Luminous satellite galaxies in gravitational lenses

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ABSTRACT
Substructures, expected in cold dark matter haloes, have been proposed to explain the anomalous flux ratios in gravitational lenses. About 25 per cent of lenses in the Cosmic Lens All-Sky Survey (CLASS) appear to have luminous satellites within \( \sim 5 h^{-1} \) kpc of the main lensing galaxies, which are usually at redshift \( z \sim 0.2–1 \). In this work, we use the Millennium Simulation combined with galaxy catalogues from semi-analytical techniques to study the predicted frequency of such satellites in simulated haloes. The fraction of haloes that host bright satellites within the (projected) central regions is similar for red and blue hosts and is found to increase as a function of host halo mass and redshift. Specifically, at \( z = 1 \), about 11 per cent of galaxy-sized haloes (with masses between \( 10^{12} \) and \( 10^{13} h^{-1} M_\odot \)) host bright satellite galaxies within a projected radius of 5 \( h^{-1} \) kpc. This fraction increases to about 17 per cent (25 per cent) if we consider bright (all) satellites of only group-sized haloes (with masses between \( 10^{13} \) and \( 10^{14} h^{-1} M_\odot \)). These results are roughly consistent with the fraction (\( \sim 25 \) per cent) of CLASS lensing galaxies observed to host luminous satellites. At \( z = 0 \), only \( \sim 3 \) per cent of galaxy-sized haloes host bright satellite galaxies. The fraction rises to \( \sim 6 \) per cent (10 per cent) if we consider bright (all) satellites of only group-sized haloes at \( z = 0 \). However, most of the satellites found in the inner regions are ‘orphan’ galaxies where the dark matter haloes have been completely stripped. Thus, the agreement crucially depends on the true survival rate of these ‘orphan’ galaxies. We also discuss the effects of numerical resolution and cosmologies on our results.

Key words: gravitational lensing – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation.

1 INTRODUCTION
In the hierarchical scenario of structure formation, structures in the Universe are assumed to have grown from tiny quantum fluctuations (generated during an inflationary period) through gravitational instability. Due to the shape of the power spectrum, structures form hierarchically – larger structures form via accretion and merging of smaller structures. Dense cores of the smaller structures often survive the merging process and manifest as subhaloes in the primary haloes. If substantial star formation occurs in these subhaloes (or their progenitors), then they will appear as satellite galaxies.

In the Milky Way, hundreds of subhaloes are predicted, starting from earlier semi-analytical studies (Kauffmann, White & Guiderdoni 1993), to more recent high-resolution simulations (Klypin et al. 1999; Moore et al. 1999; Gao et al. 2004a,b; Diemand, Kuhlen & Madau 2007b). A few years ago, there were only a dozen or so satellites known, far fewer than the predicted number of subhaloes. However, very recently, a new population of satellites has been discovered in the Sloan Digital Sky Survey data (e.g. Belokurov et al. 2007). It should be noted though that these satellites are compact and, in general, much fainter than the previously known ones, thus it is likely that even this new population of satellite galaxies cannot completely remove the discrepancy between simulations and observations (Madau, Diemand & Kuhlen 2008). It is possible that many subhaloes are dark due to inefficient star formation, for example, due to its suppression by the ultraviolet (UV) background radiation (e.g. Doroshkevich, Zel’Dovich & Novikov 1967; Couchman & Rees 1986; Efstathiou 1992).

