Understanding the Fundamental Properties of Dark Matter & Dark Energy in Structure Formation and Cosmology

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1 Introduction

The program is concerned with developing and verifying the validity of observational methods for constraining the properties of dark matter and dark energy in the Universe. This is the final of three annual reports on progress achieved.

Excellent progress has been made in comparing observational projects involving *weak gravitational lensing* using both ground and space-based instruments, in further constraining the nature of dark matter via precise measures of its distribution in clusters of galaxies using *strong gravitational lensing*, in demonstrating the possible limitations of using *distant supernovae* in future dark energy missions, and in investigating the requirement for ground-based surveys of *baryonic acoustic oscillations*.

The grant has been used primarily to provide support for a very productive postdoctoral researcher - Dr Richard Massey. A small amount of funding has covered research done under Caltech's summer undergraduate research program (Mikelsons) and a visitor program (High - Harvard; Refregier & Bergé - CEA, Paris; Leauthaud - Marseille; Sullivan - Toronto; Nugent - LBL).

Strong collaborative programs have continued with others at JPL (Seiffert, Rhodes), Caltech (Gal-Yam), Arizona (Sand), UC Santa Barbara (Treu), in Japan (Miyazaki, Suto) and the UK (Lahav, Peacock, Smith). Much of the dark energy studies fall under the umbrella collaboration of the SNAP mission (LBL PIs: Levi, Perlmutter) - a strong contender for the DoE/NASA Joint Dark Energy Mission (JDEM).

During this 9 month reporting period, 16 refereed papers have appeared or been accepted, a further 4 submitted for publication. 5 further papers are nearing completion.

2 Gravitational Lensing

Weak gravitational lensing utilizes the distorted shapes of thousands of faint background galaxies to infer the foreground distribution of dark matter. Slicing the background population via photometric redshifts enables the growth of structure to be measured and this, in turn, represents a powerful measure of the balance between gravity and dark energy. We have made particularly good progress in this area, both technically through comparative tests of simulations, and scientifically in demonstrating the first time-dependent dark matter signal with actual faint data. A major thrust is the technical evaluation of the future prospects for weak lensing as a dark energy probe via the analysis of both simulated and real data.

Weak lensing can also be used to locate individual dark matter halos and hence to count their distribution in space and time. With the addition of strong lensing constraints, the dark matter distribution can be determined over both the linear and non-linear regimes for comparison with numerical simulations. Good progress has also been made in these areas.

2.1 Weak Lensing

Caltech has maintained a leading role in the Shear TEsting Program (STEP), an expanding, worldwide collaboration of groups interested in the technical aspects of weak lensing. Various simulated datasets are generated whose weak lensing 'shear' is known *a priori*. The collaborating groups run independent analysis codes on these datasets in a blind manner and the results are collated and analyzed. A second STEP collaboration meeting was held in Pasadena in August 2007. The STEP collaboration is now focused on examining biases associated with space-based measurements (the so-called Space-STEP project); this work is being led by J. Rhodes (JPL) but with strong Caltech participation. To overcome the biases and limitations of current shear measurement methods, we are continuing to develop the Caltech "shapelets" pipeline, which is now better able to deal with the effects of image pixelation.

Studies of real (as opposed to simulated) datasets at Caltech have moved forward from our demonstration in 2007 of 3D tomography in the HST COSMOS field[1]. Noting the high fidelity of HST data, we have directly compared the imaging performance of a premier ground-based facility, the Subaru 8m telescope, in the same 2 deg^2 area. This study represents the first concerted effort to compare, quantitatively, a ground- and spaced-based dataset for weak lensing (Kasliwal et al). The study complements work done under the STEP program described above because it is based on a comparison of actual, rather than idealized, data. Our shear comparison demonstrates the significant increased surface density of useable background galaxies achieved with a space-based platform and discusses the implications for proposed deep 3D tomography experiments. We also undertook independent searches for cluster halos and cataloged their derived masses.Here the Subaru data is reasonably adequate in comparison with HST.

