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Image analysis for cosmology: Shape measurement challenge review & results from the Mapping Dark Matter challenge☆

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ABSTRACT

In this paper we present results from the Mapping Dark Matter competition that expressed the weak lensing shape measurement task in its simplest form and as a result attracted over 700 submissions in 2 months and a factor of 3 improvement in shape measurement accuracy on high signal to noise galaxies, over previously published results, and a factor 10 improvement over methods tested on constant shear blind simulations. We also review weak lensing shape measurement challenges, including the Shear TEsting Programmes (STEP1 and STEP2) and the GRavitational lEnsing Accuracy Testing competitions (GREAT08 and GREAT10).

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1. Introduction

Image analysis in cosmology is a process that involves taking pixelised and noisy images of objects, extracting information from them, and using these to infer properties of the large scale structure of the Universe. This is of paramount importance for the endeavour of understanding dark matter and dark energy, those phenomena whose mass–energy account for approximately 26% and 70% of the Universe respectively and whose fundamental nature is entirely unknown. Of particular interest is *weak lensing* that has been identified as one of the primary tools with which we can map the large scale structure and evolution of the Universe (see reviews e.g. Albrecht et al., 2006; Peacock et al., 2006; Massey et al., 2010; Bartelmann and Schneider, 2001; Weinberg et al., 2012 and references therein).

Weak lensing is the effect whereby the integrated mass along the line of sight acts through gravitational tidal forces to induce

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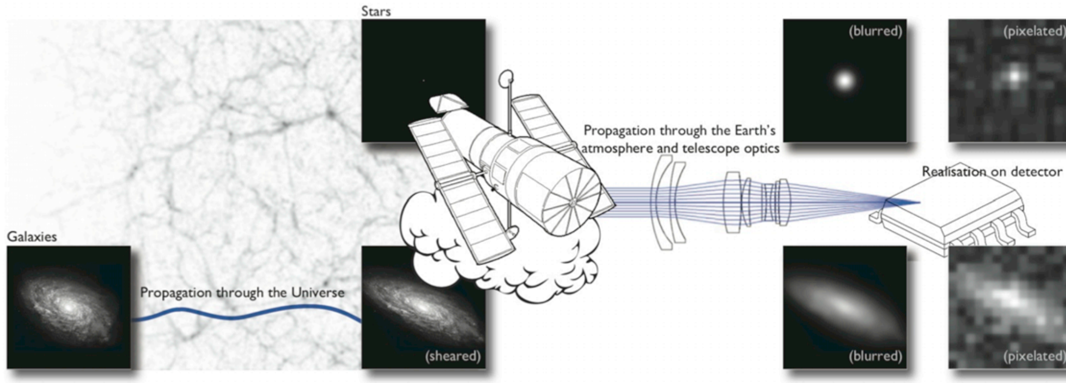

Fig. 1. As light propagates through the large scale structure of the Universe an additional ellipticity 'shear' is imprinted on a galaxy's observed image. We observe sheared galaxies in the presence of a blurring convolution kernel (PSF), pixelisation from detectors and in the presence of noise. Shape measurement algorithms must be designed that measure the ellipticity of galaxies in the presence of these effects to enable the statistical properties of the shear field to be inferred. Star images can be used to estimate the PSF, since they approximate a point-source response to the convolution and pixelisation but are not affected by the shear.
Source: This figure is reproduced from the GREAT10 Handbook (Kitching et al., 2011) with permission.

an additional ellipticity to the observed light profile of an object, this additional ellipticity is called shear. Distant galaxies have a measurable additional ellipticity, because of the large amount of integrated mass along the line of sight, but local objects do not. If we can therefore measure the ellipticity of distant galaxies we can make statistical statements about the properties of the intervening distribution of matter; see Fig. 1. These statements are necessarily statistical because for an individual object the additional ellipticity cannot be disentangled from the object's 'intrinsic' (un-sheared) ellipticity. The ellipticity of any object can be measured, but to make matters worse galaxies are inherently elliptical themselves However we can assume that on average there is no preferred orientation for galaxies in the Universe, that the mean ellipticity should be zero if there were no intervening mass. Therefore by averaging over many galaxies any residual shear can then be attributed to the matter distribution. In general cosmological information comes not from the mean but the variance of the ellipticities (see Kitching et al., 2011).

