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Strong Lensing by Galaxy Clusters and ΛCDM

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Abstract. We discuss how strong lensing by galaxy clusters may be used to study the properties of dark matter halos and the expansion history of the universe. First, we show how the characteristics of ΛCDM clusters determine their lensing properties, and show how these properties are manifested in some of the new giant arcs discovered behind SDSS clusters. Next, we compare the statistics of strong lensing by clusters expected in the ΛCDM model to the observed statistics of giant arcs and wide-separation quasars. Finally, we discuss the cosmographic uses of clusters with multiple arcs, pointing out several sources of noise which can produce $\gtrsim 100$ % errors in derived cosmological parameters.

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1. Strong lensing by dark matter halos in the ΛCDM model

Numerical simulations of mass clustering in the cold dark matter (CDM) model appear generically to predict the following properties for dark matter halos :

(a) Radial density profiles steeper than isothermal on large scales, but significantly shallower than isothermal on small scales (Navarro *et al.* 1997, hereafter NFW).

(b) Triaxial profiles with typical axis ratios of order $c/a \sim 0.6$ (Jing & Suto 2002).

(c) Copious mass substructure, with $\lesssim 10\%$ of typical halo mass comprised of gravitationally self-bound subhalos (Klypin *et al.* 1999).

There is a large scatter in these properties among halos of a given mass. Dynamically young systems, like galaxy clusters, tend to have especially strong triaxiality and substructure, and tend to have low central density concentrations. All of these properties depend upon DM properties, as departures from the simplest CDM models (e.g Bode *et al.* 2001; Spergel & Steinhardt 2000) produce different levels of substructure, triaxiality, etc. So by measuring halo profiles, axis ratios, etc., we can probe the nature of dark matter particles.

The strong lensing properties of CDM halos are directly determined by the above-mentioned properties. First, because CDM halos are *marginal* lenses (with shallow radial profiles), their lensing properties are extremely sensitive to halo mass, concentration, and so on. This can easily be understood using the following argument. For spherical lenses, the critical curves (where images are created or merge together) occur at the radius where the average interior surface density equals the lensing critical density, $\bar{\Sigma}(r_{\rm crit}) = \Sigma_{\rm crit}$; this is approximately true for aspherical lenses as well. Because the density profiles are shallow, $r_{\rm crit}$ is a steep function of the normalization of Σ. For example, for the NFW profile, the central density behaves as $\rho \propto r^{-1}$, so $\Sigma \propto \log r$, implying that $r_{\rm crit}$ is exponentially sensitive to mass and concentration.

This fact, combined with the strong triaxiality and abundant substructure in cluster-sized halos, also implies that the critical radii and lensing cross section vary significantly with viewing angle. Orientations which project substructures onto small radii, or which

