Final Scientific Report

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Recipient: University of Pittsburgh / Jeffrey Newman

Title: Optimizing New Dark Energy Experiments

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Executive Summary:

Considerable resources are being invested in experiments to study Dark Energy which will rely on estimates of the redshifts (a measure of when light left a distant object on its journey to us, which is closely related to distance) of objects based only on their observed colors in imaging data (commonly called "photometric redshifts"). However, any bias in the mean or scatter of these photometric redshift measurements must be extremely small (below ~ 3 parts in 1000) for these projects' sensitivity to the parameters of dark energy models not to be overwhelmed by photometric redshift systematics. No calibration technique employed so far has come close to this limit; addressing this issue is one of the top priorities from the recent interagency Dark Energy Task Force. It currently appears that photometric redshift calibration will be the primary obstacle for a variety of Dark Energy experiments both of the current generation (commonly referred to as "Stage III" surveys) and the next generation such as LSST ("Stage IV" surveys). This will be a difficult challenge: the largest spectroscopic surveys on existing telescopes are only able to obtain secure redshifts for 40–70% of their targets, making all calibration samples systematically incomplete.

This grant funded further development of a new technique (described in Newman 2008) which can provide the needed calibration even in the presence of large incompleteness. Photometric redshift systematics a negligible issue. This method can calibrate photometric redshifts (also known as "photo-z's") with high precision, even if it is only possible to obtain spectroscopic redshifts for a bright, biased subset of the galaxies at a given redshift (which is generally the case), and even if the true, underlying spectra of galaxies at high redshift are unknown (Newman 2008). This technique relies on the fact that all galaxies – from the faintest to the brightest –

cluster together on large (~ 1 Megaparsec, i.e. $\sim 3 \times 10^{22}$ m) scales, as galaxies reside in dark matter concentrations, commonly known as "halos", which themselves cluster together in space. As a result, those galaxies in a spectroscopic sample that are at a given, known redshift will cluster on the sky with the subset of galaxies in some sample that are at or near that redshift, but not with closer or more distant objects. We can exploit this fact to accurately determine the true redshift distribution of objects in the sample, which is the information required for calibrating dark energy experiments.

In particular, this grant funded tests of this technique and development of optimized methods using realistic mock survey catalogs based on the Millennium Simulations (Croton et al. 2006).

This technique proved effective in our tests, though errors were greater than expected due to the presence of an error term which is commonly ignored in large-scale structure in the weak-clustering limit, but proves to have nonnegligible impact. This error term becomes negligible if a relatively large area of sky (~ 1000 sq. deg.) is surveyed; hence wide-area surveys like BigBOSS would be ideal for applying this technique.

Photometric redshift calibration via cross-correlation will enable extremely large cost savings for future experiments. For instance, even obtaining 90% (not 100%) complete spectroscopy for a set of targets down to the LSST photo-z sample magnitude limit would require more than 150 nights on one of the Keck telescopes (with value of more than 5 million dollars, based on amortized costs and operations budget); but with current instruments, that would yield only ~ 100 redshifts, out of at least 20,000 required for LSST calibration with such techniques. Clearly, a new instrument would be required; a ~ 2500 -fiber spectrograph for Keck might be feasible, but would cost a minimum of \$100 million, and more than 4 years' worth of Keck time (considering weather losses), worth more than \$40 million, would still be needed.

By contrast, cross-correlation methods can utilize redshifts of much brighter objects that are much easier to obtain. Planned overlap between BigBOSS and LSST would be sufficient; that instrument would cost of order \$40 million, time has already been allocated for the survey, and it would simultaneously provide a unique and powerful test of dark energy via the baryon acoustic oscillation methods. The resulting cost savings are tremendous.

Comparison of Accomplishments to Goals:

The U. Pittsburgh portion of our collaborative proposal (UC Davis PI: Tony Tyson) was focused on testing and further developing cross-correlation techniques for photometric redshift calibration. These techniques can be used to calibrate redshift distributions for observed samples, even for objects too faint to ever obtain statistically complete spectroscopy for, which will be vital for both Stage III and

Stage IV dark energy surveys.