We also derived tighter constraints on the dark energy equation of state parameter w by combining our 3-D tomography studies in the HST COSMOS data with those of the intergalactic Lyman-alpha forest (Lesgourgues et al.). These two very different experiments were seen to give consisttent results; however, the dark matter is again observed to be more clustered than that indicated from measures of the Cosmic Microwave Background (CMB). This study also led to the online publication of a module for the popular COSMO-MC package (Lewis & Bridle, Phys. Rev. D, 66, 103511, 2002), to calculate the expected cosmic shear signal for a variety of cosmological models. This has made cosmic shear data accessible to the wider cosmological community, allowing non-experts to include constraints from weak lensing in their analyses.

The merit of counting clusters as a probe of dark energy and other cosmological parameters is under continuing investigation in a survey spanning 22 deg^2 undertaken with Japanese collaborators using the prime focus camera, SuPrime-Cam, on the Subaru 8-m telescope. Weak shear has been measured across this survey and $\simeq$100 massive clusters have been located as peaks in the resulting convergence (projected dark matter) maps. The redshift distribution and relative masses of these halos provides a valuable pilot study of the possibility of constraining cosmological parameters.

In Miyazaki et al., we publish a detailed analysis of 25 clusters located via weak lensing where X-ray and galaxy velocity dispersion data are available for calibration purposes. This paper demonstrates convincingly the reliability of selecting clusters via weak lensing. In Green et al. we extend the catalog to a larger sample with less precise ancillary data and use the redshift distribution and cluster counts to

[1]A result recently hailed as one of the top 10 science stories of 2007 by *Discover Magazine*

realistically assess the challenges of constraining dark energy from cluster surveys. In the latter work, we see some evidence for a systematic 'dilution' of the highest convergence peaks, which we believe is due to contamination of the source (i.e. background) galaxy population by cluster galaxies. These complex systematics, which present important caveats for future ground and space-based cluster surveys, have only come to light due to the quality of the Subaru imaging data and wide area covered by the survey.

Using weak lensing data from the Canada-France-Hawaii telescope, we have also calibrated cluster masses from X-ray data for systems 4 times less massive than hitherto. The relationship between the observed X-ray temperature and a cluster's total mass remains consistent with model predictions. However again, intriguingly, this study indicates a higher level of clustering than that predicted from the CMB. Additional data from the Subaru survey discussed above will clarify this discrepancy.

Our work on analyzing the impact of point spread function (PSF) uncertainties and charge transfer (in)efficiency (CTE) in Hubble data has become the standard reference in the community. Together with our already popular 'shapelets' method for shear measurement, this means that the Caltech group is widely sought after for collaborative programs in gravitational lensing. We have embraced these opportunities as not only does additional science get done but it also increases knowledge in the broader US community about the opportunities offered by lensing. It also brings additional HST imaging data to our group, data that would not be available to us given the demise of the Advanced Camera for Surveys.

With Gavazzi et al., we have investigated the distribution of mass in the extended wings of early-type galaxies. We find that the inner luminous material and outer dark matter components conspire to produce the overall "isothermal" mass distribution. With Bradac et al. we are analyzing the mass distributions in galaxy clusters that have recently undergone major collisions that may provide vital additional examples like the 'Bullet Cluster' in which the dark matter is viewed distinctly from the baryonic component.

Turning to technical progress, we have also investigated the use of higher order measures of shear, such as the so-called "flexion" signal which represents the non-elliptical nature of an image induced by lensing. The flexion signal is particularly strong near the cores of galaxy clusters and along the line of sight of any substructure: two locations in which the exact distribution of mass is a powerful discriminant between different types of dark matter. Consequently, we have developed a new method to measure the flexion signal (Massey et al.) and successfully detected signals for the first time. Leonard et al. detected the flexion signal in HST images around a massive galaxy cluster. Rowe et al. measured the cosmic flexion signal in the blank HST GEMS field. Work is now being led at at Caltech to analyse the flexion signal in the much larger COSMOS field. An attempt has also been made to use the flexion method to investigate apparent discrepancies between strong and weak lensing signals seen in the 'Bullet Cluster' (Massey & Goldberg)

In parallel with this series of papers applying the flexion technique to real datasets, a FLexion Improvement Programme (FLIP) has been set up by Massey, alongside the STEP program. The idea, as with STEP, is to calibrate algorithms for recovering, in a blind manner, the flexion signal. The ability to include a known flexion signal has been incorporated into Caltech's image simulation pipeline, and a first set of simulated images has been distributed to three external groups. Initial results demonstrate the validity of our first detections, and the variations realized will enable us to improve our measurement methods in the coming year.

