometric redshifts is needed to fulfill cosmological requirements in weak lensing surveys. The synergy between LSST, Euclid, and WFIRST beyond sharing the spectroscopic samples guarantees a better strategy in the selection of the calibration sample. Among the promising strategies for photometric redshift calibration which are more tractable compared to random sampling are clustering redshifts based on the angular cross-correlation of the photometric sample with an overlapping spectroscopic sample (e.g., Newman 2008, McQuinn & White 2013), as well as a direct mapping of the empirical color-redshift relation of galaxies with spectroscopy (e.g., Masters et al. 2015, Masters et al. 2017). The multi-dimensional manifold of galaxy color-space defined by the combination of optical and near infrared data is directly used in the latter method to find a tight mapping to redshift. As described above, deblending of the underlying galaxy samples requires some level of joint processing to achieve the needed accuracy in photo-z and color gradient measurement.

3. Shear Measurement

To maximize both the precision and accuracy of cosmological constraints from weak lensing measurements requires deep and wide-area surveys with high resolution and high signal-to-noise imaging (Massey et al. 2013). LSST will collect high signal-to-noise imaging over the full Southern sky, but will lack the resolution afforded by space-based surveys. Euclid's space-based imaging will have exquisite resolution over a similar total area, but will lack signal-to-noise at faint magnitudes. WFIRST, in contrast, will collect both high resolution and high-S/N imaging, but over a reduced sky area.

Weak lensing cosmology in the 2020's will significantly benefit from the combination of these contrasting survey designs due to their complementary nature. Schuhmann et al. 2019 demonstrate that in a combined LSST-Euclid survey analysis, the precision in the measurement of cosmic shear from a deep sample of galaxies fainter than $i \sim 24.5$, would increase by ~ 50 percent in comparison to an analysis of each survey alone. Furthermore, significant improvements in the accuracy of the shear measurement were found when adopting a joint-survey pixel-level analysis. With 7000 square degrees of overlapping sky between LSST and Euclid (and possibly more, pending proposals to extend LSST coverage further North), this figure should be viewed as the minimum expected improvement for weak lensing cosmology, given the additional expected benefits for photometric redshift calibration and object detection and deblending described above.

The accuracy and calibration of shear measurements derives from both the data (Sheldon & Huff 2017) and from image simulations (e.g. Kannawadi et al 2019). A precise representation of the galaxy population within the mock data, even beyond the magnitude limits of the survey, is, however, likely critical to ensure robustness (Hoekstra et al 2017). Ultra-deep high resolution images from WFIRST and the Euclid Deep Fields will therefore be of great benefit to both the internal calibration of those surveys but also to LSST shear measurement calibration.

4. Transients and SN

Coordinated observations using LSST and Euclid/WFIRST (possibly requiring coordinated or joint processing) will significantly boost transient studies by increasing the dynamic range of discovery in both wavelength and cadence. LSST will observe 'deep drilling fields' (DDF, combined ~50 deg^2) with 2-3 night cadence (and multiple visits within a night) and the 'wide-fast deep' survey (WFD, combined ~18k deg^2) with cadence every ~10 nights. The

WFIRST SN program will observe ~30 deg^2 every 5 nights over a period of two years, with a field center tied to an LSST deep field center (and Euclid deep field), as discussed below. The WFIRST SN survey will be especially powerful sue to prism and grism spectroscopy of the SN. A review of the transient studies enabled by WFIRST is given in a 2020 Decadal Survey white paper submitted by Foley. While the WFIRST High-Latitude Survey will not provide regular cadenced observations, the observations will overlap with the LSST WFD survey. The Euclid wide survey will have significantly more overlap with the LSST WFD survey (7000 or more square degrees), providing serendipitous NIR photometry and grism spectroscopy of many LSST transients, making for better-calibrated standard candles (Rhodes et al., 2017)

LSST will likely measure ~300k Type Ia supernovae (SNIa), but almost exclusively at z<1. WFIRST can measure ~20k SNIa up to z~2 (Hounsell et al. 2018), allowing for increased redshift leverage which will improve discrimination of dark energy models. Furthermore, WFIRST's NIR data will improve LSST's reddening and classification systematics, likely two of the largest SNIa cosmology systematics. WFIRST and Euclid will also provide high-resolution images for a large sample of the LSST-discovered SNe. For more exotic transients like kilonovae, the increased dynamic range in depth and wavelength from the combination of ground/space telescopes will prove vital for serendipitous detections (Scolnic et al. 2018).

