1 INTRODUCTION

According to the standard Λ cold dark matter (ΛCDM) cosmological model, the majority of the total energy density of the Universe is deposited in the form of dark energy and dark matter (Rozo et al. 2010; Komatsu et al. 2011). The former is a homogeneously distributed component responsible for the observed acceleration of the Universe expansion, whereas the latter is highly clumped, setting up a base for the growth of cosmic structures. Dark matter (hereafter DM) assembles within quasi-spherical haloes that host cosmological objects of all scale, from dwarf galaxies to clusters of galaxies. The properties of such haloes are one of the most fundamental predictions of the current cosmological model. As first discovered by Navarro, Frenk & White (1995, 1996), and confirmed in many more recent and much better resolved cosmological simulations (e.g. Springel et al. 2005, 2008; Klypin, Trujillo-Gomez & Primack 2011), a key feature of DM haloes is the universal shape of their (hereafter NFW) density profile, whose logarithmic slope varies from −1 in the centre to −3 at large radii, while the transition scale between these two slopes is correlated with the halo mass (Navarro, Frenk & White 1997; Ludlow et al. 2011). This property is the subject of various observational tests at all halo masses.

Studying the properties of DM distribution in galactic haloes is a challenge. Most methods rely on tracers whose positions coincide with the stellar component. Therefore, they probe only the inner part of an underlying gravitational potential of DM halo on the scale of a few per cent of the virial radius. Common means to study the inner part of DM density profiles is the measurement of rotation curves for spiral galaxies (Sofue & Rubin 2001), the line-of-sight (LOS) velocity dispersion profiles of stars (Bertin et al. 1994; Cappellari et al. 2006) or planetary nebulae (e.g. Napolitano et al. 2011), strong (Koopmans et al. 2006) and weak lensing (Mandelbaum et al. 2006a; Gavazzi et al. 2007) or X-ray observations (Humphrey et al. 2006) for early-type galaxies. The main difficulty in the interpretation of these data arises from the fact that the mass of DM is comparable to the baryonic component and, therefore, constraints on the DM mass profile depend critically on the mass estimate of the stellar component (Mamon & Lokas 2005a). In particular, the uncertainty of stellar population models, when applied to elliptical galaxies, leads unavoidably to an ambiguity about the shape of the DM density profile (e.g. Grillo 2012).

There are only two methods that allow us to measure the DM distribution at distances comparable to the virial radius of the halo:
weak lensing and kinematics of satellite galaxies.\(^1\) Due to a very weak signal per galaxy, both methods rely on stacking the data, giving insights into the properties of spherically averaged rather than individual haloes.

Lensing analyses were successfully applied to measure projected mass profiles in galactic haloes. Most results are consistent with a universal NFW (Navarro et al. 1997) density profile of DM and the mass–concentration relation emerging from cosmological simulations of a standard ΛCDM model (Mandelbaum et al. 2006a; Mandelbaum, Seljak & Hirata 2008). Nevertheless, one weak lensing study (Gavazzi et al. 2007) concludes to a shallower DM density profile at large radii around massive elliptical galaxies, even slightly shallower than the singular isothermal sphere model with \(\rho \propto r^{-2}\). Moreover, strong lensing studies of ellipticals also point to a density profile with slope very close to \(-2\) between \(0.3R_e\) and \(0.9R_e\) (Koopmans et al. 2006, 2009).\(^2\) However, the naïve superposition of NFW DM and the observed Sersic (1968) model for the stars lead to a slope close to \(-2\) [from the model of Mamon & Łokas (2005b), we predict a slope of \(-2.2 \pm 0.1\) in the range of radii studied by Koopmans et al.]; the stars dominate the mass profile within \(\approx 2R_e\) (Mamon & Łokas 2005b), but at large radii the NFW DM component should dominate and the slope should be considerably steeper than \(-2\) (\(\approx -2.6\) at the virial radius from the model above).