Such dark substructure can, potentially, be detected through several means, for example, through gamma-ray radiation due to annihilations of dark matter (DM) particles (Stoehr et al. 2003; Diemand, Kuhlen & Madau 2007a). Gravitational lensing is, in principle, another way to detect dark (and luminous) substructure. Flux anomalies (Mao & Schneider 1998), astrometric perturbations (Chen et al. 2007) and time delays (Keeton & Moustakas 2008) can be used to infer the presence of substructure in strong gravitational lenses. The results of these studies are so far inconclusive (e.g. Kochanek & Dalal 2004; Mao et al. 2004). If all substructure is equally efficient in affecting the flux ratios, then it is clear that there is more than sufficient mass in subhaloes to explain the flux anomalies.
Unfortunately, most subhaloes are in the outer part of the galaxy halo, which means they will have relatively little impact on the flux anomalies occurring in the central parts of lensing galaxies. Curiously, as emphasized by Schneider (2007, private communication), three of the six radio lenses studied by Kochanek & Dalal (2004) exhibit luminous satellite galaxies close to the primary lensing galaxy, namely MG0414+0534, B1608+6656 and B2045+265. A question naturally arises: are such luminous satellite galaxies expected this frequently in the current structure formation theory?

The lensing cross-section is dominated by elliptical galaxies, thus for lensing applications it is important to divide galaxies into different types, and see whether the subhalo populations are different. Furthermore, we explore, in more detail, the evolution of satellite galaxies as a function of redshift. If the evolution is slow, we can more conveniently use studies of nearby galaxies to infer the properties of the luminous satellite population of galaxies at intermediate redshift (between 0.5 and 1, where most lensing galaxies lie). These are the two specific aspects of the subhalo population that we will address in this paper. For this purpose, we will use the largest cosmological simulation combined with semi-analytical catalogues to select haloes and study their satellite populations. We compare our results to the Cosmic Lens All-Sky Survey (CLASS) (Browne et al. 2003; Myers et al. 2003).

The plan of the paper is as follows. In Section 2, we describe the Millennium Simulation and the semi-analytical galaxy catalogue we use. Our main results are presented in Section 3, and we finish with a summary in Section 4.

2 NUMERICAL SIMULATION DATA

2.1 Millennium Simulation

The Millennium Simulation, run by the Virgo Consortium1, follows the evolution of 2160$^3$ particles within a comoving box of length 500 h$^{-1}$ Mpc with a force softening length of 5 h$^{-1}$ kpc (where the Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$). A $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology is assumed, using parameters consistent with the results obtained from the first year Wilkinson Microwave Anisotropy Probe (WMAP) data (Spergel et al. 2003): $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $h = 0.73$, $n = 1$ and $\sigma_8 = 0.9$. Haloes are identified using the SUBFIND algorithm to detect self bound groups of at least 20 particles. This implies a minimum mass for a detected halo of $1.7 \times 10^{10}$ h$^{-1}$ M$_\odot$. For a full description of the simulation, the reader is referred to Springel et al. (2005).2

2.2 Semi-analytic galaxy catalogues

There are three publicly available galaxy catalogues that have been created using the Millennium Simulation to trace the underlying DM (Bower et al. 2006; Bertone, De Lucia & Thomas 2007; De Lucia & Blaizot 2007). We have used the De Lucia & Blaizot (2007) galaxy catalogue for this analysis. It is based on the model described in Springel et al. (2005) and Croton et al. (2006) and is similar to the techniques employed by Springel et al. (2001) and De Lucia, Kauffmann & White (2004). The catalogues created by De Lucia & Blaizot (2007) and Bertone et al. (2007) are based on similar semi-analytic models, differing only in their implementation of galactic feedback. We expect that the results we present here would not be significantly affected by the differences in the models. The third model, produced by Bower et al. (2006), does not differentiate between ‘orphan’ galaxies and galaxies that are still associated with their DM haloes.