Work is now beginning to improve our correction algorithms for of charge transfer (in)efficiency (CTE) in astronomical data. CTE proved one of the most troublesome hardware flaws of the HST COSMOS data for lensing analysis, and it worsens with time. The Caltech/JPL group are developing a pixel-by-pixel correction scheme for HST data that will be essential for any lensing analysis if the Advanced Camera for Surveys can be repaired during Servicing Mission 4 in September 2008. We are also investigating the limitation that this will impose on the lifetime performance of the proposed SNAP satellite, and working with the detector/hardware groups to investigate possible mitigation techniques.

2.2 Strong Lensing

Lensing also contains valuable information on the *distribution of dark matter* for comparison with numerical simulations. Here, individual clusters of galaxies act as excellent 'laboratories'. The goal of this work is to use strongly lensed features of known redshift in the cores of clusters to constrain the *small scale distribution* of dark and baryonic matter, and weak shear to determine the *large scale behavior*. Theoretically, we expect the dark matter to follow the so-called Navarro-Frenk-White (NFW) profile. Although the literature is full of observational analyses supporting this profile, in most cases the datasets are simply insufficiently precise to provide a robust test.

During the reporting period, we completed a definitive study of the dark matter radial profile over large scales in Abell 1689 based on Canada France Hawaii telescope data (Limousin et al). We are now working on analysis of an unique HST ACS mosaic of the rich cluster MS0451-03 (Smith et al). This will complement an earlier mosaiced WFPC-2 study made of the cluster Cl0024+16 (Kneib et al, Ap J 598, 804, 2003). Until recently, these 3 clusters remained the only well-studied examples where the NFW profile could be reliably tested on large scales.

On smaller scales, where non-linear effects and separating baryons and dark matter become important, we have continued to examine strong lensing and stellar dynamical data for two clusters (Abell 383 and MS2137-03, Sand et al.). Here we found convincing evidence that dark matter does *not* follow the precise form postulated in the latest numerical simulations.

In a significant new development we have now secured exquisite data from Subaru for 10 clusters for which both strong *and* weak lensing data is now available. This data, just being analyzed by a new graduate student (A. Newman) represents a significant advance over the piecemeal progress done earlier. For each cluster, Keck and Magellan spectroscopy has defined the strong lensing geometry and the Subaru imaging defines the large scale distribution.

In a parallel effort, we have collaborated with Naranjan et al to explore the effect the dark matter potential in clusters has upon the halos associated with individual galaxies. Across a dynamic range corresponding to cluster-centric radii 0 to 5 Mpc we see a clear signal of the tidal destruction of dark matter halos on infalling field galaxies.

The foreground observational studies represent the frontier in our current understanding in how dark matter is distributed over scales from $\simeq$10 kpc to 5 Mpc.

3 Distant Supernovae

Supernovae of type Ia (SNe Ia) represent the most well-explored tool for probing dark energy. The primary goal of the work funded via this grant at Caltech in this area is to verify their future use as precision probes of the cosmic expansion history. Given supernovae are events that occur in evolving stellar populations, a key issue is whether there is some form of 'systematic floor' in their calibration and application, arising perhaps from time evolution in their behavior, intrinsic dispersion in their properties or hitherto unknown correlations in their properties with redshift or their host galaxy characteristics.