In fact there are two 'modes' of using weak lensing data to investigate the dark matter distribution, both are statistical but treat the data and observations in different ways. One is a 'holistic' measure (we use the word in its meaning of emphasising the importance of the whole and the interdependence of its parts) where power spectra/correlation functions are created: one averages over all galaxies in a survey and determines the two-point (or more generally n-point) functions and compares these to theoretical predictions. The second approach is 'atomistic' where we also look at individual mass peaks and make dark matter maps: one identifies individual objects of interest (e.g. galaxy clusters) and generates a visual map of dark matter.

The task of measuring the weak lensing effect is particularly difficult because of noise in the images, pixelisation, and that we do not know in detail how to model the surface brightness distribution of undistorted galaxies. As a result of these difficulties many methods have been proposed to measure the weak lensing effect, either using direct model-independent pixel-level extraction of parameters (for example Kaiser et al., 1995; Melchior et al., 2011) or using forward modelling of the galaxies (for example Kuijken, 1999; Refregier, 2003; Miller et al., 2007; Kitching et al., 2008).

Importantly for weak lensing, to test the ability of a method to extract the shear information from an ensemble of galaxies we cannot take an observation that removes the shear effect, and because of the statistical nature of the shear information we cannot compare the fidelity of an individual object's inferred shear against what we would have hoped to observe in the presence of perfect data. This is in contrast to photometric redshifts for example where a spectra of an individual object can be taken and compared to the photometrically inferred redshift estimate. To test shape measurement methods we therefore must have accurate simulations whose aim is to test fidelity of these methods under controlled conditions.

Within the weak lensing community a number of such simulations were started and run as competitions/challenges (the Shear TEsting Programme, STEP; Heymans et al., 2006 and Massey et al., 2007a) under blind conditions, which are a necessity so that algorithms cannot be tuned with calibration factors. Reaching beyond the weak lensing community these competitions were opened up to public participation (the GRavitational lEnsing Accuracy Testing, GREAT08 and GREAT10; Bridle et al., 2009 and Kitching et al., 2012) in an effort to spawn new ideas and approaches to this algorithmic challenge. In this article we will review previous shape measurement challenges, we will also present results from the most widely participated and successful of these to date, the Kaggle[1] Mapping Dark Matter challenge, which attracted over 700 submissions in two months and saw an improvement in the achieved accuracy of shape measurement methods by a factor 3, over previously published results (Bernstein, 2010; Gruen et al., 2010), and a factor 10 improvement over methods tested on blind simulations (STEP and GREAT08, GREAT10). If the challenge of shape measurement can be overcome then current surveys such as KiDS (de Jong et al., 2013), DES,[2] HSC[3] and future surveys such as Euclid[4] (Laureijs et al., 2011), AFTA-WFIRST (Spergel et al., 2013) and LSST,[5] promise to revolutionise cosmology by measuring the dark matter distribution and expansion history of Universe to unprecedented accuracy.

This article is arranged as follows in Section 2 we will review shape measurement challenges STEP and GREAT, and we refer the reader to Kitching et al. (2011, 2012) for a full review of the GREAT10 challenge. In Section 3 we will present the Mapping Dark Matter challenge simulations and results as well as some commentary on the nature of setting crowdsourcing challenges in astronomy. In Section 4 we will discuss conclusions.

2. Shape measurement challenges

Because we can never observe the unlensed ellipticity of objects algorithms that attempt to measure shear parameters must be

1 http://www.kaggle.com/c/mdm.
2 www.darkenergysurvey.org.
3 http://www.naoj.org/Projects/HSC/.
4 http://euclid-ec.org.
5 http://lsst.org.

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