While the Euclid wide and deep survey cadences will not yield a stand-alone transient survey of the same constraining power as WFIRST or LSST, Euclid's deep survey will allow for the discovery of ~200 superluminous SN over the course of the mission (Inserra et al., 2018). Overlapping observations will be useful for systematic studies; thus, to the extent possible, coordinating Euclid and LSST observations should be a priority (especially in the deep fields).

By independently searching for transients in each survey and cross referencing, we will be able to test the data reduction pipelines, detection algorithms and selection effects for each survey. This is particularly true for WFIRST discoveries, which will typically be fainter than LSST SNe and possibly coming from different populations (e.g., dusty SNe). Since the surveys have overlapping filter sets, one can cross-calibrate the surveys using the SNe themselves. Ultimately the best distances will come from a simultaneous fit to data from all telescopes. Doing this will require a detailed internal understanding of each survey and knowledge of the key observational difference between the surveys to avoid systematic biases.

5. Supercomputing

Stage IV cosmological surveys rely on cosmological simulations for their success, and a new paradigm is needed to ensure that the cosmological simulation staff and efforts are being supported in the same way as other key survey infrastructure tasks. Upcoming wide-field surveys require significant high-performance computing resources for a number of interrelated tasks, including carrying out numerical simulations, transforming them into synthetic sky maps, validating the results, and serving the data in an easily accessible way. These efforts require substantial computing and storage resources as well as people with specialized expertise to develop the modeling/analysis pipelines and databases. Many of the tasks are common between the major cosmological surveys and it is therefore strongly advisable to evaluate common approaches and inter-project resource sharing.

In 2018, a TAG Cosmological Simulations task force (TACS) was assembled to evaluate how the US agencies could support these efforts. In its December 2018 report to the TAG, the TACS noted that many elements deemed necessary for survey success are considered part of the infrastructure; these include efforts like ground operations, analysis pipelines, and data management pipeline development, but not necessarily cosmological simulations. Although it is currently widely accepted that cosmological simulations are essential to upcoming Stage IV surveys, the support for these efforts is still largely only being covered by competitively selected R&D proposals (both in the US and Europe). As a result, key work is difficult to undertake in a timely or planned manner due to the uncertainty of proposal selection. This has resulted in efforts being limited to those groups that have been successful in securing short-term funding and resources for very specific tasks. The report further found that it would be beneficial for the agencies to prioritize key R&D tasks related to investigations of systematic uncertainties and advanced statistical methods in their existing calls, while directly funding specific infrastructure efforts including improving synthetic sky generation software and building an infrastructure for hosting and serving simulated data between projects.

Addressing Tensions with multiple probes: Recent measurements of the growth of cosmic structure made by weak lensing (Hildebrandt et al 2019, Troxel et al 2018, Hikage et al 2019) are, taken as a set, possibly in tension with the Planck constraints on a LCDM cosmology. Supernova measurements of the Hubble constant that rely on the determination of distances in the local universe are in somewhat stronger tension (Riess, et al. 2018a) with those that rely on the determination of the scale of the sound horizon in the CMB. There is not consensus on whether these tensions should be seen as statistical flukes, attributed to systematic errors in one or more of the measurements, or hints of extensions to the consensus model. With Stage IV data, these tensions may grow or vanish in significance. However, they are precisely the sort of signatures of new physics that the next generation of cosmological probes hopes to find.