During the reporting period we reached a milestone in this program by publishing (Ellis et al) the first detailed study of possible evolution in the spectral properties of SNe Ia. In a 4 year survey of over 50 SNe selected mostly within the redshift range $0.4< z <0.6$ from the Canada France Hawaii SN Legacy Survey (SNLS), we examined the case for evolution in the mean spectrum with look-back time as well as the dispersion from one event to another. In our study we focused in particular on the *rest-frame ultraviolet spectra* which, according to contemporary models, act as a valuable proxy for *metallicity* changes - the most likely evolutionary variable.

Our unique high redshift data demonstrate a remarkably similar mean spectrum at $\overline{z} \simeq 0.5$ to that observed locally, giving considerable reassurance to their use in cosmology over the redshift range $0< z <0.8$. In a further development, we have recently compared our spectra with those in much higher redshift SNe Ia spectra secured with the ACS grism (Sullivan et al, in prep) whose mean redshift is $\overline{z} \simeq 1.3$. Reassuringly, there is only marginal evidence for evolution over $0.5< z <1.3$.

However, although there is little evidence for a systematic evolution in the SN Ia spectra over the past 10 Gyr, there is a very large dispersion in UV behavior from one event to another. Attempts to correlate these variations with the light curve shape and host galaxy luminosity have had only limited success. Such a large intrinsic dispersion could represent a major hurdle for future missions, particularly those targeting SNe beyond redshift 1, where the UV signal is crucial in determining the cross-color k-correction.

The Keck spectroscopic dataset represents a substantial step forward in supernova research. The individual spectra have higher quality than many local examples, especially in the rest-frame ultraviolet where most of the key diagnostic features occur. Work is now proceeding to archive this data and to collaborate with leading supernova modeling groups to physically understand the trends seen.

4 Baryonic Oscillations

Finally, we have completed a detailed study of the feasibility of tracing dark energy by measuring, at various redshifts, the scale of baryonic oscillations in the large scale distribution of galaxies. This represents possibly the cleanest method for tracing dark energy although the instrumental and observational requirements may be formidable.

The PI has formed a strong collaborative science team to begin consideration of this issue. Together with Suto (Tokyo), Lahav (UC London) and Peacock (Edinburgh), he organized a further meeting in Edinburgh to evaluate quantitatively the constraints that might emerge from a possible future survey of $\simeq 10^7$ redshifts at $z \simeq 1$ with a 8-m ground-based telescope.

Work within Caltech Optical Observatories and JPL (not funded by this grant) has completed a conceptual study to define a robotic means for positioning 2500-3000 fibers across a 1.5 deg^2 field to secure the required number of redshifts in $\simeq$200-400 nights of observing time on the Subaru 8 meter telescope.

As a result of this international collaboration, Japanese interest in the Caltech cosmology program has been considerably enhanced and Prof. Suto has succeeded in securing national support for furthering this collaborative effort. Discussions are continuing with the newly-formed Institute for Physics and Mathematics of the Universe at Tokyo University (`http://www.ipmu.jp/`).

5 Refereed Publications from this Award During the Reporting Period

1. *Astrometric Perturbations in Substructure Lensing*, Chen, J., Dalal, N., Taylor, J. E., & Rozo, E., *Astrophys. J.*, **659**, 52 (2007)

2. *A Statistical Study of Multiply-imaged systems in the Lensing Cluster Abell 68*, Richard, J., Kneib, J-P., Jullò, E., Covone, G., Limousin, M., Ellis, R.S., Stark, D.P., Bundy, K., Czoske, O., Ebeling, H. & Soucail, G. it Astrophys. J., **662**, 781-796 (2007)

3. *The Stability of the Point Spread Function of the Advanced Camera for Surveys on Hubble Space Telescope: Implications for Weak Gravitational Lensing*, Rhodes, J., Massey, R.J., Albert, J., Collins, N.,, Ellis, R.S., Heymans, C., Gardner, J.P., Kneib, J-P., Koekemoer, A., Leauthaud, A., Mellier, Y, Refregier, A., Taylor, J.E. & Van Waerbeke, L., *Astrophys. J. Suppl.*, **172**, 203-218 (2007)