For each halo identified in the simulation, a central galaxy is ‘created’ with a mass fraction in baryons of 17 per cent (corresponding to the global ratio, $\Omega_b/\Omega_m$, as measured by WMAP first year data). Initially, the ‘created’ galaxy has no stellar mass, no cold gas and zero luminosity. The attributed baryons are in the form of diffuse gas with primordial composition. The semi-analytic model uses merger trees taken from the Millennium Simulation to describe the evolution of haloes that host the galaxies. The formation and evolution of the galaxies is then followed by implementing simple physical prescriptions for the baryonic physics, such as gas cooling, star formation and feedback processes [including active galactic nuclei (AGN) feedback]. These processes depend on the properties of the host halo. When two haloes merge, the galaxy associated with the larger halo remains the central galaxy while the galaxy attributed to the lower mass progenitor becomes a satellite. Satellite galaxies are stripped of their hot gas and have no new supply of cool gas. They are allowed to form stars until their cool gas reservoir is exhausted. Subhaloes are followed, after merging with a larger system, until the DM subhalo is completely disrupted by tidal forces. These tidally stripped ‘orphan’ galaxies are then assumed to follow the position of the most bound particle in the subhalo before it was disrupted, until it merges with the central galaxy on the dynamical friction time-scale. More details on the formation and evolution of the galaxies can be found in Croton et al. (2006).

We note that, as the minimum mass of a resolved halo is $1.7 \times 10^{10}$ h$^{-1}$ M$_\odot$ and the creation of a galaxy relies on the existence of a halo, the number of low-mass galaxies may well be underestimated. This is unlikely to affect our results as the low-mass satellites will have lower circular velocities and are likely to be faint. This is discussed in more detail in Section 3.3.

2.3 Galaxy sample

We study the satellite population within massive galaxy-sized haloes (haloes with a virial mass$^3$ between $10^{12}$ and $10^{13}$ h$^{-1}$ M$_\odot$ and group-sized haloes (with $10^{13} \leq M_{vir} < 10^{14}$ h$^{-1}$ M$_\odot$). We do not consider cluster-sized haloes as none of the CLASS lenses are found in such environments. The number of galaxy-sized host haloes considered in this analysis is around $3 \times 10^2$, varying little between $z = 0$ and 1. For group-sized haloes, the number is around $3 \times 10^3$ at $z = 0$ decreasing to $\sim 2 \times 10^2$ at $z = 1$. As in Sales et al. (2007), we have imposed a brightness cut-off of $M_g < -20.5$ on our central (host) galaxies to ensure that they have a reasonable chance of hosting detectable satellites. In any case, faint central galaxies have small lensing cross-sections, and will have little effect on the statistics (see Section 3.1). We consider all galaxies (within the virial radius of their host) with $M_g < -17$ as luminous satellites. This corresponds, approximately, to a 100 particle halo – the morphological resolution limit of the simulation (see Croton et al. 2006). This cut would not

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1 www.virgo.dur.ac.uk
2 http://www.mpa-garching.mpg.de/galform/virgo/millennium
3 The mass enclosed within the virial radius. (We define the virial radius to be the radius of a sphere, centred on the most bound particle, within which the average density is 200 times the critical density.)
excludes any of the observed luminous satellites within the CLASS sample. Furthermore, to aid in direct comparison with observation, bright satellites are required to have $R$-band luminosities between 10 and 50 per cent of that of their host. For completeness, we also consider fainter satellites by dropping the $R$-band magnitude and lower luminosity ratio cuts on our satellite sample.

Since the lensing crossing-section is dominated by massive, red elliptical galaxies, we wish to divide our sample by galaxy type and determine whether there is a significant difference in the subhalo population of red and blue galaxies. To do this, we divide our sample according to the $B - V$ colour of the host galaxy. The galaxy populations are bimodal as a function of colour, with a well-defined red sequence and a blue cloud (see e.g. Croton et al. 2006; their fig. 9). We adopt a $B - V$ colour cut of 0.8 at $z = 0.0$, and use $B - V$ values of 0.70 and 0.65 as colour cuts at $z = 0.5$ and 1.0, respectively. We have found that 67, 52 and 37 per cent of our observed galaxy-sized haloes (and 97, 97 and 94 per cent of our group-sized haloes) are associated with red central galaxies at $z = 0.0, 0.5$ and 1.0, respectively.

