Astro2020 Science White Paper
Cosmology in the 2020s Needs Precision and Accuracy: The Case for Euclid/LSST/WFIRST Joint Survey Processing

"The whole is greater than the sum of its parts"

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Thematic Areas: Cosmology and Fundamental Physics

Scientific Motivation: We have made tremendous progress in understanding the energy budget and the expansion rate of our Universe over the past 20 years (Planck Collaboration 2018, 2015; WMAP Collaboration 2013, Riess et al. 2016, Freedman et al. 2010). Yet, different measurements of some of these parameters appear to be loosely in tension at the ~2-3sigma level (e.g. Addison et al. 2018, Auborg et al. 2015). While work by Mantz et al. (2015) has shown that Ω_M-σ_8 parameters (Ω_M is the cosmological matter density and σ_8 is the amplitude of z=0 matter density fluctuations on $8h^{-1}$ Mpc scales) derived from galaxy clusters are in agreement with those derived from the cosmic microwave background (CMB), Hubble constant (H0) measurements from the CMB are ostensibly in some tension with those from BAO or Cepheids/Type Ia SNe (e.g. Riess et al. 2016, DES Collaboration 2018). Although the individual measurements by themselves are increasing in precision, it is unclear which one, if either, is more accurate. Furthermore, the discrepancies may actually be providing a window into new astrophysics in individual classes of sources such as the Cepheids/Type Ia SNe. Identifying these, requires the next generation of cosmology measurements to have increasingly greater precision, with careful attention to systematics, particularly when the primary goal is to constrain the redshift evolution of the dark energy equation of state.

The Problem: The blending of sources due to the presence of nearby companion sources (e.g. Samuroff et al. 2018), affects flux density measurements, source centroids and source shape estimates, which together are the most common metrics in observational astronomy (Figure 1). Although confusion is generally negligible in deep, optical/near-infrared surveys from space, it plagues ground-based observations, particularly at the depth of upcoming surveys such as with LSST and Subaru/HSC. To illustrate, at 25.5 AB mag depth in the optical with 0.7" full width at half maximum seeing, 25% of sources are affected by source confusion. At depths of 27.5 AB mag, the number increases to ~50%, with cosmic variance defining the exact percentage. Confusion will therefore introduce systematic biases in ellipticity and photometric redshift estimates, translating to a bias in cosmological parameters derived through weak lensing.

A Solution: Joint analyses of space-based and ground-based datasets, particularly at the pixel level, including an accurate representation of the source-color-dependent point spread function, can dramatically alleviate this problem, enabling precise and consistent multi-wavelength photometry, source shape and position measurements, and allow photometry to be undertaken down to the shot noise limit of the instruments.

The Euclid, LSST and WFIRST projects are undertaking the flagship cosmological surveys of the next decade. By mapping several thousand square degrees of sky and covering the electromagnetic spectrum from the optical to the near-infrared with sub-arcsec resolution, these projects will detect several tens of billions of sources, enable a wide range of astrophysical investigations by the astronomical community and provide unprecedented constraints on the nature of dark energy and dark matter. In addition, a host of other wide-area surveys with VISTA, ZTF, PanSTARRS and SkyMapper sample the sky with different cadences and at different wavelengths, enabling photometric constraints on temporally evolving events to be placed, especially with post-facto knowledge of the sky from space-surveys. The ultimate cosmological, astrophysical and time-domain science yield will require ``joint survey processing" (JSP) functionality at the pixel level that is outside the scope of the individual projects. Pixel-level processing involves measuring the location, shapes, brightness and sizes of sources in the co-spatial space-based surveys, accounting for color gradients in the source and the color-dependent point spread function and fitting for their flux densities in the lower resolution ground-based data. Due to the variable seeing, optimal precision may be obtained through fits to the single-visit ground-based data and combining those measurements. However, the degradation in photometric precision from fitting to image coadds is <15%, with the significant benefit of manageable data volume.

