The Dark Matter Telescope

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Abstract. Weak gravitational lensing enables direct reconstruction of dark matter maps over cosmologically significant volumes. This research is currently telescope-limited. The Dark Matter Telescope (DMT) is a proposed 8.4 m telescope with a 3° field of view, with an etendue of 260 m\(^2\) deg\(^{-2}\), ten times greater than any other current or planned telescope. With its large etendue and dedicated observational mode, the DMT fills a nearly unexplored region of parameter space and enables projects that would take decades on current facilities. The DMT will be able to reach 10\(\sigma\) limiting magnitudes of 27-28 magnitude in the wavelength range \(3 - 1\mu m\) over a 7 deg\(^2\) field in 3 nights of dark time. Here we review its unique weak lensing cosmology capabilities and the design that enables those capabilities.

1 Breaking Degeneracies, Testing Foundations

Direct information on cosmology – and thus on the early history of the universe – can in principle be obtained by measuring the spectrum of mass as it evolves with cosmic time. The current set of cosmological models (cf. Zaldarriaga et al. 1997, Hu 1998, Turner & Tyson 1999), has over ten free parameters. Each type of observational test encounters degeneracies among the parameters that cannot be resolved without additional information. Measuring the mass distribution at redshifts 0.2–1 breaks this degeneracy because it is sensitive to different parameter combinations than is the cosmic microwave background (CMB). More importantly, such observations and their concordance with the CMB results will provide an independent test of the validity of the entire theoretical framework.

From work spanning more than five decades, it has become apparent that light and mass are not identically distributed. It is now possible to discover mass concentrations that are not evident in the light distribution. Ultimately, such studies will define the distribution of mass on a variety of scales. What do the inferred dark mass concentrations imply for cosmological simulations that are normalized to the number density of luminous mass concentrations? Such questions will not be addressed by spectroscopic surveys, even those as large as the Sloan survey.

The only way to directly “weigh” the mass distribution is through weak gravitational lensing. In its simplest form, gravitational lens distortions of the distant galaxies enables a reconstruction of the projected mass density map for the intervening lens. But one can do even better: photometric redshifts enable us to slice the projected sky in redshift bins. By obtaining weak lensing maps for sources at a variety of redshifts, we could obtain a three-dimensional mass map of
the universe back to half its current age. This is called cosmic weak gravitational lens mass tomography. In addition to enabling a measurement of the geometry of the universe, a weak lensing survey will also lead to an understanding of the relationship between mass and light on galactic and cosmological scales.

Because structure on the scale of $\sim 120$ Mpc exists, only a survey that samples mass in volumes significantly larger than 120 Mpc on a side will provide a definitive, representative measurement of the distribution of mass. Moreover, a form of dark energy – quintessence – should itself clump on several hundred Mpc scales, so that a direct mass survey covering tens of degrees (for mass-energy at redshift 0.5) would probe this. The metric size of the mass structures, and the redshift at which they most powerfully lens 24-27 mag background galaxies, sets the angular scale for each field. In fact, the best way to ensure a fair sampling of the universe is to study several such large, well-separated fields.

Pilot weak lensing surveys are currently underway, but due to the limitation of existing facilities and time, such studies can at best cover only much smaller areas (in fewer colors) than the definitive survey discussed here. One requires good angular resolution over a 3° field, coupled with the light gathering power of an 8 m class mirror. However, the 8 m class telescopes now coming online fall far short of the field-of-view requirement. The DMT could reach the required depth of 29.5–28 mag arcsec$^{-2}$ throughout the wavelength range 0.3-1 micron (driven by the need for color redshift resolution) over a 1000 deg$^2$ area using half the dark nights over five years, whereas such a survey on existing 8 m telescopes would take half a century.

The various direct observational tests of cosmology (weak lensing, CMB anisotropy, and SNe) separately and in combinations can remove model degeneracies or uncover model failures. For example, a 1000 deg$^2$ weak lensing project without any photometric redshift information can only determine $\Omega_{\text{matter}}$ to $\pm 0.3$ and $\Omega_{\Lambda}$ to about $\pm 0.5$, because these parameters affect the formation of structure in compensating ways. Including photometric redshift information breaks this degeneracy through a measurement of the redshift evolution of structure; errors on the parameter can in principle be reduced to $\pm 0.02$ and $\pm 0.04$ for $\Omega_{\text{matter}}$ and $\Omega_{\Lambda}$ respectively. The degeneracy can alternately be broken by CMB anisotropy observations on angular scales of less than 1 deg. Recently, the BOOMERANG experiment results were announced, showing that the universe appears to be flat to within ten percent. Assuming there are no difficulties due to scattering from the reionization epoch, even higher accuracy CMB observations over the whole sky are coming in several years (MAP satellite), and even more cleanly later with the Planck satellite data. The combination of weak lensing (with photometric redshifts) and CMB data provides a sharp consistency test for the theory. In addition the combination would constrain most of the parameters (e.g. Turner & Tyson, 1999) of current theories substantially better than either alone.