Satellite kinematics provide a popular means to estimate halo masses. Because host galaxies possess a very small number of observable satellites, usually one or two, one must stack the satellites over many host galaxies. Still, early attempts (Zaritsky et al. 1993; Zaritsky & White 1994) suffered from their small sample sizes. The Sloan Digital Sky Survey (SDSS) is the first very large spectroscopic sample of galaxies with accurate redshifts and digital photometry for a credible analysis of satellite kinematics. McKay et al. (2002) estimated host galaxy masses out to a fixed radius using \(M(r_{ap}) = C r_{ap} \sigma_{ap}^2(r_{ap}) / G\), where \(C\) is the logarithmic slope of the tracer density determined by fitting a power law to the stacked satellite surface density profile, \(r_{ap}\) is the aperture radius and \(\sigma_{ap}\) is the velocity dispersion inside the aperture. Brainerd & Specian (2003) perform a similar analysis on the Two Degree Field Galaxy Redshift Survey (2dFGRS), where they measure the LOS velocity dispersion by fitting the LOS velocity distribution by a Gaussian plus a constant term for interlopers (instead of simply removing the high-velocity interlopers). They were the first to obtain mass-to-light ratio (M/L) as a function of luminosity, both for red and blue hosts. But their analysis suffered from the relatively inaccurate velocities and photometry of the 2dFGRS. Prada et al. (2003) were the first to notice a decline of LOS velocity dispersion at projected radii. They showed that the distribution of satellites in projected phase space (PPS) is consistent with the expectations from ΛCDM. Conroy et al. (2007) analysed the satellites from the Data Release 4 of the SDSS and from the DEEP2 survey at \(z \approx 1\), again with a model for the interlopers, and were the first to derive the variation of virial mass with host galaxy luminosity, separating red and blue galaxies. They found that red host galaxies of given blue luminosity have double the halo mass as their blue counterparts. More et al. (2011) added a second Gaussian to the Gaussian+flat distribution of LOS velocities and fitted aperture velocity dispersions (which are less sensitive than LOS velocity dispersions to the unknown orbital anisotropy and its radial variation) to find a halo versus stellar mass relation in close agreement with that of Conroy et al. Yegorova, Pizzella & Salucci (2011) showed that the halo mass from the velocity dispersion of satellites around spiral galaxies is consistent with that from the rotation curves extrapolated to large radii.

Unfortunately, all these analyses have flaws. For example, they all assume that the LOS velocity distribution is a Gaussian (generally plus a uniform interloper distribution), while it is known that anisotropic velocities lead to non-Gaussian LOS velocities (Merritt 1987). Thus, by taking into account the non-Gaussian nature of the LOS velocity distribution (see also Amorisco & Evans 2012), one can both obtain more accurate constraints on the mass profile and derive constraints on the orbital anisotropy. We (Wojtak et al. 2009) have recently developed a self-consistent method to derive at the same time the mass and velocity anisotropy profiles of spherical systems. Our method is based on the fact that the distribution of objects in PPS is a triple integral (Dejonghe & Merritt 1992) over the LOS and the two plane-of-sky velocities of the six-dimensional distribution function (DF) parametrized in terms of energy and angular momentum that Wojtak et al. (2008) measured on the haloes of a ΛCDM simulation. This approach gives much deeper insights into the data than tests of consistency shown before. It allows for a self-consistent comparison between a set of physical parameters determined from cosmological simulations and observations. Furthermore, analysis based on a PPS model does not rely on data binning which always introduces an artificial signal smoothing.

This paper is organized as follows. In section 2, we describe the data and criteria for selecting isolated galaxies and their satellites. Section 3 presents our dynamical model and a method of constraining parameters of the systems. The results of data analysis and discussion are presented in Section 4. The summary and a discussion follow in Section 5. In this work, we adopted a flat ΛCDM cosmological model with \(\Omega_m = 0.3\) and \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\).