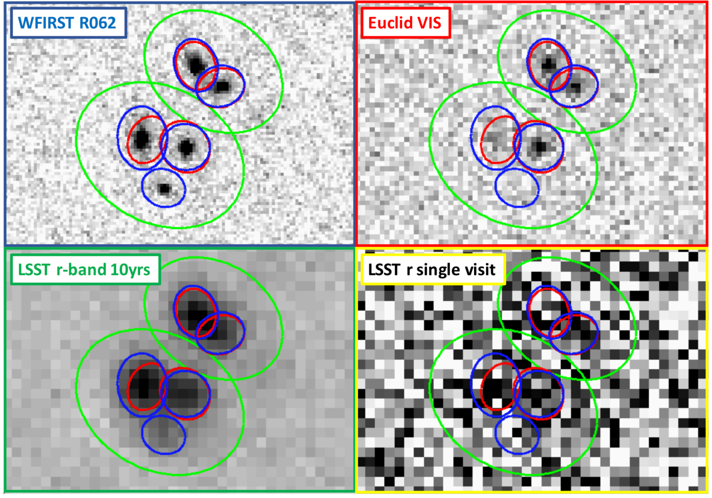

Figure 1: An illustration of source confusion in the optical bands from Euclid/LSST/WFIRST, along with the isophotes derived from photometry on each of the images. The green isophotes are derived from the LSST full-depth data of 27.5 AB mag, the red isophotes are from the Euclid only VIS data while the blue isophotes are for the WFIRST data. The sources are barely detected in LSST single-epochs. In the absence of the deep, space-resolution data, confusion would result in both erroneous shape and photometry estimates in LSST data and also affect catalog matching. Conversely, both Euclid and WFIRST rely on deconfused accurate optical photometry from LSST to get reliable photometric redshifts for galaxies that are detected in their respective surveys.

Broad Impact: Two broad examples of high-impact scientific topics which benefit from such precise joint survey processing are:

1. The nature of dark matter and dark energy through:
    a. improved precision of photometric redshifts and galaxy shape measurements for three-dimensional weak lensing (Figure 2);
    b. lensing time delays in multiply lensed quasars (e.g. Suyu et al. 2014, Birrer et al. 2019);
    c. selection of uniform Type Ia SNe based on the properties of their host galaxy (e.g. Sullivan et al. 2010).
    d. Measuring the location and magnification of background lensed galaxies to obtain a better handle on dark matter substructure in the lensing galaxy.

2. A census of the ionizing photon budget from galaxies and quasars at the epoch of reionization (z>6) through accurate resolution-matched color-selection (Fig. 3);

However, it can easily be demonstrated (e.g. Joint Survey Processing Report 2019) that such precise combination of ground- and space- datasets positively impact all areas of astrophysics.

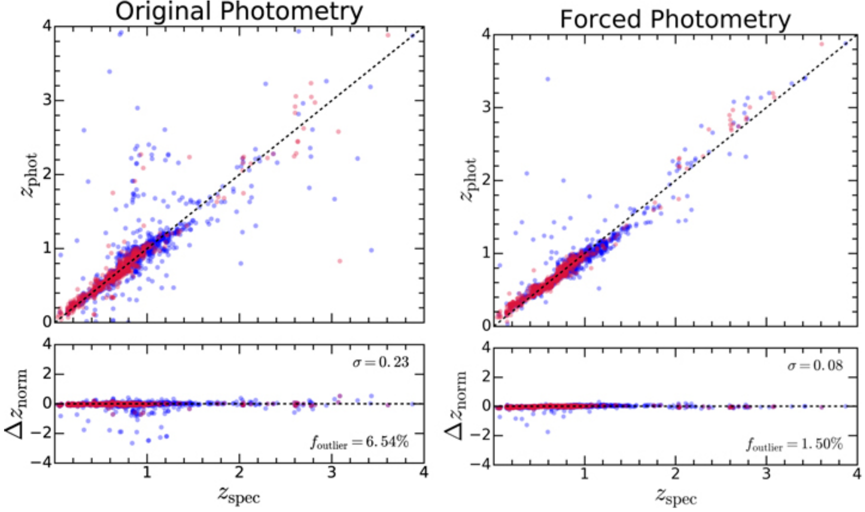

Figure 2: Comparison (from Nyland et al. 2017) between spectroscopic and photometric redshifts derived by using catalog matching (left) versus by doing forced photometry using positional priors (right panel). Red sources have high quality spectroscopic redshifts while blue sources have lower quality redshifts. The scatter in photometric redshifts is reduced by a factor of 3 while the outlier fraction has been reduced by a factor of more than 4. When combined with lower-order corrections to the photometry, like due to Galactic extinction, the errors in photometric redshifts can be dramatically mitigated at an even higher level through pixel-level joint processing of the data.