For nearly all of the observed lensed systems, with which we wish to compare, the projected (physical) separation between the main lensing galaxy and the luminous satellite galaxy is about 1 arcsec, corresponding to 4.2 $h^{-1}$ kpc at $z = 0.5$ and 5.5 $h^{-1}$ kpc at $z = 1$. To explore whether current simulations produce enough satellite galaxies in the inner region of a galaxy halo to explain flux anomalies, we have counted all satellite galaxies (satisfying the restrictions outlined above) within a $5 h^{-1}$ kpc projected region from the centre of the host galaxy (defined as the position of the most bound particle), and will refer to these galaxies as bright central substructures. We also explore the effect of increasing this to a $10 h^{-1}$ kpc projected region.

### 3 RESULTS

#### 3.1 Theoretical predictions

In Fig. 1, we show the fraction of galaxy-sized ($10^{12} < M_{\text{vir}} < 10^{13} h^{-1} M_\odot$) haloes with satellite galaxies, satisfying our magnitude cuts, within the central region (projected) of the halo. The fraction is plotted as a function of the host galaxy’s $I$-band luminosity (for ease of comparison with the CLASS data). The fraction shown is the mean value, when averaged over three independent projections. The uncertainty corresponds to the Poisson scatter within each bin. The top row shows the fraction of haloes with bright satellites within the central $5 h^{-1}$ kpc (projected) while the bottom row shows the fraction of haloes which contain any (dark or bright) substructure within the same region. In these plots, the red population is depicted using filled circles, while the blue population is shown using squares. The three columns show the fraction of haloes containing substructure for the three different redshifts we have considered (left-hand side: 0.0, middle: 0.5 and right-hand side: 1.0). Note that the most luminous blue hosts are not necessarily the most massive haloes but are likely to have undergone recent star formation.

We find that at $z = 0$, about 3–4 per cent of all of our galaxy-sized haloes appear to have bright satellite galaxies within $5 h^{-1}$ kpc (projected) of the centre of the host. While this fraction is similar in both types of galaxies, it is found to increase with redshift (rising to around 11–12 per cent at $z = 1$). Extending the central region to $10 h^{-1}$ kpc (not shown), we find that about 10 per cent of our galaxy-sized haloes host bright central substructure at $z = 0$, and this increases to almost 27 per cent at $z = 1$. If we consider all substructure within the projected central region, not restricting the
search to ‘observable’ satellite galaxies, the fractions do not change significantly. This is illustrated in the bottom panels, where we have dropped our lower magnitude and luminosity ratio cuts. The fraction of haloes containing any substructure within 5 $h^{-1}$ kpc (projected) of the centre of the host increases only moderately from $\sim$3 per cent to about 5 per cent at $z = 0$. This conclusion remains valid all the way up to $z = 1$, where the fraction increases from $\sim$11 per cent to about 15 per cent.

Since some of the lensing galaxies reside in groups (see Section 3.2), we explicitly check the fraction of haloes with bright satellites within a projected 5 $h^{-1}$ kpc region in group-sized haloes (with $10^{13} \leq M_{\text{vir}} < 10^{14} h^{-1} M_\odot$). The results are shown in Fig. 2. The fraction of group-sized haloes with bright central substructure is higher than in galaxy-sized haloes, increasing to $\sim$6 per cent at $z = 0$ and to $\sim$16 per cent at $z = 1$ for red galaxies, which dominate the lensing cross-sections; the fraction is slightly higher for blue galaxies.

The lensing cross-section is roughly proportional to $\sigma^4$ (e.g. Turner, Ostriker & Gott 1984), where $\sigma$ is the velocity dispersion of the system and, from the Faber-Jackson relation, $L \propto \sigma^2$ for ellipticals (Faber & Jackson 1976), thus to compare with observations, the fraction should be weighted by luminosity. The luminosity weighted fraction of hosts with bright central substructure is given in Table 1. At $z = 0$, the fraction is of the order of 3 per cent for galaxy-sized haloes, increasing to about 6 per cent if we consider only group-sized haloes. At $z = 1$, the fraction for galaxy-sized haloes is about 11 per cent, rising to $\sim$17 per cent for group-sized haloes, still slightly below (but possibly consistent with) the observed fraction of galaxies with bright companions (see Section 3.2).