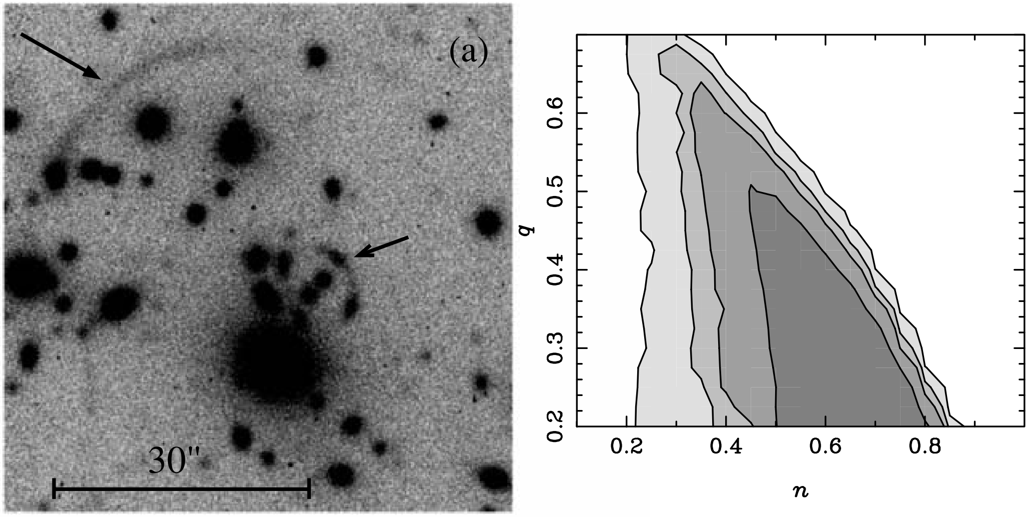

Figure 1. (Left) One of the strong lensing SDSS clusters. The arrows indicate the two unambiguous arc systems. (Right) Preliminary constraints from fits to ellipsoidal power-law models with $\Sigma \propto R^{-n}$, with radial slope n and axis ratio q.

view clusters down their major axes, can have cross sections an order of magnitude larger than orientations which do not (Dalal *et al.* 2004b).

Marginal lenses are also rather unstable to perturbations from ellipticity or external shear. A simple way to understood this is that the critical lines form at the locations where $1 - \kappa \pm |\gamma| = 0$, so if we add extra shear γ to a lens with slowly varying $\kappa(r)$, the critical lines must move a large distance in r for κ to compensate the change in γ. Accordingly, the critical lines for marginal lenses (like NFW lenses) are affected much more strongly than the critical lines for lenses with steep (e.g. isothermal) profiles. For a fixed ellipticity in the density, making the radial profile shallower increases the ellipticity of the critical lines. For shallow profiles like NFW, the critical radius can be a factor of $\sim 2-3\times$ larger along the major axis than the minor axis; see Dalal & Keeton (2003) for a discussion of the perils of neglecting ellipticity!

2. SDSS Lenses

We have undertaken a survey of the richest clusters in the Sloan Digital Sky Survey to look for giant arcs (Hennawi *et al.* 2004, in prep.). Our SDSS clusters typically have redshifts $z \gtrsim 0.2$, although our highest redshift lensing cluster is at $z = 0.68$. At present, we have found giant arcs behind ~ 50 % of the clusters we have observed, and these lenses already exhibit some of the properties described in the previous section. To illustrate, we show in Fig. 1 a strong lensing cluster at $z = 0.286$. We have labeled two unambiguous arc systems, one on the major axis at $\sim 30''$ radius and the other on the minor axis at $\sim 10''$. Note that the minor axis arc consists of three merging images. Tellingly, the major-axis arc occurs at much larger radius than the minor-axis arc; as discussed above, this requires high ellipticity / shallow radial profile. To illustrate this, we plot in Fig. 1 constraints from preliminary modeling of this system with a simple ellipsoidal power-law profile, $\Sigma \propto R^{-n}$. As expected, high ellipticity and small n are required by the data.

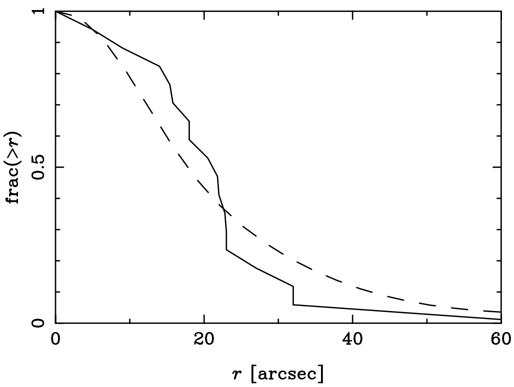

Figure 2. Observed (solid) and expected (dashed) radial distribution of giant arcs.

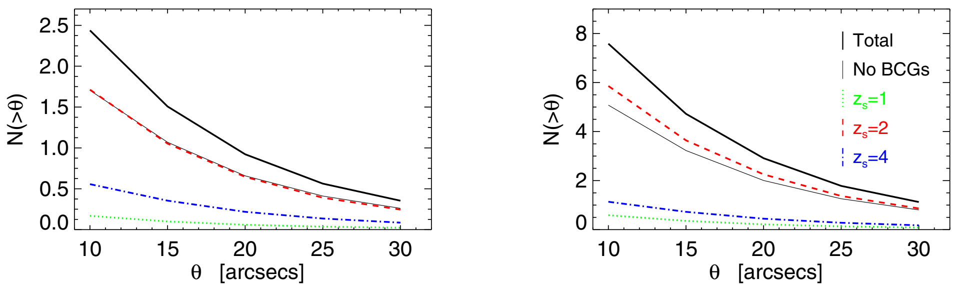

Figure 3. Predicted number of wide-separation QSO lenses expected in the SDSS, for the (left) spectroscopic and (right) photometric samples.

