Cosmology with Shear Selected Galaxy Clusters

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Large Synoptic Survey Telescope

LSST has the potential to identify over a hundred thousand galaxy clusters from weak lensing shear maps. This cluster sample will have statistically well-controlled mass estimates, and can place precise and robust constraints on cosmological parameters. We use a Fisher matrix approach to forecast the level of these constraints. We utilize cosmological N-body simulations to include the mass-shear relation, including its scatter and false projections. We find that by combining measurements of the evolution of cluster abundance, (dN/dz), and the spatial power spectrum, (P[k]), degeneracies among cosmological parameters, and also between cosmological parameters and systematic errors in the analysis, can be broken, yielding percent-level constraints on individual parameters. We focus on the evolution of the dark energy equation of state w(z), and on a measurement of the neutrino mass Σm_ν. Combining the cluster data with CMB anisotropy measurements by Planck results in tighter constraints than possible from either experiment alone. The LSST cluster constraints are also complementary to those from LSST shear tomography and from SN studies.

1. Cluster Selection

- **Weak gravitational lensing (WL)** is the small distortion of the images of background galaxies by the foreground mass distribution, quantified for small distortions by the tangential shear γ_T. The benefit of WL selection of clusters for cosmological studies is that the mass-observable relation (*i.e.* between shear and mass), can be accurately calibrated from simulations. The details of an eventual selection procedure that also depends, *e.g.*, on galaxy properties of WL cluster candidates, will have to be understood to comparable accuracy to avoid systematic biases.

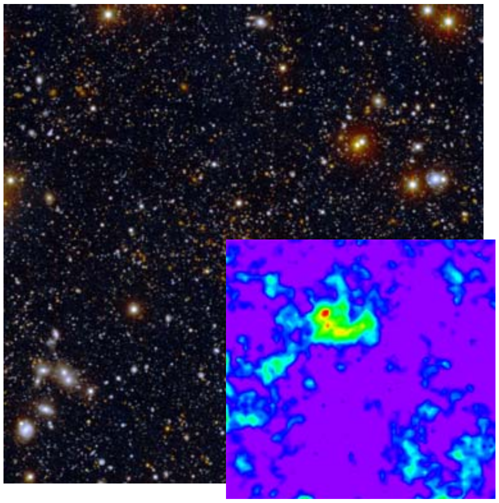

Figure 1: Field in Deep Lens Survey *reveals galaxy cluster in smoothed shear map.*

- **Galaxy Cluster Selection.** Galaxy clusters can be selected as a set of peaks in a smoothed two-dimensional shear map (see Fig. 1). Using a filter with angular scale θ_G we identify peaks above a threshold ν_T corresponding to a multiple of the noise, $\gamma_T = \nu_T\sigma_\varepsilon$. Here σ_ε is the uncertainty in the mean intrinsic ellipticity of the galaxies within a smoothing aperture. The correspondence between peaks and clusters is imperfect due to (a) missing a fraction of the real clusters, and by (b) false detections of over-dense structures, projected along the line of sight. These effects are quantified by the *number of real clusters detected* (clusters that produce peaks with $\nu \geq \nu_T$), and the *purity* (fraction of peaks that correspond to real clusters).

- **Selection Criteria from Simulations.** We analyzed N-body simulation data (due to White & Vale, Astroparticle Physics, 2004) to quantify the statistics of the correspondence between *real clusters* and *peaks* in the shear map, for various choices of filter shapes and size, and for various values of ν_T. These statistics can be computed *ab initio* and change only statistical errors on the derived cosmological parameters.

2. Error Forecasts

- **Survey Specifications.** We assume the survey covers 20,000 square degrees, and detects galaxy clusters to redshift of 1.4 (out to which photometric redshifts will be available). We adopted the fitting formula for the mass function from Jenkins *et al.*, MNRAS (2001), which results in a total of ~200,000 clusters. In the future, when results from LSST are available, greatly improved N-body simulations will determine the mass function far better than the Jenkins approximation. Residual non-gravitational effects due to baryons will have a small effect on the mass function and may have to be determined from the data. We assume the power spectrum of the clusters is boosted according to the halo bias of Sheth and Tormen, MNRAS (1999).

- **Fisher Matrix Formalism.** We computed the 1σ uncertainties using the Fisher matrix formalism, and assumed a fiducial ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_b = 0.045$, $w_0 = -1$, $w_a = 0$, $\Omega_\nu = 0$, $h = 0.7$, $\sigma_8 = 0.9$, and $n_s = 1$. We studied constraints on the evolution of the dark energy equation of state $w(a)=w_0+w_a(1-a)$ (Fig. 3) and the contribution of neutrinos to the energy density Ω_ν (Fig. 4). A flat universe was assumed ($\Omega_m + \Omega_{DE} = 1$).