2 DATA

We made use of the SDSS Data Release 7 (SDSS DR7; Abazajian et al. 2009) to select isolated galaxies and the satellite galaxies orbiting them. To search for the host galaxies, we considered a volume-limited subsample of the spectroscopic part of the survey defined by an r-band Petrosian absolute magnitude threshold \(M_r = -19.0\) and the redshift range of \(3000 < c z < 25,000\) km s\(^{-1}\). The apparent magnitudes were converted to the absolute scale for our adopted cosmology and assuming colour-based k-corrections from Chilingarian, Melchior & Zolotukhin (2010).

We defined isolated central galaxies as those that are brighter by \(\Delta M\) than every other galaxy lying inside an observational cylinder of a projected radius \(\Delta r\) and an LOS velocity range \(\Delta v_{los}\). We fixed all fiducial parameters at values defining a rather restrictive criterion for galaxy isolation: \(\Delta M > 1.505\) (corresponding to the flux ratio of at least 2), \(\Delta R < 1\) Mpc and \(\Delta v_{los} < 1500\) km s\(^{-1}\) (for comparison, see McKay et al. 2002; Prada et al. 2003; van den Bosch et al. 2004; Conroy et al. 2007; Klypin et al. 2011). All galaxies lying in the cylinder and that are dimmer than the magnitude threshold are considered to be the satellites of the central galaxies. Due to a rather wide velocity cutoff, some of them are galaxies of background or foreground (interlopers). Disentangling between these two classes of galaxies is an intrinsic part of data analysis described in the following section.

We split the sample of the selected host galaxies into red and blue galaxies using \(g - r + 0.017M_r\), colour diagnostic (see Roche,
Bernardi & Hyde 2010), where \( g \) and \( r \) are \( k \)-corrected Petrosian magnitudes. A boundary value of this diagnostic was fixed at 0.25 which is a minimum of the colour distribution lying between two Gaussian components corresponding to two galaxy populations. Using the publicly available catalogue of the stellar mass estimates from the SDSS DR7,\(^3\) we found the masses of the stellar component of all central galaxies. Stellar masses were estimated using the Bayesian approach, outlined in Kauffmann et al. (2003) with fits of the observed photometry as described in Salim et al. (2007). The model assumes the Chabrier (2003) initial mass function (IMF). We neglected 8 per cent of host galaxies for which stellar mass estimates were not available.

Our final sample consists of 8800 and 2600 satellites around 3800 red and 1600 blue hosts, respectively. The host galaxies cover the stellar mass range from \( \log_{10}(M_*/M_\odot) = 10.0 \) to \( \log_{10}(M_*/M_\odot) = 11.8 \) for red galaxies and from \( \log_{10}(M_*/M_\odot) = 9.5 \) to \( \log_{10}(M_*/M_\odot) = 11.0 \) for the blue ones. Since the stellar mass is a better indicator of the halo mass than galaxy luminosity (More et al. 2011), we split the sample of the host galaxies into several bins of the stellar mass. We used six and three bins for the red and blue hosts, respectively, as indicated in Table 2. This procedure guarantees that the kinematic sample in every bin represents a homogeneous sample of DM haloes.

3 INFERENCE OF PHYSICAL PARAMETERS

The velocity distribution of satellite galaxies is mostly determined by the gravitational potential of DM haloes of the central galaxy. The second factor is the orbital anisotropy describing the fraction of radial-to-tangential orbits in the system. This additional degree of freedom makes data analysis more complex due to a well-known fact of the mass–anisotropy degeneracy (Binney & Mamon 1982; Merrifield & Kent 1990). Breaking this degeneracy requires using rather complicated models accounting for higher order corrections to the Jeans equation (e.g. Merrifield & Kent 1990; Łokas 2002; Łokas & Mamon 2003; Wojtak et al. 2009). On the other hand, the advantage is that the same data allow us to study two physical properties of the host–satellite systems at the same time – the mass distribution of DM halo and the orbital structure of the satellites (e.g. Łokas & Mamon 2003; Łokas 2009; Wojtak & Łokas 2010).