Of the systems found to host bright central substructure, most have only one bright central satellite. Only 2 per cent (3 per cent) of galaxy-(group-) sized hosts with bright central substructure host more than one bright central satellite at $z = 0$. At $z = 1$, 5 per cent (7 per cent) of galaxy-(group-) sized hosts have multiple bright central satellites. The largest number of bright central satellites found within any one system is four.

The force softening of the simulation is 5 $h^{-1}$ kpc (in comoving coordinates); within this region, resolution effects may be significant. For this reason, we explicitly check the fraction of the projected subhaloes within the three-dimensional central region. The fraction depends strongly on redshift. About 32 per cent of the luminous satellites found within the projected central 5 $h^{-1}$ kpc are found within the three-dimensional central region in galaxy-sized haloes at $z = 0$ (for groups, this decreases to $\sim$24 per cent). At $z = 1$, this fraction is 11 per cent, dropping to $\sim$6 per cent in group-sized haloes (see Table 2). All of the satellites within the three-dimensional central region are ‘orphan’ galaxies (see Section 3.3).

### 3.2 Substructure in CLASS lenses

We use the CLASS as the primary observational data. This survey discovered 22 new gravitational lenses in the radio (Browne...
satellites; for B1127+385, its luminosity is unknown due to the uncertain lens redshift.

The right-hand panel of Fig. 3 shows the redshift distribution of the CLASS lenses. All of the lenses with luminous satellites have redshifts higher than the median value of \( \sim 0.6. \) About 75 per cent of the lenses with \( z > 0.8 \) have luminous satellites. We caution that the six remaining lenses of the CLASS sample (with unknown redshifts) may be, on average, at higher \( z \). By ignoring these lenses, the redshift distribution may be somewhat skewed. This could mean that the probability of a high-redshift lens hosting a luminous satellite may not be as high as implied.

Fig. 4 shows the difference in magnitude between the host and satellite galaxy versus the projected separation of the satellite galaxy from the host. We show a random selection of our group-sized haloes with ‘dark’ substructure (crosses) and bright substructure (circles) from our \( z = 1 \) sample. The five CLASS lenses found to have luminous satellite galaxies are plotted with solid circles; for B1127+385, the horizontal bar shows the range of separations when the lens redshift is varied from 0.5 to 1. Selection effects may be complicated and have not been taken into account in this study. While it will be difficult to observe satellites with large magnitude differences at small separations, we find that there are also few simulated satellites at very small separations. (The increase in number with separation is due to the larger area considered.) As illustrated with the histograms in Fig. 4, we find that our sample of host galaxies and their luminous satellites is comparable to the observed galaxies in the (small) CLASS sample.

### 3.3 Resolution effects

As haloes fall into a larger system, they are exposed to tidal forces and are stripped as they orbit the host system. The extent to which a halo is stripped depends on resolution and the inner density profile of the halo (Moore, Katz & Lake 1996). The simulated subhaloes have artificially low-density cores (due to force softening) that make them more susceptible to tidal stripping. Including baryons (and gas cooling) will increase the central density and make the galaxy more resistant to tidal stripping (Moore et al. 1996; Macciò et al. 2006), although the cooling of baryons toward the central host will also increase the tidal forces experienced by subhaloes that come close to the centre.

Nearly all of the satellite galaxies we find in the projected central regions are tidally stripped ‘orphan’ galaxies (see Table 3). The semi-analytic model we have used follows the orbit of galaxies which have lost their DM subhalo, by assuming that they follow the motion of the most bound particle of the parent subhalo before it was destroyed (this is shown to be a good estimate of the subhalo’s position by Springel et al. 2001). Since the effects of dynamical friction on the orbit of these galaxies is not considered in detail, caution is required when interpreting our results. As noted in Sales et al. (2007), this may affect the overall abundance and radial distribution of these stripped haloes.