- **Tomography and Optimal Filtering.** We adopt a smoothing scale of 1 arcmin and a threshold $\nu_T = 5$, which correspond to detection of 10 clusters/deg^2 with purity of 75% (star-shaped symbols, Fig. 2, from Kehayias, Wang, and May, in preparation). The calculation was done by using the LSST computer cluster with 72 processors (Haggerty and Throwe) and it shows that the selection efficiency can be significantly improved by using tomography (see Hennawi and Spergel, Astrophys. J., 2005), *i.e.* to use a matched filter that weights the contribution of the lensing from different redshifts to the shear signal, optimized given the photometric redshifts of the background sources.

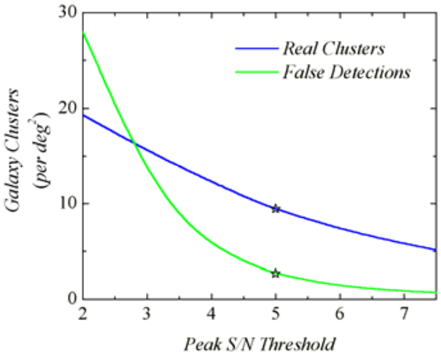

Figure 2: Cluster Selection from Tomography. *Blue curve shows the expected number of real clusters detected by LSST using tomography and various signal thresholds; green curve shows the false detections due to projection effects and intrinsic ellipticity noise of the source galaxies.*

3. Conclusions

- **Dark Energy.** We find the dark energy properties can be constrained to $\Delta w_0 = 0.037$, $\Delta w_a = 0.12$ and $\Delta\Omega_{DE} = 0.0037$, from LSST clusters alone. These numbers include a 50% increase in errors from the uncertainties on completeness and purity, and are marginalized over all other parameters. We find that dN/dz contains most of the information on w_a, while P(k) substantially improves the constraints on w_0. Adding Planck to the LSST data results in relatively modest improvements (Fig. 3, from Wang *et al.*, Phys. Rev. D, 2004).

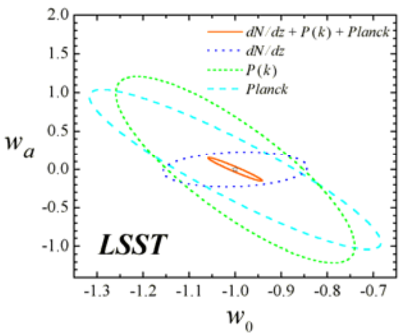

Figure 3: Constraints on Dark Energy Equation of State. *The contours are marginalized over all other relevant parameters.*

- **Neutrinos.** We find a sensitivity on the sum of all neutrino species $\Sigma m_\nu = 0.36$eV from LSST clusters alone. Most of the information on neutrinos is in P(k), but adding information from dN/dz results in ~30% improvement. Adding WMAP or Planck data further improves the Σm_ν constraints by a factor of 3 or 10, respectively. LSST + Planck results in the limit $\Sigma m_\nu = 0.031$eV. Since this is above current lower limits on the mass of at least one neutrino species from atmospheric neutrino oscillation experiment (~0.05eV), detection of a non-zero neutrino mass is very possible at this sensitivity (Fig. 4, from Wang *et al.*, Phys. Rev. Lett. 2005). An independent constraint on the sum of neutrino masses is achievable from the shear tomography + Planck at a similar level of precision (Song and Knox 2004); combining this with our result can yield an even tighter bound.

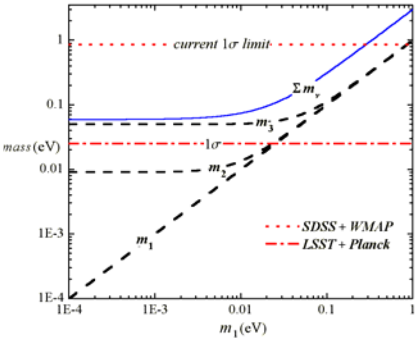

Figure 4: Constraints on Neutrino Mass. *The blue curve corresponds to the constraints from current neutrino oscillation experiments; dash-dot orange line at 0.03eV shows the expected sensitivity on the sum of three neutrino masses from LSST.*

4. New Method

We have developed a new method using the statistics of the high shear regions (regardless of whether they correspond to real clusters or not) directly to constrain the cosmology hence avoiding the missing and false cluster problem (Wang, Haiman, and May, in preparation).

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