We analysed the kinematic data in terms of the PPS density, i.e. the density of satellite galaxies on the plane spanned by the LOS velocity \( v_{\text{los}} \) and the projected distance from the host galaxy \( R \) (see an example of the kinematical data in Fig. 1). Due to projection effects, the \( v_{\text{los}}-R \) plane is populated by the true physical satellite galaxies of the central galaxies as well as interlopers. We did not apply any interloper removal to the data, but rather we accounted for the presence of interlopers in a statistical sense as an inherent part of a proper analysis. This approach is particularly justified in the case of the composite kinematic data for which the phase-space distribution of interlopers is smooth enough to be modelled by a continuous probability function and is commonly adopted in many studies on kinematics of satellite galaxies (Prada et al. 2003; Conroy et al. 2007; Klypin & Prada 2009). The probability describing the phase-space distribution of interlopers introduces an additional degree of freedom to the proper model associated with the physical properties of the host–satellite systems. The observed PPS density \( p_{\text{los}}(R, v_{\text{los}}) \) may be expressed as the following sum:

\[
g(R, v_{\text{los}}) = (1 - p_i) g_{\text{sat}}(R, v_{\text{los}}) + p_i g_i(R, v_{\text{los}}),
\]

where \( g_{\text{sat}}(R, v_{\text{los}}) \) and \( g_i(R, v_{\text{los}}) \) are the PPS densities of satellite galaxies and interlopers, respectively, and \( p_i \) is the probability of a randomly picked galaxy being an interloper.

3.1 Phase-space density model

As a model of the phase-space distribution of satellite galaxies, we used an anisotropic model of the DF developed by Wojtak et al. (2008). The model was designed to describe the phase-space properties of simulated DM haloes and it was successfully utilized to constrain the mass profile and the orbital anisotropy in nearby galaxy clusters (Wojtak & Łokas 2010). The only modification required to adjust the model to the new context of systems of hosts and satellites is a non-constant ratio of the DM-to-tracer density profile. Constant M/L appears to be a robust assumption in galaxy clusters (Biviano & Girardi 2003; Łokas & Mamon 2003), but it is not justified for the systems of satellite galaxies for which observations point to a bias between spatial distribution of DM and the satellite (Guo et al. 2012).

Following Wojtak et al. (2008), we considered the phase-space density \( f(r, v) \) of the following form:

\[
f(r, v) = f_E(E) L^{-2\beta_0} \left( 1 + \frac{L^2}{2\sigma_v^2} \right)^{(\beta_0-\beta_\infty)},
\]

where \( E \) and \( L \) are positively defined binding energy and angular momentum per unit mass, \( \beta_0 \) and \( \beta_\infty \) are the asymptotic values of the anisotropy parameter at small and large radii, respectively. The anisotropy parameter quantifies the orbital anisotropy in terms of the ratio of the radial-to-tangential velocity dispersion and is traditionally defined as

\[
\beta(r) = 1 - \frac{\sigma_r^2(r)}{2\sigma_v^2(r)},
\]

where \( \sigma_r \) and \( \sigma_v \) are the velocity dispersions in radial and tangential directions, respectively. The angular momentum part of the DF (2) is a generalization of a well-known \( L^{-2\beta} \) ansatz for systems with a constant anisotropy parameter (Hénon 1973). It permits a wide family of the anisotropy profiles, suitable for constraining not only a global degree of the anisotropy, but also its radial profile. The anisotropy profiles are monotonic functions changing between two
asymptotic values with the radius of transition given by the $L_0$ parameter (see Wojtak et al. 2008 for details).

The energy part of the DF (2) is related to the distribution density of satellite galaxies $\rho_{sat}(r)$ (the number density profile) and an underlying absolute value of the gravitational potential $\Psi(r)$ through the following integral equation:

$$\rho_{sat}(r) = \frac{\int \int f(E) E^{-2} \left(1 + \frac{L^2}{2L_0^2} \right)^{\left(\beta_f - \beta_{\inf}\right)} d^3v}{\left(1 + \frac{L^2}{2L_0^2} \right)^{\left(\beta_f - \beta_{\inf}\right)}},$$

(4)

where $E = \Psi(r) - \frac{1}{2}v^2$ is the binding energy. The mass profile at large distances from the central galaxies is dominated by DM; therefore, we choose to neglect the contribution of stars (or in other words, to assume that they are distributed like the DM). We checked that this assumption has negligible effect on our analysis (see Section 5).