4. *Weak Gravitational Lensing with COSMOS: Galaxy Selection and Shape Measurements*, Leauthaud, A., Massey, R.J., Kneib, J-P., Rhodes, J., Johnston, D.E., Capak, P., Heymans, C., Ellis, R.S., Koekemoer, A., Le Fevre, O., Mellier, Y., Refregier, A., Robin, A., Scoville, N., Tasca, L., Taylor, J.E. & van Waerbeke, L. *Astrophys. J. Suppl.*, **172**, 219-238 (2007)

5. *COSMOS: 3D Weak Lensing and the Growth of Structure*, Massey, R.J., Rhodes, J., Leauthaud, A., Capak, P., Ellis, R.S., Koekemoer, A., Refregier, A., Scoville, N., Taylor, J.E., Albert, J., Berge, J., Heymans, C., Kneib, J-P., Mellier, Y., Mobasher, B., Shopbell, P., Tasca, L. & van Waerbeke, L., *Astrophys. J. Suppl.*, **172**, 239-253 (2007)

6. *Gravitational Shear, Flexion and Strong Lensing in Abell 1689*, A. Leonard, D. Goldberg, J. Haaga & R. Massey 2007, *Astrophys. J.*, **666**, 51 (2007)

7. *The Sloan Lens ACS Survey. IV: The Mass Density Profile of Early-type Galaxies out to 100 Effective Radii*, Gavazzi, R., Treu, T., Rhodes, J., Koopmans, L., Bolton, A., Burles, S., Massey, R.J. & Moustakas, L., *Astrophys. J.*, **667**, 51 (2007)

8. *Solving the Abell 1689 Puzzle: A Combined Strong and Weak Gravitational Lensing Analysis*, Limousin, M., Richard, J., Kneib, J-P., Jullo, E., Fort, B., Soucail, G., Eliasdottir, A., Natarajan, P., Smail, I., Czoske, O., Hudelot, P., Bardeau, S., Ellis, R.S., Ebelin, H. & Smith, G.P., *Astrophys. J.*, **668**, 643-666 (2007)

9. *Subaru SuPrime-Cam Weak Lensing Survey - I: Cluster Candidates and Spectroscopic Verification*, Miyazaki, S., Hamana, T., Ellis, R.S., Kashikawa, N., Massey, R.J. Taylor, & Refregier, A., *Astrophys. J.*, **669**, 714-728 (2007)

10. *Weak Gravitational Shear and Flexion with Polar Shapelets*, Massey, R.J., Rowe, B., Refregier, A., Bacon, D.J. & Bergé, J. 2007, *Mon. Not. Roy. astr. Soc.*, **380**, 229 (2007)

11. *A Combined Analysis of Lyman-α forest, 3D Weak Lensing and WMAP Year Three data*, Lesgourgues, J., Viel, M., Haenhelt, M. & Massey, R.J., *J. Cosm. Astroparticle Phys.*, **11**, 8 (2007).

12. *Pixellation Effects in Weak Lensing*, High, F.W., Rhodes, J., Massey, R.J. & Ellis, R.S., *Publ. Astron. Soc. Pac.*, **119**, 1295-1307 (2007)

13. *Weak Lensing Ellipticities in a Strong Lensing Regime*, Massey, R.J. & Goldberg, D., *Astrophys. J. Lett.* in press (astro-ph/0709.1479)

14. *Separating Baryons and Dark Matter in Cluster Cores: A Combined 2D Lensing and Dynamic Analysis of MS2137-23 and Abell 383*, Sand, D.J., Treu, T., Ellis, R.S., Smith, G.P. & Kneib, J-P, *Astrophys. J.*, in press (astro-ph/0710.1069)

15. *Verifying the Cosmological Utility of Type IA Supernovae: The Effect of a Measured Dispersion in Ultraviolet Properties*, Ellis, R.S., Sullivan, M., Nugent, P.E. , Gal-Yam, A. & Howell, D.A., *Astrophys. J.*, in press (astro-ph/0710.3896)