3. Arc statistics

With the SDSS and other ongoing lensing surveys (e.g. RCS-2, see talk by M. Gladders at this meeting), we will soon have a large catalogue of strong lensing clusters against which we can compare theoretical predictions. At present, the largest arc survey with well-defined selection criteria has been for EMSS clusters (Luppino *et al.* 1999). To compare, we have computed theoretically expected arc statistics by ray-tracing through N-body simulations of the ΛCDM model (Dalal *et al.* 2004b). In general, we have found good agreement between theoretical predictions and observed arc statistics. For example, the total number of giant arcs observed by Luppino *et al.*, if extrapolated over the full sky, would correspond to ~ 900 arcs, while our ray-tracing simulations produce ~ 1000 arcs over the full sky. The arc properties also appear to agree reasonably with expectations; for example, Fig. 2 shows the expected and observed radial distributions of giant arcs.

In addition, we can also compare with the statistics of observed wide-separation QSO lenses, as the lensing population is the same as that for giant arcs. To date, only one such system has been discovered, SDSS J1004+4112 with a splitting of $14.6''$ (Inada *et al.* 2003, also see talk by M. Oguri at this meeting). In comparison, the expected statistics of such objects is shown in Fig. 3. In the SDSS spectroscopic quasar sample, we expect ~ 2 wide-splitting QSO lenses, in good agreement with the observed number (one). Interestingly, we expect many more to be found in the deeper photometric sample.

For the future, we can expect giant arcs to provide accurate measurements of the density profiles for a wide selection of clusters, which should provide a stringent test of

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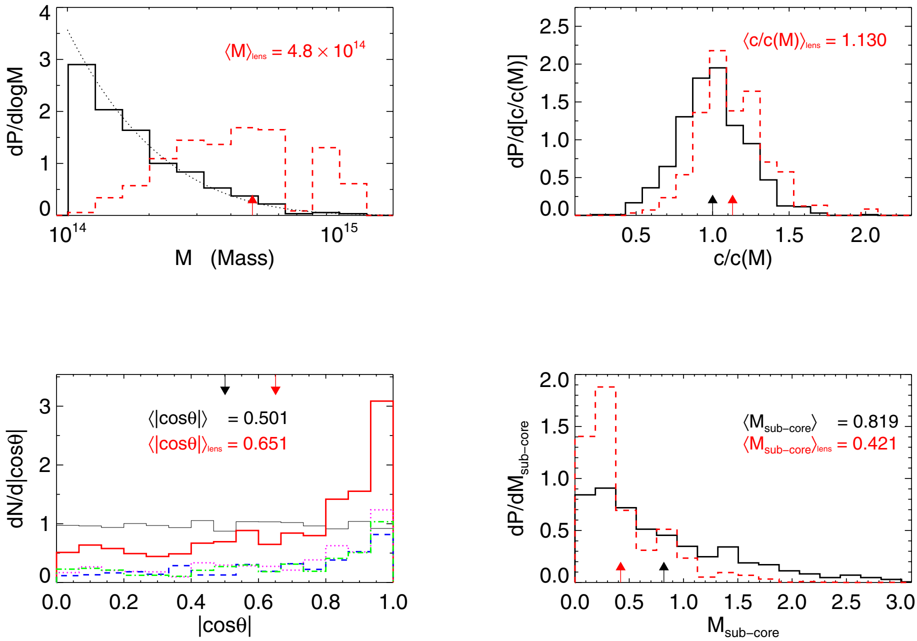