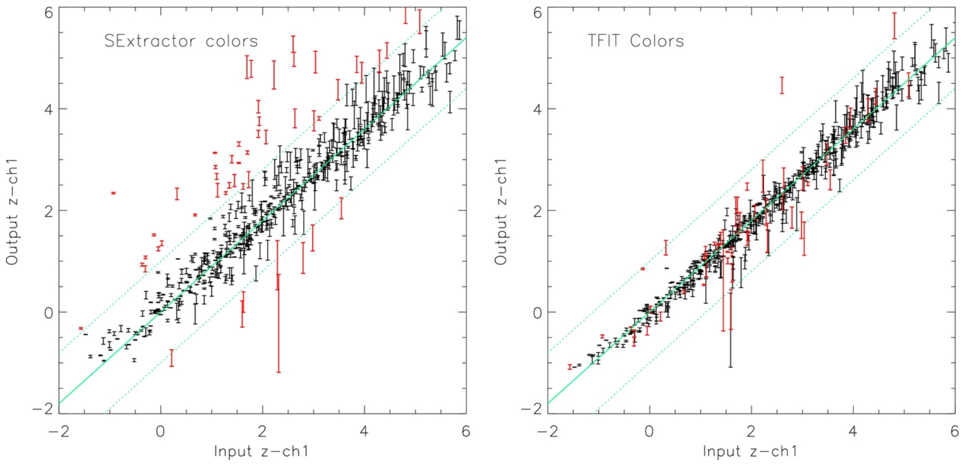

Figure 3: Simulation from Lee et al. (2012) showing improvement in the measured z-[3.6µm] (z-band is from Hubble/ACS while ch1 is Spitzer/IRAC channel1 at 3.6 microns) colors of objects when using high-resolution priors in position and morphology to extract photometry (right panel), compared to when using catalog matching (left panel). The red points are used to identify sources whose blind catalog photometry was biased by >1 mag. Priors clearly reduce both the number of catastrophic outliers and the color scatter. Accurate color selection enables an accurate estimation of the ionizing photon budget from z>6 sources.

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Feasibility: The techniques for joint survey processing have been developed in various forms in the last decade and applied to astronomical surveys such as those with *Hubble*, *Spitzer and Herschel* (Figure 4; e.g.Magnelli et al. 2010, Laidler et al. 2007, Chary et al. 2004). They involve:

1) Aligning the astrometry of the higher resolution and lower resolution data to within 10 milli-arcsec, including the effects of different epochs of observation;
2) using a template for each source, either by fitting an analytical function to the shape of the source in the space-quality data or by taking a cutout of the source out to its isophotal radius;
3) convolving for the difference in the point spread function between the space-platform data and the ground data which naturally suffers from worse resolution and accounting for source-color dependent PSF terms;
4) Fitting for the sources in the lower resolution datasets taking into account the prior information that one has from the higher resolution dataset.

This has been implemented using software like TPHOT (Merlin et al. 2015), SCARLET (Melchior et al. 2018) and TRACTOR (Lang et al. 2016).

In addition, a systematic in the derivation of photometry and photometric redshift arises from substructure in the Galactic extinction model on 10s of arcsecond spatial scales. By our estimates, substructure in dust extinction corresponds to a >2% impact on the photometric redshift scatter although the exact magnitude of improvement needs a better high resolution extinction map of the Galaxy (current spatial scales are 5 arcminutes!). Shifts of a tenth of a magnitude that may arise due to inaccurate extinction corrections or imprecise cross-project calibration would correspond to a shift in the mean derived photometric redshift of 0.02 (e.g. Bordoloi et al. 2009; J. Coupon et al., Euclid technical report). Precise multi-wavelength photometry of stars with Gaia-measured distances, in conjunction with WISE images of diffuse dust emission can yield a high resolution extinction map in each Euclid/LSST/WFIRST band that will yield more accurate and precise photometry of galaxies, improving the cosmological constraints. However, precision photometry for stars, cannot be derived from fits to co-added data due to stellar motions (parallax and proper motion) over the multi-year baseline of the surveys; the optimal treatment thus requires photometry from the single-visit data to be combined.

While technically challenging, JSP is tractable based on existing techniques and current computing technology and infrastructure.