16. *Combined Analysis of Weak Lensing and X-ray Blind Surveys*, Bergé, J., Pacaud, F., Refregier, A., Massey, R.J., Pierre, M., Amara, A., Birkinshaw, M., Paulin-Henriksson, S., Smith, G.P. & Willis, J., *Mon. Not. Roy. astr. Soc.*, in press (astro-ph/0712.3293)

Articles Submitted for Publication

17. *A Comparison of Weak Lensing Measurements from Ground- and Space-Based Facilities*, Kasliwal, M., Massey, R.J., Ellis, R.S., Miyazaki, S. & Rhodes, J., *Astrophys. J.*, submitted (astro-ph/0710.3588)

18. *Light Curves of Five Type Ia Supernovae at Intermediate Redshift*, Amanullah, R., Stanishev, V., Goobar, A., Schahmaneche, K., Astier, P., Balland, C., Ellis, R.S., Fabbro, S., Hardin, D., Hook, I.M., Irwin, M.J., McMahon, R.G., Mendez, J.M., Mouchet, M., Pain, R., Ruiz-Lapuente, P. & Walton, N.A., *Astron. Astrophys.*, submitted (astro-ph/0711.1375)

19. *The Survival of Dark Matter Halos in the Cluster Cl0024+16*, Natarajan, P., Kneib, J-P., Smail, I., Treu, T., Ellis, R.S., Moran, S., Limousin, M. & Czoske, O., *Astrophys. J.*, submitted (astro-ph/0711.4587)

20. *Multicolor Image Simulations with Shapelets*, Ferry, M., Rhodes, J., Massey, R. & Ellis, R.S., *Astropart. Phys.*, submitted

Articles in Preparation

21. *The Subaru SuPrime-Cam Weak Lensing Survey - II: Exploring the Potential of Mass-Selected Clusters as a Cosmological Probe*, Green, A., Taylor, J., Ellis, R.S., Massey, R.J., Miyazaki, S., Hamana, T., Refregier, A., in preparation

22. *New, Old and Combined Supernova Datasets for Cosmological Measurements*, Kowalski, M., Rubin, D., Agostinho, R.J., Aldering, G., Amadon, A., Amanullah, R., Balland, C., Barbary, K., Bl;anc, G., Conley, A., Connolly, N.V., Dawson, K., Deustua, S.E., Ellis, R.S., Fadeyev, V., Fan, X., Farris, B., Folatelli, G., Frye, B.L., Garavini, G., Gates, E.L., Goldhaber, G., Goldman, B., Goobar, A., Groom, D.E., Haissinski, J., Hardin, D., Hook, I., Kent, S., Kim, A. G., Knop, R.A., Lidman, C., Linder, E.V., Mendez, J., Meyers, J., Miller, G.J., Moniez, M., Mourao, A-M., Newberg, H., Nobili, S., Nugent, P.E., Pain, R., Perdereau, O., Perlmutter, S., Prasad, V., Quimby, R., Regnault, N., Rich, J., Richards, G.T., Ruiz-Lapuente, P., Santos, C.A., Schaefer, B.E., Spadafora, A.L., Strovink, M., Suzuki, N., Walton, N.A., Wang, L., Wood-Vasey, W.M. & Yun, J.L., in preparation

23. *A Test for Evolution in the Mean Spectrum of Type Ia Supernovae*, Sullivan, M., Ellis, R.S., Riess, A., Nugent, P., Howell, A. & Gal-Yam, A., in preparation

24. *The Distribution of Baryons and Dark Matter in the Massive Cluster MS0451-03 at z=0.54: Analysis of a Unique Panoramic ACS Mosaic*, Smith, G.P., Marshall, P., Ellis, R.S., Treu, T. & Moran, S., in preparation

25. *Flexion Analyses in the HST GEMS Field*, Rowe, B., Massey, R.J., Heymans, C., Bacon, D.J. & Taylor, A., in preparation

26. *Weak and Strong Lensing Mass Reconstruction in Colliding Galaxy Clusters*, Bradac, M., Treu, T., Marshall, P. & Massey, R.J., in preparation