We also approximated the DM density profile by the universal NFW profile (Navarro et al. 1997) for which the gravitational potential takes the following form (Cole & Lacey 1996; Lokas & Mamon 2001):

$$\Psi(r) = \Psi_0 \frac{\ln \left(1 + r/r_{DM}^*\right)}{r/r_{DM}^*},$$

(5)

where $r_{DM}^*$ is the scale radius at which the logarithmic slope of the DM density profile equals to $-2$. Our choice of the NFW parametrization is motivated not only by cosmological simulations, but also by observational results showing consistency between satellite kinematics and dynamical predictions for DM haloes with the NFW density profile (Prada et al. 2003; Klypin et al. 2011). We note that the $\Psi_0$ and $r_{DM}^*$ are the principal parameters in the analysis which can easily be converted into more popular quantities describing the mass profile of DM haloes such as the virial mass or the concentration parameter (see Lokas & Mamon 2001 for all equations needed for parameter transformations).

The number density profile of satellite galaxies may be effectively approximated by the NFW profile with a scale radius unrelated to the concentration of DM (e.g. Guo et al. 2012). This property is independent of the morphological type and the stellar mass of the host galaxy. Following this observational motivation, we adopted

$$\rho_{sat}(r) \propto \frac{1}{\left(1 + r/r_{sat}^*\right)^2},$$

(6)

as the number density of the satellites, where $r_{sat}^*$ is a new scale radius.

Having specified $\rho_{sat}(r)$ and $\Psi(r)$ one can solve equation (4) for the energy part of the DF. As shown by Wojtak et al. (2008), the integral over velocity space may be reduced to a one-dimensional problem. Then, the resulting integral equation may be inverted numerically. We used the same scheme of the integral inversion as outlined in Wojtak et al. (2008). Although the algorithm was designed to work for a single-component system with an NFW density profile, we checked that it is also feasible in the case of two-component systems.

The PPS density of satellite galaxies in (1) was obtained by integrating the full phase-space density (2) over velocities $v_{\perp}$ perpendicular to the LOS and a spatial coordinate $z$ parallel to the LOS (Dejonghe & Merritt 1992)

$$g(v_{los}, R) = 2\pi R \int dz \int d^2v_{\perp} f(E, L).$$

(7)

Following the scheme outlined by Wojtak et al. (2009), we calculated this integral numerically using Gaussian quadrature. We did not apply any fiducial truncation to the distance along the LOS keeping the upper limit of the corresponding integral as defined by the condition of positive binding energy, i.e. $E = \Psi(\sqrt{R^2 + z^2}) - v_{los}^2/2 \geq 0$.

For interlopers, we adopted a uniform PPS distribution, i.e. $g_{s} \propto R$. It has been demonstrated that this model effectively separates gravitationally bound members of the central system from interlopers whose velocities are mostly dominated by the Hubble flow (Wojtak et al. 2007; Mamon, Biviano & Murante 2010).

As a consistency check, we verified the robustness of this model by comparing it with the distribution of galaxies at $R > 100$ kpc and velocities $|v_{los}| > 1000$ km s$^{-1}$. The red (filled symbols, solid lines) and blue colour (empty symbols, dashed lines) correspond to red hosts with stellar masses smaller and greater than $10^{11}\ M_{\odot}$, respectively. The lines show a uniform model and a model with a broad Gaussian component (see equation 8).
3.2 Incompleteness

A spectroscopic survey of the SDSS is not complete on angular scales smaller than 55 arcsec imposed by the minimum separation of the fibres in the spectrograph (Blanton et al. 2003). The limit of the completeness corresponds to the physical scale of 92 kpc at the maximum redshift defining the sample of isolated galaxies. This distance is a substantial fraction of the virial radius and, therefore, it is relevant to correct the PPS density model for the incompleteness. The correction was incorporated by means of weighting the PPS density according to the local value of the completeness \( w(R) \),

\[
\hat{g}(R, v_{\text{los}}) = \left[ g(R, v_{\text{los}}) \right]^{1/w(R)}. \tag{9}
\]