Summary: The value of the Hubble Constant, dark energy equation of state as a function of redshift, and the impact of dark matter on galaxy substructure are some of the most pressing problems in cosmology. If the dark energy equation of state w(z) is constant with redshift to z~2, to within the measurement precision of Euclid, LSST and WFIRST, it would likely imply a cosmological constant. This would be a remarkable, if frustrating result, suggesting that our Universe may be a bubble among a multitude of bubbles, as postulated by the 10^{500} possibilities for vacuum energy from string theory (e.g. Kachru et al. 2003, Chary 2016). Testing this requires unprecedented accuracy and precision in photometric measurements of galaxies with forthcoming surveys. Measurements will need to account for mundane problems such as mismatched isophotes, source confusion, Galactic extinction, PSF variations including source-color-dependent terms and color-gradients. Joint pixel level analysis of the next generation optical/near-infrared surveys promises to provide a manageable way to address each of these issues. Building the software and computational infrastructure including server-side analysis, to easily handle the 100 PB of multi-wavelength data with joint pixel processing would enable a range of ancillary astrophysics not highlighted here, while providing immense cosmological benefit, at a cost which is less than 1% that of building these surveys.

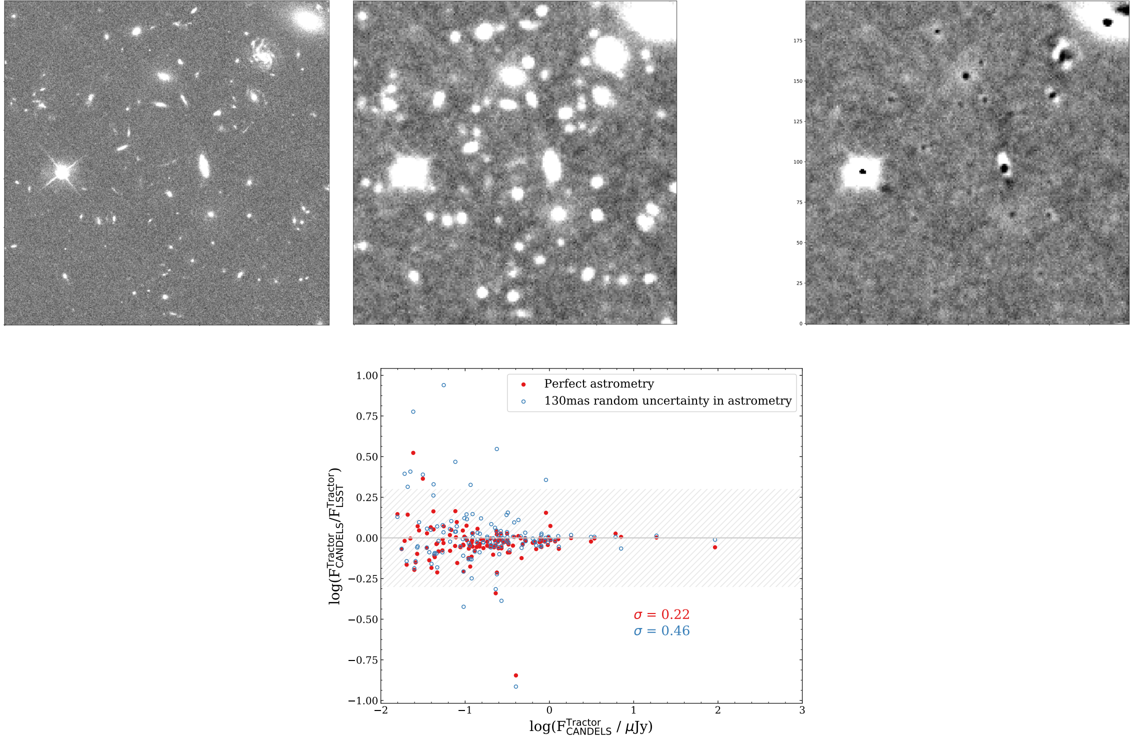

Figure 4: Top left: a high resolution WFIRST-quality R062 (optical filter) image derived using HST data from CANDELS (Grogin et al. 2011; Koekemoer et al. 2011). Top middle: the equivalent LSST r-band image; Top-right: residuals after sources are modeled in the space-quality data and fit in the ground-based data using TRACTOR. The quality of the resultant photometry is shown in the lower panel, where the x-axis is the true photometry and the y-axis is the log of the ratio between the true and deblended TRACTOR photometry (hatched band shows a factor of ±2 difference). The red points show the photometric scatter with no astrometric error while the blue points show the scatter when an arbitrary 1sigma astrometric scatter of 130mas is introduced on a source by source basis. The standard deviation increases by a factor of ~2 due to astrometric inaccuracy. Accurate cross-project astrometry is crucial for photometric precision!

References:

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