The first task for this project was completed essentially as planned: a University of Pittsburgh graduate student working with me, Dan Matthews, has used realistic mock catalogs produced from the Millennium Simulations (Croton et al. 2006) to select samples which emulate both a set of objects in a single photometric redshift bin and a spectroscopic sample consisting of a fraction of the bright galaxies in each mock catalog. He has applied cross-correlation techniques to reconstruct the true redshift distribution of the photometric sample using only the clustering of galaxies in the mock catalogs, including only the same information available to the real observer. We have found that cross-correlation techniques accurately reconstruct the true redshift distribution, though with errors 2-4 times larger than those estimated by Newman 2008. The increased errors turn out to be associated with an extra contribution to the variance which is ignored in most work in the field, but was previously identified by Bernstein (1994); the result is that larger (or at least wider-area) spectroscopic samples than previously estimated (though still well within range of what is currently planned) will be required to apply cross-correlation techniques to calibrate Stage IV surveys.

Dan completed a paper on the results during this grant's term. This work was also presented in posters at the Summer AAS conference in Pasadena in 2008.

However, the next stage -- applying cross-correlation techniques to calibrate photometric redshifts in state-of-the-art datasets -- did not occur during this grant's term. This is partially because our original timeline was overambitious, as it took some time for graduate student Dan Matthews to get up to speed. A second cause was the fact that photometric redshifts for AEGIS were slow in coming from other members of the collaboration. However, the largest reason is simply that we instead focused on attempting to develop methods to mitigate the extra error term, as this would have particularly strong impact on tests with AEGIS data (which consists of a single field of limited size). Dan spent roughly a year exploring a variety of techniques, largely based on work by Padmanabhan et al.; ultimately, we achieve a roughly factor-of-two reduction of errors from his original work, though this occurred after this grant's timespan.

Fig. 1: Locations on the sky of those objects within a limited range ($\Delta z = 0.04$) of redshift (or, equivalently, distance away from us) from a simulation of dark matter galaxy evolution (Croton et al. 2006). The region shown is a square 2 degrees (roughly 4 times the diameter of the Full Moon) across. Blue points indicate fainter objects with imaging (photometric) observations but no spectroscopy, while red points correspond to objects in a smaller, brighter spectroscopic sample. The locations of both sets of galaxies trace the same underlying web of dark matter which dominates the large-scale structure of the Universe; as a result, both classes of objects cluster together on the sky. Figure made by Dan Matthews.

Project Activities

Some relevant details are provided under Comparison of Accomplishments to Goals, above. We used the general approach of testing techniques directly with simulations that are as realistic as possible. The Millenium mock catalogs of Croton et al. do include a state-of-the-art implementation of the physics of galaxy evolution, which yields a relationship between galaxies and dark matter at least as complicated as that present in the actual Universe, though the mock catalogs fail to match reality in detail.

The key problems encountered were 1) bringing a student whose background was in condensed matter physics up to speed on this project; and 2) the presence of additional error terms which had been ignored in most work in the weak-clustering regime (for the last 30 years, essentially). Determining the origin of this additional error component (e.g. showing it was not due to some bug in code) and exploring its impact took a considerable amount of time.

Examples of products of Dan's work are shown in the included figures; see Matthews & Newman 2008 for more details.

Fig. 2: A demonstration of the effectiveness of cross- correlation techniques in realistic mock catalogs from Croton et al. (2006). Plotted are the true redshift distribution for a faint galaxy sample (solid) and the median and 1-sigma range of the distribution recovered with cross- correlation techniques (points and error bars) when using a spectroscopic sample of bright galaxies in four 0.5×2 degree fields to do the reconstruction. The recovery is accurate in the mean, with larger errors than in the model of Newman 2008 due to variance in clustering on large scales. Figure made by Dan Matthews.

Products developed:

Publications:

D. J. Matthews & J. A. Newman 2010, “Reconstructing Redshift Distributions with Cross-correlations: Tests and an Optimized Recipe,” *Astrophysical Journal*, volume 721

Networks or collaborations fostered:

The work funded by this grant helped lead to a substantial portion of the photometric redshift discussion in the LSST Science Book. The discovery that large-area surveys are key to cross-correlation techniques helped lead to Jeffrey Newman joining the BigBOSS collaboration in 2009.

Software

Daniel Matthews developed and tested a complete suite of correlation-function-measurement software (including angular autocorrelations, three-dimensional autocorrelations, and angular cross-correlations) through funding from this grant.