We measured the completeness of the data by computing the ratio of the surface number density of galaxies with spectroscopic redshifts to the surface density of all galaxies brighter than the magnitude limit of the SDSS spectroscopic survey, i.e., \( r = 17.7 \) in the \( r \)-band of Petrosian magnitude (see Fig. 3). In order to account for a redshift dependence we split the sample of red and blue galaxies into two bins of the stellar mass corresponding to two classes of the absolute magnitude. We found that the completeness may be well fitted by the following analytical form:

\[
w(R) = w_0 \frac{(R/R_w)^{\alpha}}{1 + (R/R_w)^{\alpha}}, \tag{10}
\]

where \( w_0, R_w \) and \( \alpha \) are free parameters. We fitted this profile to the data in all mass bins of the host galaxies. The resulting best-fitting profiles of \( w(R) \) (see the solid lines in Fig. 3 and best-fitting parameters in Table 1) were used as the final weighting function in (9). The final procedure of parameter inference was positively tested on incomplete mock data generated from the DF with a uniform background of interlopers.

3.3 Parameter estimation

We made use of kinematic data of satellite galaxies to place constraints on parameters of the DM mass profile and the orbital anisotropy. For this, we adopted a Bayesian approach, maximizing the likelihood of the distribution of satellites in PPS. The likelihood function \( \mathcal{L} \) was defined as

\[
\ln \mathcal{L} = \sum_{j=1}^{N} \ln \frac{\hat{g}(R_j, v_{\text{los}}|a)}{w(R_j)},
\]

\[
= \sum_{j=1}^{N} \frac{1}{w(R_j)} \ln g(R_j, v_{\text{los}}|a), \tag{11}
\]

where the sum is over all satellite galaxies in a given stellar mass bin of the host galaxies and \( a \) is a vector of the model parameters. Both \( R_{\text{vir}} \) and \( g_j \) are normalized to 1 over the area confined by velocity cutoff \( |v_{\text{los}}| < 1500 \text{ km s}^{-1} \) and radius range \([R_{\text{min}}, R_{\text{max}}] \). We used the virial radius (see the next paragraph) as the maximum radius \( R_{\text{max}} \), as it determines a natural boundary of the equilibrated part of DM haloes. Since the virial radius is a function of some model parameters, its value was estimated in an iterative approach starting with the best initial guess based on the halo–stellar mass relation provided by Dutton et al. (2010). For the most massive host galaxies, we imposed an additional limit \( R_{\text{max}} < 400 \text{ kpc} \) which prevented from including the satellites which may be common to the host galaxy and surrounding group or cluster of galaxies. We also imposed a minimum radius, because (1) our correction to the spectroscopic incompleteness is uncertain at small radii where our measured completeness is low and (2) photometric pipelines such as those of the SDSS tend to fragment large (host) galaxies into one big one and many small ones surrounding it, that appear like satellites, but are H II regions or spiral arms instead. The minimum radius \( R_{\text{min}} \) was fixed at 5\( R_a \) for red galaxies and 15 kpc for the blue ones. Effective radii were estimated independently for every stellar mass bin using a scaling relation with the stellar mass found by Hyde & Bernardi (2009). The resulting minimum radius \( R_{\text{min}} \) changes from 10 kpc for \( \log_{10}(M_*/M_\odot) = 10.0–10.5 \) to 55 kpc for \( \log_{10}(M_*/M_\odot) = 11.5–11.8 \).

