Workshop Outcomes

Foreground Physical Effects on LSST Weak Lensing Science:

A Workshop on the Impact of the Last Kiloparsec

Held at UC Davis, December 14-15, 2015

http://wlsys.physics.ucdavis.edu
https://indico.bnl.gov/conferenceDisplay.py?confId=1604

Background and Context

Achieving the ultimate sensitivity of the LSST to weak lensing (WL) science places stringent requirements on our ability to accurately measure galaxy shapes and redshifts, which in turn demands precise and accurate knowledge of the point spread function, astrometry, and photometry. These measurements are influenced by the interaction of light with Galactic dust, the Earth's atmosphere, the telescope optics, and the CCD sensors. The LSST Project is developing mechanisms for correcting for systematic effects, once known. We held a two-day workshop, supported by the LSSTC, to focus expertise in these areas on assessing our current understanding of these physical effects and to address the following questions:

1. What currently limits our understanding of important foregrounds in the last kiloparsec?
2. How well must we understand each physical effect so that residual biases do not limit WL science with the LSST, given the unprecedented statistical precision?
3. Can current simulation efforts be augmented to improve our understanding of these effects?
4. What data could we take now or during LSST commissioning to improve and test our understanding?

Questions 1 and 2 are addressed in the workshop materials archived on Indico. In this document, we summarize outcomes of the workshop that focus on questions 3 and 4.

One of the benefits of the workshop was that a group of scientists with very diverse expertise developed a broad appreciation of the importance of the various foreground physical effects on WL science. We expect that this will lead to more 'cross cultivation' of ideas. However, the breadth of the workshop also meant that there was not time in only two days to thoroughly discuss all the issues and come up with a consensus on new ideas for tackling each potential systematic. Therefore, this document is a compilation of ideas we think warrant further consideration -- not a definitive or complete list of outcomes. We also acknowledge that the ideas described here reflect much work and discussion in the community before, during, and even since, the workshop.

Outcomes

After hearing overview presentations and reviewing poster presentations of recent work, the 60 workshop participants broke up into five round table discussion groups in three separate sessions, each focused on aspects of systematics in weak lensing measurements due to physical effects in the last kiloparsec. These included patchy dust in our Galaxy, atmospheric effects, and charge transport anomalies in CCDs.

While the emphasis was to think out-of-the-box about novel ways of testing for known and unknown systematics, many round table groups naturally rediscovered some of the planned tests. In the summary below we emphasize mainly the new ideas that emerged, while mentioning the planned tests of systematics only in cases where they are still being debated.

There was a healthy and productive interaction with participants from the LSST Project and a heightened level of collaboration. Almost half the attendees were students and postdocs, and all benefitted from their inclusion and participation. Below we summarize the ideas that were generated in the discussions, that could provide useful directions for simulations, for ancillary data, and for commissioning camera (ComCam) and early survey tests. Since the ideas were collected from fifteen different round tables, the style and voice varies throughout the document, and we have made no attempt to make them consistent.

Milky Way Dust

How are cosmological weak lensing measurements affected by dust extinction and reddening? Variations in extinction on tens of arcminute scales can create galaxy sample selection variations on the same angular scales as the peak cosmic shear signal. In addition, corresponding photometric zero-point errors create correlated photo-z biases, which propagate into biased cosmological constraints. Finally, this creates potentially large angular biases in weak-lensing magnification by modulating the number counts of galaxies.

Needed precision

All these effects need to be characterized better: what level of precision is required, and on which angular scales, so reddening is not a dominant systematic error? To this end, we need simulations based on the best available dust data, and we require end-to-end tests of how improperly corrected reddening would affect parameters of interest.

Existing reddening constraints based on far-infrared data (e.g., SFD98[1] and Planck) have limitations in that they measure dust emission rather than the absorption that we need. In addition, there is large-scale structure leakage into the maps due to confusion with the Cosmic Infrared Background, which is undesirable, and can add spurious dust signal due to the presence of large scale structure. Stellar reddening maps based on observations in the optical have useful features: they measure the dust absorption that we want, and are limited by the same photometric calibration precision that is in the data. However, there is still some uncertainty in the universality of the reddening law. There are also potential systematic errors due to variations in stellar populations. These could be surmounted via, e.g., a narrow-band Ca HK survey to pin down metallicity variations, but it was noted that this is a major effort. We will also have access to Gaia data, which should be explored for these purposes.

Tracers

There are other tracers of dust which may be useful as cross-checks. Quasars, via line ratios, could be used, though the IGM may be an issue. Red galaxies have standardizable colors. Perhaps we could use galaxy counts to correct large-scale errors in the dust map; however, this would couple in a bias from WL magnification unless we were careful to do this in the corrected r-band where magnification is nulled.