Also, it is assumed that the ‘orphan’ galaxy remains completely undisturbed for a merging time, based on the dynamical friction formula of Binney & Tremaine (1987), until it merges with the central galaxy. This assumption may result in an overestimate of the number of ‘orphan’ galaxies and their associated luminosity. Henriques, Bertone & Thomas (2007) take the opposite approach and assume that all ‘orphan’ galaxies which have not merged with the central galaxy by \( \sim 0 \) are completely disrupted, and are responsible for the diffuse intracluster light. While their results suggest an improved match to the luminosity function in groups and clusters,
Figure 3. Histogram showing the distribution of the 16 CLASS lenses with available redshifts and $I$-band magnitudes, while the solid histogram shows the distribution of the four CLASS lenses with luminous satellites (B1127+385, is not shown due to its uncertain lens redshift). $K$-correction values have been taken from Poggianti (1997), interpolated using a polynomial fit.

Figure 4. Difference in $I$-band magnitude between the host and satellite galaxy versus the projected separation (in $h^{-1}$ kpc) of the satellite galaxy from the host. We show a random selection of our group-sized haloes (selected at redshift 1.0) with ‘dark’ substructure (crosses) and bright substructure (circles). The five CLASS lenses found to have luminous satellite galaxies are plotted with solid circles; for B1127+385, the horizontal bar shows the range of separations when the lens redshift is varied from 0.5 to 1. The histograms show the distribution of bright substructure found within the central $10h^{-1}$ kpc (projected) as a function of separation and magnitude difference.

4 SUMMARY AND DISCUSSION

In summary, for the CLASS, approximately five of the 22 primary lensing galaxies appear to have a faint companion within the

| Table 3. Percentage of bright satellite galaxies without a surviving DM subhalo within the virial radius and within the central $5h^{-1}$ kpc (projected) region for galaxy-sized hosts. Numbers in brackets correspond to values for group-sized haloes. |
|-----------------|-------|-------|-------|
| Redshift        |       |       |       |
| 0.0             | 74 (68) per cent | 81 (76) per cent | 87 (83) per cent |
| 0.5             | 98 (98) per cent | 99 (98) per cent | 99 (99) per cent |
| 1.0             |       |       |       |

‘orphan’ galaxies (at least to some extent) has been shown by Wang et al. (2006) to be essential in order to explain the observed correlation signal at small scales. This study used the Millennium Simulation to construct a new model of galaxy clustering. They found that if ‘orphan’ galaxies were excluded from the analysis, the correlation signal decreases at small scales in contrast to observations.

A related question is: if we were to increase the numerical resolution of the simulation, would the fraction of luminous satellites rise significantly? Clearly, the number of subhaloes (dark or luminous) must rise further since the subhalo mass function roughly follows a power law with $dn/dM \propto M^{-\alpha}$, $\alpha = 1.7–1.9$ (Moore et al. 1999; Ghigna et al. 2000; De Lucia et al. 2004; Gao et al. 2004b; Diemand et al. 2007b). The lowest mass subhaloes we can resolve have circular velocities at the virial radius, $v_c$, of the order of $\lesssim 50$ km s$^{-1}$; haloes with $v_c \lesssim 30$ km s$^{-1}$ may be inhibited from star formation (e.g. Rees 1986; Efstathiou 1992; Thoul & Weinberg 1996; Gnedin 2000). Thus many subhaloes may remain dark, and the fraction of bright subhaloes will not increase significantly. Increasing the resolution of the simulation would also mean that some of the ‘orphan’ galaxies would be resolved. Since only ‘orphan’ galaxies are allowed to merge with the central galaxy, increasing the resolution may prolong the lifetime of some of our ‘orphan’ galaxies. To fully understand the impact of this effect, a more quantitative analysis is required. Clearly, a firm conclusion can only be reached with higher resolution simulations with realistic treatment of the gas processes.
projected central 5 $h^{-1}$ kpc. The companions have luminosities of about 2–40 per cent of the primary galaxy. We have studied host galaxies covering a comparable range of luminosities and host-to-satellite separations to the CLASS lenses, and found that the predicted fraction of galaxy-(group-) sized haloes hosting central luminous satellites ($\sim 3$ per cent (6 per cent) at $z = 0$; $\sim 11$ per cent (17 per cent) at $z = 1$) is slightly lower than (but possibly consistent with) the observed value.