Taken together with the weak lensing survey and upcoming MAP CMB anisotropy results, a program of SN Ia observations can put strong constraints on the equation of state of the contributions to the mass-energy of the uni-
verse, which would easily discriminate between most of the current contenders: constant vacuum energy density (dark energy) vs. variable dark energy (quint-essence) vs. topological defects of various kinds. Next-generation deep wide-field SN photometric surveys, covering a range of redshifts within the same calibrated survey, will make a significant advance. The Dark Matter Telescope will discover and follow thousands of SNe per year. Accurate multi-color photometry on 3000 high redshift SNe per year will be obtained in the deep survey mode, and 200,000 moderate redshift SNe will be found in the wide-deep mode, per year. Finally, including the results on large-scale structure as reflected in the luminous local baryonic component (e.g. Sloan survey) will yield a complete picture of the development of the rich structure we see around us.

2 Cosmology with Weak Lensing

For more than thirty years, the search for cosmic shear, or weak gravitational lensing by large-scale structure, was stymied by limitations in instruments (e.g. Kristian 1967; Valdes, Tyson & Jarvis 1983; Mould et al. 1994). Advances in instruments (large mosaics of sensitive and linear CCDs, coupled with better telescope image quality) and data reduction techniques (cancellation of point-spread function anisotropy) stimulated the first detections of cosmic shear (Wittman et al. 2000; van Waerbeke et al. 2000; Bacon et al. 2000; Kaiser et al. 2000). Figure 1 illustrates the detection of Wittman et al. and the predictions of three cosmological models. The four papers agree roughly with each other and with the predictions of $\Lambda$CDM, but the error bars are large; only SCDM can be ruled out on the basis of the current weak lensing measurements alone. However, when these preliminary results of weak lensing cosmic shear are combined with the latest cosmic microwave background determinations of a nearly geometrically flat universe, the $2\sigma$ region of concordance suggests that $0.25 < \Omega_m < 0.5$ and that the cosmological constant is non-zero and in the range $0.4 < \Omega_\Lambda < 0.8$. A dramatic increase in accuracy for this cosmic shear measurement will occur in just a few years.

The next generation of cosmic shear measurements is already underway and will provide smaller errors over larger angular scales. The Deep Lens Survey (http://dls.bell-labs.com), for example, will cover seven 2° square fields, while the first-generation measurements used 40' fields at best. At large scales, cosmic variance is expected to be the dominant source of error, so covering a number of different fields is critical. This project has been granted a large amount of telescope time (86 nights on 4 m telescopes), reflecting the increasing importance of cosmic shear measurements, but that time is stretched over five years. Several other groups have surveys underway, and they all seem to be telescope-time limited.

In most physics experiments, one has the ability to repeat measurements while chopping possible sources of error. Although astronomers are limited in this respect due to the great distances of their sources, they are also limited by a lack of telescope time. Weak lensers could (indeed, should) repeat their
Fig. 1. The cosmic shear detection of Wittman et al. (2000), showing the correlations of $e_1 = e \cos(2\beta)$ and $e_2 = e \sin(2\beta)$ (where $e$ is the ellipticity and $\beta$ is the position angle) for pairs of distant galaxies as a function of angular separation $\theta$. The predicted correlations depend on the redshift of the source galaxies and on the cosmological model. The measured correlations are plotted here with the predictions of three cosmologies for their best estimate of the source redshift distribution: $\Lambda$CDM (solid line), SCDM (short-dash), and OCDM (dotted). The long-dash line shows the effect of a 20% error in the mean source redshift for $\Lambda$CDM. A cosmological model must match both autocorrelations; SCDM is ruled out at many sigma by $\langle e_1 e_1 \rangle$, while $\Lambda$CDM and OCDM match $\langle e_1 e_1 \rangle$ very well and are consistent with $\langle e_2 e_2 \rangle$ at the 3-sigma level. The cross-correlation $\langle e_1 e_2 \rangle$ (not shown) is consistent with zero, as expected in the absence of systematic error. The Deep Lens Survey now in progress will provide a much stricter test of cosmological models, or suggest the need for new models. As shown in the next two figures, the 8.4 m DMT deep weak lensing data will lead to precision measurements of the mass spectrum and will tightly constrain several cosmological parameters, independent of the SN observations.
measurement in a different area of the sky, at different wavelengths, under different atmospheric conditions, with different exposure times, and so on; but they normally do not, simply because of insufficient telescope time. Any hope of doing precision cosmology rests on semi-dedicated facilities which can repeat the measurement numerous times under different conditions, chopping sources of systematic error on the relevant timescales. The design of such a facility is driven by the need to survey large amounts of sky fairly rapidly, and in the next section we introduce such a design in some detail. Figure 2 shows how accurately a weak lensing survey on such a telescope would measure the shear power spectrum, and Figure 3 demonstrates how such a survey, when combined with data with NASA’s MAP mission, breaks degeneracies on numerous cosmological parameters.