Figure 4. Histograms of cluster properties for all clusters (black, solid) and for lensing clusters (red, dashed). Going clockwise from upper left, we show histograms of mass, concentration (in units of the mean $c_{\rm vir}$ for each mass), substructure mass, and orientation angle.

the ΛCDM model. Before comparing to N-body simulations, however, it is important to note that strong lenses are a highly biased selection of clusters. In Fig. 4 we illustrate some of these biases. For instance, strong lenses are much more massive, and somewhat more concentrated than average clusters. They are also viewed preferentially down their major axes, which further biases upward the mass and concentration inferred from the projected surface density. Perhaps most interestingly, there appears to be a strong, highly significant *anti*-correlation between lensing cross section and substructure. This is perhaps not so surprising; we would naively expect that, at a fixed mass, strong lenses would be those objects that are the most relaxed and concentrated, and not those with much of their mass distributed among multiple substructures. This anti-correlation is, however, strongly at odds with suggestions that recently merged clusters are more efficient lenses than dynamically older clusters (see the talk by M. Meneghetti, this meeting).

4. Strong lensing cosmography?

One of the most exciting prospects for cluster strong lensing is that of cosmography, using systems with multiple arcs at different redshifts. A1689 provides a spectacular example of such a system (Broadhurst *et al.* 2004, also see talk by K. Sharon at this meeting). In principle, by comparing arcs at different redshifts, we can determine distance ratios and thereby make a purely geometric determination of dark energy properties. In practice, such a test appears quite difficult, in part because of modeling uncertainties, and in part because of line-of-sight projections (Dalal *et al.* 2004a). Density fluctuations

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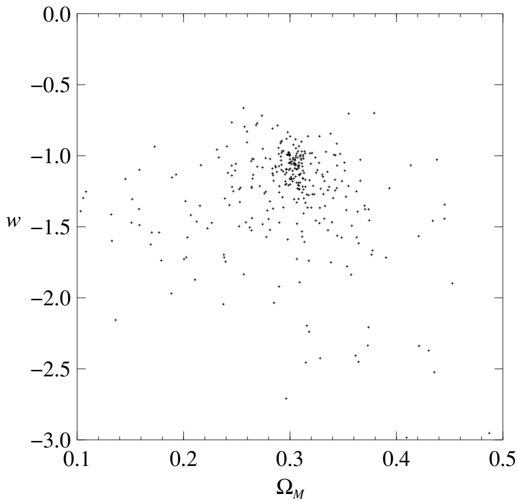

Figure 5. (Left) Observed [solid] and expected [dashed] radial distribution of giant arcs. (Right) Expected errors for strong lensing cosmography with giant arcs. Each point corresponds to a Monte Carlo realization of a cluster with 50 giant arcs, which have been fit using an ellipsoidal NFW model in which the cosmological parameters Ω_M and w have been allowed to vary in the fit. Input parameters were $\Omega_M = 0.3$ and $w = -1$.

from large-scale structure along the line of sight will be indistinguishable from a cosmology with different parameters, severely limiting the cosmographic potential of individual lensing clusters. In Fig. 5, we show the errors expected for strong lensing cosmography using 50 giant arcs; nearly 100% errors arise from these sources of noise.

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Discussion

G. Smith: I would like to comment that in our survey (Smith *et al.* 2004), we have indeed found a higher strong lensing rate among relaxed clusters than un-relaxed clusters.

C. Kochanek: Would it be fair to say, for simplicity, that "relaxed, concentrated" clusters are just those with big cD galaxies? Do you see a correlation between strong lensing and bright cD galaxies?

N. Dalal: Yes, based upon our small sample to date, it does appear that lensing correlates quite well with the *central* richness of the cluster.

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U. Seljak: How much do baryons affect your conclusions?

N. Dalal: For giant arcs at large radius (e.g. $\gtrsim 20''$) the galaxies do not comprise a large fraction of the mass, so it's hard to see how they can have much effect. On the other hand, arcs at small radius are significantly affected by the galaxies. For example, none of the minor-axis arcs I showed would likely have appeared in the absence of the central galaxies.

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