At the present time, we are not doing the best we can with photometry. Uncertainty is currently ~0.03 mag, but we can do better with more bands, more stars, and better dust priors. A stellar metallicity narrow-band survey for dust calibration would be essential to exploit stars to their fullest. Having a sample of stars with well-known metallicities across the sky could help quite a bit with extinction maps, and could help with photometric calibration as well. It is quite likely that the best dust extinction maps will come directly from the stars observed by LSST itself, rather than long wavelength data.

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[1] Schlegel, D.J., Finkbeiner, D.P. Davis, M. *1998*, ApJ 500, 525

Where to correct

At what stage in data processing should dust correction be made? Better dust maps will come out over time, people will disagree on the best dust correction, different corrections are appropriate for different types of work, and the reddening correction depends on the source SED. So dust corrections are likely best done at the catalog level.

Atmosphere

Turbulence at various layers in the atmosphere generates most of the PSF width and exposure-to-exposure variation in PSF, and these effects scale with airmass. Are there advantages to purposefully observing at higher airmass? Perhaps for calibration of chromaticity and reddening, but not for most LSST main survey science, including weak lensing (e.g., DES has no use for very high airmass data, but a range of airmass is essential for chromatic calibration). Perhaps training a ML code on data from varying airmass would be able to pick up features more easily. A test using Com-Cam time makes sense here.

Chromaticity

Simulations of the atmospheric PSF dependence on wavelength are not consistent with the Kolmogorov model, and also suggest a dependence on outer scale. We chose to explore this further including its effects and what we can do to further understand this. This has an effect on the size measurements of the PSF for weak lensing studies; the effect is observation dependent and does not average out over 10 years. Are the chromaticity of the stellar PSFs with LSST data sufficient to do everything we need? How can we achieve a better understanding of how the seeing affects PSF chromaticity?

Tests and other data

We need multi-band, simultaneous measurements of high-density stellar fields in various seeing conditions. PISCO -- a four-band multi-imager on Magellan -- could do this. Also valuable is the capability to separate optical and atmospheric contributions to the PSF. The purely optical contribution can be determined using out-of-focus engineering images. In addition, instrumental artifacts of individual channels can be removed using the in/out of focus CWFS technique.

How should we use space-based data to constrain atmospheric effects? WFIRST: band overlap with LSST is not set yet; IFU goes to 0.5 micron. Write HST proposals for calibration?

During operations

One of the most useful suggestions was to track a field for the night. This would be useful for initial studies of the sensitivity of PSF corrections to image quality (using, for example, an open cluster field), and then later for tests of sensitivity to image quality of residual weak lens shear after DM correction.

We could use large-scale patterns of distortions over the 20,000 stars per exposure for PSF regularization in the per-CCD PSF fitting. In the per CCD fits, there is a benefit to setting aside some stars for validation tests of PSF extrapolation. Additionally, periodic visits to low galactic latitude, high stellar density fields could be used to constrain the prior probability of the atmospheric PSF size and ellipticity two-point functions.

In addition to using all the stars in a given visit, there is useful information in the wavefront sensors and the guide CCDs that may be used to regularize the PSF reconstruction in a visit. We might read out guider CCDs in different ways to better monitor the atmosphere, since we don't need all the guide CCDs for guiding. For example, faster guider readout than 9 Hz should be possible if smaller regions of interest are used. Or, for special studies a single start in the wavefront sensors could be readout at a high rate, to measure a portion of the atmospheric power spectrum. Take images with different exposure times at different wind speeds to explore spatial and temporal correlation lengths of atmospheric effect on PSF. A case was made for getting a differential image motion monitor to capture variation and wandering of image centroid. The guide CCDs could also be used for this.

Observe at a range of precipitable water vapor (PWV) values to generate sufficient data early to verify y-band calibration. It is hard, of course, to control PWV, but we should confront this early. Thus it would be desirable to have an automated PWV site monitor with sub-mm PWV precision.

CCD systematics

While the atmosphere contributions to the PSF over most of the sensor area are dominant and variable, the CCDs exhibit position and intensity dependent charge transport anomalies which need to be understood and corrected in order to reach the WL shear measurement goals. Long misinterpreted as QE variations, we must correct for these small-scale astrometric variations in the thick fully depleted CCDs. The effective pixel grid is not exactly rectangular; it is warped. Several effects contribute to this charge redistribution: fringing transverse electric fields around the edge of the chip; space charge repulsion of arriving photoelectrons near cores of bright stars; chemical potential variations frozen into the silicon. Nearly all the small-scale features we see in flat field images actually represent shifted pixel boundaries (and hence shifting pixel positions), and that means we should be including them as a remapping rather than dividing them out.