3 Telescope Design

3.1 Optics

In given integration time, the size of field larger than $\Omega$ that can be explored to given depth is directly proportional to the figure of merit $A\Omega\eta/d\Omega$, where $A$ is the collecting area, $\Omega$ the solid angle of the field of view, $\eta$ the detector quantum efficiency and $d\Omega$ the solid angle of the seeing-limited image. Today’s 8 m class telescopes are superb at optimizing all of these factors except $\Omega$. Conventional designs, including Schmidt telescopes and other corrected systems based on one or two mirrors, are incapable of wide fields at the fast focal ratios required to match detector requirements and minimize overall cost.

Fundamental to any design are the image size and detector pixel size, which set the focal length. At good sites, the atmosphere will deliver 0.5 arcsec images, while CCDs with 13–15 $\mu m$ pixels are likely to provide enough full well capacity. For Nyquist sampling of 0.5 arcsec images, a plate scale of 50–60 $\mu m$ arcsec$^{-2}$ is required. This implies a focal length of 10–12 m, or a speed of up to f/1.25 for an 8m primary. Conventional designs, including Schmidt telescopes and other corrected systems based on one or two mirrors, are incapable of wide fields at so fast a focus.

However, three-mirror designs with this capability were first explored by Paul (1935). He gave a design with a parabolic primary, convex spherical secondary and a concave spherical tertiary of equal but opposite curvature. The image is formed midway between secondary and tertiary, with good correction over a wide field. One can think of the design as a reflective Schmidt telescope used as a corrector for a large afocal Cassegrain telescope. The secondary, located at the center of curvature of the tertiary, has added correction for spherical aberration similar to a reflecting Schmidt plate. A telescope of this type was built by McGraw et al. (1982), using a 1.8 m parabolic primary at f/2.2, giving images no more than 0.2 arcsec rms diameter at the edge of the field. In addition, an all-reflective design is critical for reducing the scattered light problems that accompany a large field of view.
Fig. 2. Projected errors in the convergence power spectrum from a 1000 square degree survey with the Dark Matter Telescope, shown attached to the predictions of $\Lambda$CDM. The shaded region on the right is where current theory for nonlinear evolution is unreliable. Courtesy W. Hu.

Angel et al. (2000) used this design as the starting point for exploring more general three-mirror systems using computerized optimization. An optimum design balances obscuration and field of view to maximize etendue or $A\theta$ product for given primary aperture. They found that very well corrected fields of up to $3^\circ$ diameter could be formed at f/1.15 using the three mirrors alone. The mirrors are arranged so the light from the secondary passes through a half-diameter hole in the primary to a near-spherical tertiary behind, and the light comes to a focus near the primary vertex (Figure 4). To minimize the secondary obscuration, the primary focal ratio was held at f/1.0. Detector obscuration was minimized by making the primary and secondary together afocal. When the $3^\circ$ field is
Fig. 3. Combining the results of the 1000 square degree survey with MAP data breaks degeneracies and pinpoints several cosmological parameters to much greater accuracy. The numbers just above the horizontal axis are the estimated errors of MAP alone. Courtesy W. Hu.

3.2 Sky Baffling

Through most of the telescope’s spectral range, up to 1.8µm, its sensitivity is limited by photon noise from optical emission by the atmosphere. To prevent additional skylight from reaching the focal surface indirectly, two black conical baffles will be used. The first, 4 m in diameter, extends 0.5 m below the secondary...
mirror. The second, 3.8 m diameter, rises 1.1 m above the primary hole. These two give complete sky baffling out to the full 3° field.