The current lack of a consensus interpretation of these tensions can be attributed in part to the complexity of the measurements themselves and in part to the lack of tools and methods for rigorously probing the nature of disagreement between these kinds of measurements at sufficient precision. The former is not going to improve, but a community invested in the robustness of the ultimate scientific outcomes will take great care to improve on the latter. To do this, we should maximize the exposure of potential sources of systematic error in one survey to measurement in others; invest in resources that allow us to trace disagreement in the space of high-level parameters back to primitive elements of the underlying data vector, and take full advantage of overlapping survey footprints that allow us to ensure that similar experiments are seeing appropriately similar skies.

While these points may seem uncontroversial, research efforts that account for all of potential sources of difference between experiments are still fairly rare, due to the high complexity of modern cosmological measurements (c.f. Troxel, et al. 2018), and frequently controversial (Riess, et al. 2018b), and future survey teams should make this comparison process easier and more frequent.

Final Recommendation: While each of the major cosmological experiments of the 2020s should first make its own stand-alone measurements, the ultimate result will be more than the sum of the parts if the community has the resources and direction to properly coordinate the joint processing and analysis. The appropriate US agencies should work with our international partners to see that this is made a reality, and to share high-performance computing resources and products across surveys.

References

Albrecht, et al., “Report of the Dark Energy Task Force,” 2006, astro-ph/0609591

Bosch, et al. “The Hyper Suprime-Cam software pipeline”, 2018, PASJ, 70, 1

Dawson, et al. “The Ellipticity Distribution of Ambiguously Blended Objects”, 2015, ApJ, 816, 11

Drlica-Wagner, et al. “Dark Energy Survey Year 1 Results: The Photometric Data Set for Cosmology”, 2018, ApJS, 235, 33

Hemmati et al., 2019, ApJ submitted, arXiv:1808.10458

Hikage et al, PASJ submitted, arxiv: 1809.09148

Hildebrandt et al 2019, A&A submitted, arxiv: 1812.06076

Hoekstra, Viola & Herbonnet, 2017 MNRAS, 468, 3295H

Hounsell, et al., “Simulations of the WFIRST Supernova Survey and Forecasts of Cosmological Constraints,” 2018, APJ, 867, 23

Inserra et al., “Euclid: Superluminous supernovae in the Deep Survey”, 2018, A&A, 609, 83

Jain, Spergel, et al., “The Whole is Greater than the Sum of the Parts: Optimizing the Joint Science Return from LSST, Euclid and WFIRST,” 2015, arXiv:1501.07897

Kannawadi, et al. 2019 A&A in press doi:10.1051/0004-6361/201834819

Massey, et al. 2013: 2013 MNRAS, 429, 661

Masters, et al, 2015, ApJ, 813, 53

Master et al., 2017, ApJ, 841,111

McQuinn & White, 2013, MNRAS, 433, 2857

Melchior et al., 2019, in prep

Melchior, et al., “scarlet: Source separation in multi-band images by Constrained Matrix Factorization”, 2018, Astronomy & Computing, 24, 129

Newman, 2008, PJ, 684, 88

Rhodes, et al., “Scientific Synergy Between LSST and Euclid,” 2017, ApJS, 233, 21R

Riess, A.G., Casertano, S., Yuan, W., et al. 2018a, ApJ, 861, 126

Riess, A.G., Casertano, S., Kenworthy, D., Scolnic, D., & Macri, L. 2018b, arXiv:1810.03526

Samuroff, et al. “Dark Energy Survey Year 1 Results: The Impact of Galaxy Neighbours on Weak Lensing Cosmology with im3shape”, 2018, MNRAS, 475, 21

Scolnic, et al., 2018, APJ, 859, 101

Sheldon & Huff 2017 ApJ, 841, 24S

Schuhmann, Heymans, & Zuntz 2019, arxiv 1901.08586

Troxel, M.A., Krause, E., Chang, C., et al. 2018, MNRAS, 479, 4998

Troxel et al 2018, PhRvD, 98, 3528

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