Moreover our notion that images have a "PSF" and a "world coordinate system (WCS)" as separate entities depends on both of those being slowly-varying on the scale of the PSF. When that is not true, one must think of it as a single transfer function that maps distributions on the sky to values in pixels. One cannot fold the pixel response into the effective PSF, or use sinc interpolation to resample (since the pixel grid is not regular). The good news is that these charge transport effects are in principle fully predictive.

Need for remapping algorithm

The extra coordinate mapping is frozen in the chips, so there should be enough information to constrain the mapping from dithered star positions. Correlations in flat fields provide added information, which combined with the dithered star array data can constrain a device physics model. Once we know the mapping we can likely correct for it well enough by shifting some charge around between pixels at a very early stage in pipeline processing -- then we get back to having rectangular pixel grids, and we can proceed as before. Pixel-level corrections are most appropriate.

Lab measurements and device physics model

We should be able to fully characterize these sensor effects in the lab:

- Can control parameter space
- Disentangle them from each other
- See response of the system/effect/algorithm

Any information here should be stable (modulo catastrophe) through the survey. However, survey data may be used for updating sensor model parameters.

We heard preliminary evidence of a CCD charge transport model based on lab measurements, which shows high precision agreement with the observations and which has predictive power. The next step is to validate this with additional data and then develop a pixel-level algorithm based on this device physics model, that may be used in the LSST pipeline processing. It should be pointed out that lab characterization of each CCD in the final camera is not planned. Rather the intent is to build a model for the CCD and tune the parameters of that model for each CCD based on data taken at the telescope.

Survey Strategies

As in all WL surveys, an optimized observing strategy can go a long way towards suppressing systematics. While much has been learned from precursor surveys, the LSST capabilities are new and the statistical precision will be unprecedented. It will be important to develop a detailed understanding of the sensitivity of PSF systematics to the various observing parameters. To that end we should try all possible combinations of observing parameters without prior bias -- particularly in bad weather to see, for example, if the external water vapor measurement is useful for calibrations.

WL systematics sensitivities and null tests

One technique is to observe outskirts of globular or open clusters: observe a dense stellar field to characterize higher spatial frequency PSF error. For updating the brighter-fatter PSF dependence on contrast with sky, we can use bright or gray time to raise the sky level. The same open cluster field could be re-observed.

Applying “null tests” in cosmic shear analyses is one way to identify residual systematic uncertainties. A classic one that can be applied on any data segment is B-mode in star-galaxy and star-star correlations, excluding the PSF stars. There will be over 20,000 high S/N stars over the focal plane per exposure. In null tests, look for subsets of the data where failures are even stronger -- very informative. Any null test will have some residual bias; correlating this bias with the variables (weather, seeing, system parameters) can lead to detection of new systematics.

How can the variable seeing in the large number of LSST epochs be used to learn about the impacts of the atmosphere - e.g., for blended objects, inferring the PSF from galaxy images? Chromaticity/DCR/airmass test: go to high air mass in good seeing conditions.

Uncovering new systematics

We want to have null tests that use the observing strategy to test (extract and quantify) known systematics and then isolate unknown ones.

- To discriminate between these categories of PSF systematics, do a joint analysis of PSF(x,y,seeing,winds,exposure time, etc.)
- Use commissioning time to run a number of null tests
- Use early survey time to be able to run some tests at full depth.

Ideas for things to do early in the main survey:

- Go to full depth over part of the survey area
- Go to full deep drilling depth in a couple of DD fields that have overlap with HST fields and future WFIRST fields.
- Have a u-band campaign to increase u-band images for photo-z.
- Frequent, random rotational and translational dithering
- Create separate source catalog detected from best seeing images in each filter

Intelligent dithering

Rotational dithers are essential for attacking residual shear systematics remaining after DM pixel level pipeline correction. These must be randomized with respect to parallactic angle, telescope optics, and (possibly) wind direction. In any case, the rotational dither distribution must take account of prior data quality in that field, in order to accurately null residual additive shear systematics. Rotator slewing may have an operational cost - it would be useful to implement WL shear systematics metrics in the Metrics Analysis Framework (MAF), and then undertake full simulations once the DM correction for CCD systematics is in place and the CCD physics-based charge transport model is incorporated into PhoSim.

Concluding Thoughts

Overall the participants considered this a very successful gathering of experts from the LSST Project, from across the DESC, and from the community beyond LSST. A number of new efforts were sparked by the meeting, and we look forward to continued progress in understanding and suppressing potential sources of systematic uncertainty in extracting cosmological constraints from LSST data.

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