3.3 Mechanical Considerations

The optical assembly for an 8.4 m primary is short, only 9 meters between the secondary and tertiary, with the primary and camera set midway between. This configuration is advantageous both for making an agile telescope and an inexpensive enclosure. All three large mirrors would be stiffly mounted between two C rings, supported on a compact azimuth frame that transmits loads directly to a large diameter pier (Figure 4). The stiffness of the drives gains by the square of the C ring radius, and we find that the large semicircular rings shown, 11 m diameter, coupled with the relatively small moment of inertia lead to excellent tracking and stability. Repointing by 3° in a time as short as 5 seconds is realistic. The telescope enclosure will be smaller and hence less expensive than for a standard 8 m telescope, because of the small turning radius.
Fig. 5. The proposed DMT rigid, fast-slewing mount. The three mirrors are held between large C rings turning on a flat azimuth platform. The relatively short telescope, given its 8.4 m primary mirror, translates to a low cost dome.

3.4 Camera

CCD detector arrays are now a rather mature technology, and there is little doubt that a mosaic to cover the full 55 cm circular focal surface can be built for acceptable cost. Covering the 3° diameter field of view with 0.25 arcsec pixels (to provide critical sampling in the best seeing) requires 1.4 Gpix. The individual CCDs will be small, 1k or perhaps 2k, so that the circular field and the curvature of the focal plane can be matched precisely. This multiplexing also allows for fast readout, which will be critical for efficiency, as exposure times must be short, ~ 30 s, to avoid saturation. The CCD array will be 55 cm in diameter, in a dewar with a robust fused silica vacuum window. This
window (plus any filter) is the only refractive element in the system, so that the scattered light resulting from bright stars in the huge field will be minimized. The aberrations that would be introduced by this element are balanced by adjusting the prescriptions of the three mirrors.

A significant issue for CCDs is the control of charge blooming from bright stars. Deep wells, anti-blooming measures and the use of many smaller devices will all be important control measures. We shall suppose that detectors with 13 $\mu$m pixels (0.25 arcsec) are used. These should be manufacturable with deep wells; already full well as high as 150,000 electrons has been demonstrated for 8x8 $\mu$m pixels. In the near future, 13 $\mu$m pixels could be optimized for still greater capacity. Anti-blooming capabilities can be incorporated in the detectors, which may reduce the full well capacity. Alternatively, anti-blooming clocking schemes may be used during integrations. To avoid uncontrolled blooming from the brightest stars, (a few really bright stars will be inevitable in a 3$^\circ$ field), a large number of smaller format devices may be preferred. These could be as small as 1024 pixels square, in which case 1300 devices would be needed to tile the 55 cm diameter focal plane. We find that the read time should be no more than 5 seconds, requiring a realistic 200 kHz pixel rate to read each 1024 square device with a single amplifier.

As a way to minimize the gaps between the individual CCDs we are presently exploring detector packaging techniques which will allow the use of true, 4-side buttable devices using semiconductor industry standard packaging technologies. This development would limit the inter-device gaps to the non-imaging silicon of each detector, which is dominated by clock busses, amplifiers, and, most significantly, I/O bonding pads. With the continued industry-wide trend toward smaller I/O structures, it is not unreasonable to expect 50$\mu$m bond pads to be sufficient for future CCDs. If we therefore assume uniform gaps of 100 $\mu$m around each CCD, a fill factor of 96% can be obtained.

Cooling requirements are not severe for the CCD mosaic. The criterion is that the dark rate be less than the sky photon rate in the darkest filters. We estimate that even for the 360-nm band or the narrowest 3% filter that photon rates will be $> 1.5e^-$/pixel/sec. With an MPP device, dark rates less than this can be achieved at a device temperature of about -15 C. It follows also that in the worst case of a 20 second exposure in a dark band a read noise of $\sim 4 e^-$ rms will be acceptable.

While certainly a very large number of devices are required for this project, the CCDs themselves could be manufactured today. The DC shorts yield of several fabrication lines is now over 50%. If 50% of these unshorted thick CCDs are of astronomical quality, a mature lot run will yield about 25% usable devices from 6" silicon wafers at a typical fab facility. Assuming a 25-50% thinning and packaging yield, the final thinned device yield would be about 5-10% of the starting lot. This would then require about $\sim 200$ wafers to be fabricated with 100 devices per wafer, after one or two engineering and test lots. Cryogenic DC and AC wafer probing will allow rapid feedback to the fabricator on device quality and yield.
3.5 Comparison with some Existing and Proposed Imaging Telescopes

The etendue at the 3° focal plane of the Dark Matter Telescope is 260 m² deg². The most powerful imaging telescope currently in operation is the Sloan Digital Sky Survey. It has a modified Cassegrain system with 2.5 m aperture and a 3° field at f/5. Comparing the 8.4 m telescope with the SDSS, and allowing also for its increased pixel sampling and resolution, the advantage in figure of merit is by a factor of close to 100. The wide field optical cameras to be used with larger telescopes, such as Subaru’s Suprime and MMT’s Megacam have etendues which are not substantially larger than the SDSS, in the range 5 - 10 m² deg². This telescope will provide a capability that is completely beyond any existing telescope and uncovers a region of parameter space orders of magnitude beyond current limitations. The Dark Matter Telescope design and capabilities are discussed in more depth on the website http://dmtelescope.org.