While this fraction is largely independent of galaxy type, it is shown to increase with redshift. The Poisson probability of detecting luminous substructure in five out of 22 lenses, given that 3 per cent of haloes host luminous substructure, is $\sim 5 \times 10^{-4}$. At 17 per cent of haloes host luminous substructure, the probability of such a detection is $\sim 0.14$. Our prediction of the redshift and mass dependence appears to be roughly consistent with the data: three lenses with luminous satellites are in groups (see Section 3.2), and all appear have redshifts close to 1, higher than the median redshift ($\sim 0.6$) of all CLASS lenses (see the right-hand panel of Fig. 3). One possibility that we have not considered, is whether lensing galaxies are biased tracers of substructure; such bias may arise if substructure enhances the lensing cross-sections significantly. Previous studies, on cluster scales, for giant arcs indicates that the bias is small (Hennawi et al. 2007); it remains to be seen whether this holds true for galaxy-scale lenses. Observationally, the Sloan Lens ACS Survey (SLACS) seems to indicate that the lensing galaxies at $z \sim 0.2$ are typical early-type galaxies (Treu et al. 2008). Another possibility is that some of the luminous `satellites' are not associated with lensing galaxies at all, but just happen to be along the line of sight (Metcalfe 2005).

Shin & Evans (2008) recently studied the effect of satellite galaxies on gravitational lensing flux ratios using analytic expressions for the host potential and the satellite galaxies. They use a spherically symmetric galaxy distribution, and assume that the three-dimensional number density falls off like $r^{-3.5}$, comparable to the Milky Way. They show that the probability of finding a large dwarf is about 10 per cent within two Einstein radii and about 3 per cent within one Einstein radius. We find that our $z = 0$ results are consistent with this.

The Millennium Simulation assumes a power-spectrum normalization of $\sigma_8 = 0.9$, slightly higher than the latest WMAP 5-yr result (Komatsu et al. 2008), where $\sigma_8 = 0.8$. A lower value of $\sigma_8$ will mean that haloes are expected to form later and be less concentrated. However, the impact of this parameter on our results is complicated. The semi-analytic models allow some fine-tuning of parameters to match observations. For example, Wang et al. (2008) found no significant difference in the galaxy populations (at the redshift range relevant here) created from semi-analytic models based on the WMAP 1-yr (Spergel et al. 2003) and WMAP 3-yr (Spergel et al. 2007) $\sigma_8$ values of 0.9 and 0.722, provided suitable galaxy formation parameters were chosen (the difference becomes significant at high redshift). We find that our results do not change significantly when based on the WMAP3 galaxy catalogue produced by Wang et al. (2008) when the same merger time-scale is adopted (as in their model C). However, in their model B (which has the same star-formation efficiency but a shorter merger time-scale than the De Lucia & Blaizot 2007 catalogue), we find a factor of $\sim 2$ fewer haloes with central substructure.

To summarize, while we find that the fraction of luminous satellites in group-sized haloes at $z \sim 1$ is roughly consistent with the observational data, we caution that a firm conclusion can only be reached with higher resolution simulations involving a realistic treatment of the gas processes. At the same time, a larger sample of gravitational lenses will also be beneficial to constrain these models and allow more definitive conclusions on the properties of the substructure to be made.

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**REFERENCES**


Springel V. et al., 2005, Nat, 435, 629

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