4 Sensitivity and Observing Strategies

We have estimated imaging sensitivity by scaling the 10σ point source magnitude limits in the Johnson photometric bands U - I (0.35 - 0.90 μm) derived ab-initio by Angel et al. (1999) to an 8.4 m telescope. These included the blurring effects of atmospheric seeing and dispersion at 45° elevation. These limiting magnitudes are listed in Table 1. For this 8.4 m telescope, the red limiting magnitude for a 20 sec exposure is just sufficient for an all-available-sky survey (sharing time with the deep survey) to detect and confirm 90% of the near-Earth objects in a decade.

| Band | λ(mm) | 20 second exposure | 9 hour exposure |
|------|-------|--------------------|-----------------|
| U    | 0.365 | 22.8               | 26.8            |
| B    | 0.44  | 23.8               | 27.8            |
| V    | 0.55  | 23.9               | 27.9            |
| R    | 0.70  | 23.6               | 27.6            |
| I    | 0.90  | 22.8               | 26.8            |

Because the exposure time is limited to about 30 s to avoid CCD saturation, the deep imaging needed for lensing work must be accumulated over many exposures. This observing mode also makes the data useful for many other projects which require short exposures. The search for near-Earth objects and outer solar system objects will benefit greatly, and a vast amount of parameter space will be opened up in the search for GRB counterparts and previously unknown types of optical transients. A thorough search for high-redshift supernovae (which break
the degeneracy in cosmological parameters in a different way than weak lensing) can also be carried out with this data. The traditional mode of observing must give way to a dedicated program, with the community sharing the data.

The depth of the 20 second exposures suggests one possible observing mode: repeatedly surveying the entire observable sky to 24th magnitude in 3-4 nights. Assuming the readout is accomplished while the telescope is repointed in 5 seconds, 144 exposures an hour could be obtained in clear weather, and the 3000-exposure survey would take about 22 hours, i.e. 3-4 nights. Image differencing between successive surveys will reveal variable and moving objects, and image summation over many such surveys will provide deeper images. About half the time would also be dedicated to extremely deep multi-band images over smaller regions, such as the several thousand square degrees required for the wide-deep cosmology projects described above. The last column in Table 1 gives the limiting magnitudes for 9 hours of exposure, assuming that sensitivity increases as the square root of the integration time. In a week of clear weather, a single 3° field could be observed to the given depth in each of the five filters, for accurate photometric redshifts. The high etendue corresponding to the 8.4m aperture permits the parallel execution of these two observing modes, completing both the all-sky search and the ultra-deep projects within a decade.

The data rate from a 1.4 Gpix camera with 30 s exposures sounds prodigious—over 1 TB per night—yet such data rates are commonplace in radio astronomy and particle physics. Routine image processing on large images is easily parallelized and ideally suited to clusters of inexpensive, commodity computers, especially given the parallel nature of the readout. Data storage on commodity hardware will also be feasible by the time of DMT operation.

5 Summary

Weak gravitational lensing can break the degeneracies in CMB anisotropy measurements of cosmological parameters. To provide comparable precision, weak lensing needs a dedicated or semi-dedicated telescope facility. We propose the Dark Matter Telescope, a 8.4 m telescope with a 3° field of view and good image quality, providing an unprecedented figure of merit for deep surveys. After discussing the design and observing strategy, we conclude that such a telescope is feasible now, and show its potential impact on cosmology.

This proposed facility embodies a non-traditional approach to ground-based optical/IR astronomy: equal emphasis is placed on the survey products, their unique science capability and distribution to the community, the data pipeline, the camera and data system, and the telescope. As such, this project would be pursued in a manner similar to those of experimental high-energy physics. The 8.4 m aperture and 7 deg² field enable huge advances in other areas as well: planetary astronomy (Kuiper belt objects and near-Earth objects), and the transient universe (gamma-ray burster afterglows over large volumes, and new classes of objects). In the ranked projects in the recent NRC AASC Decadal Survey for Astronomy, the DMT was named the “Large-area Synoptic Survey
Telescope” (LSST) to emphasize its complementary applications and multiple missions.

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