The likelihood analysis was carried out using the Markov chain Monte Carlo (MCMC) technique with the Metropolis–Hastings algorithm (see e.g. Gelman et al. 2004). The set of the primary parameters used in the MCMC analysis comprises the scale radius \( r_s \) of the number density of satellites (6), the dimensionless \( r_s/\Delta_1 \) ratio, the normalization \( \Psi_0 \) of the gravitational potential (5), the asymptotic velocity anisotropy at small and large radii \( (\beta_0 \text{ and } \beta_\infty) \), respectively), the interloper probability \( p_i \) (1) and the relative weight \( p_g \) of the Gaussian part in the velocity distribution (8) of interlopers (applied only to the data of red galaxies with \( M_* > 10^{11} M_\odot \)). We determined constraints on the mass profiles by converting parameters of the gravitational potential, i.e. \( \Psi_0 \) and \( r_s/\Delta_1 \), into the standard parameters characterizing DM halo with the universal NFW density profile: the viral mass \( M_\Delta \) and the concentration parameter \( c_\Delta \). The viral mass is defined in terms of the mean density inside the sphere of radius \( r_\Delta \) (the so-called virial radius) relative to the critical density \( \rho_c \),

\[
\frac{3M_\Delta}{4\pi r_\Delta^3} = \Delta \rho_c, \tag{12}
\]

where \( \Delta \) is the virial overdensity. The concentration parameter is the virial radius expressed in the unit of the scale radius \( r_s/\Delta_1 \),
i.e. $c_A = r_A/r_{DM}$. We adopted two commonly used values of the overdensity parameter: $\Delta = 200$ and 100. The latter corresponds, to a 3 per cent precision, to the virial overdensity of a standard $\Lambda$CDM cosmological model (Bryan & Norman 1998).

We carried out the MCMC analysis assuming log-uniform priors for $r_s/\Psi$ and $r_s^{\text{sat}}/r_{DM}$, and uniform priors for all remaining parameters. We fixed $L_0$ (equation 2) at $0.2\sqrt{\Psi r_{DM}}$ corresponding to the $\sim 1r_{\text{vir}}$ transition radius between two asymptotic values of the anisotropy parameter (Wojtak & Lukas 2010). The central anisotropy $\beta_0$ was limited by $\beta_0 < 1/2$ in order to prevent DF from taking negative values (An & Evans 2006). Constraints on all parameters are based on Markov chains containing $2 \times 10^5$ models in every bin of the stellar mass. Every chain was preceded by a number of trial chains run to estimate the covariance matrix of the proposal probability distribution (Gelman et al. 2004).

4 RESULTS

Table 2 shows our constraints on the halo mass, the concentration parameter and the ratio of the tracer-to-DM scale radius of the density profile, for all bins of the host galaxies. Fig. 4 illustrates a goodness-of-fit test of our model: it compares the velocity distributions of the satellites around red hosts of the stellar mass bin $\log_{10}(M_*/M_{\odot}) = 11.00 - 11.25$ and the distributions predicted from our best-fitting phase-space density model.

4.1 Mass profile

Fig. 5 shows the comparison between our ‘observational’ constraints on the concentration–mass relation from satellite kinematics (red and blue points) and its predictions from cosmological simulations (black solid line). For the latter, we plotted the concentration–mass profile from the Bolshoi Simulation – a high-resolution simulation of a standard $\Lambda$CDM cosmological model with the most updated cosmological parameters (Klypin et al. 2011). The concentration parameters inferred from the satellite velocities are fairly consistent with the profile from cosmological simulations. However, our constraints are not tight enough to determine robustly the slope of the mass–concentration relation. Power-law fits to the data of both types of the host galaxies yield the slope $-0.26 \pm 0.23$ (purple solid line in Fig. 5), where the error is calculated by bootstrapping MCMC models. This is consistent with the predicted value of $-0.075$ (Klypin et al. 2011) as well as with a flat profile. The best-fitting normalization at $M_{100} = 3 \times 10^{12} M_{\odot}$ is $8.4 \pm 2.3$, in excellent agreement with the concentration $c_{100}$ = 9.1 from the simulations of the current $\Lambda$CDM cosmological model (Klypin et al. 2011).

Our concentration–mass relations for red and blue hosts are consistent with a flat profile. Fig. 5 shows the best-fitting power-law profiles obtained in the same way as above, but independently for the data of red and blue hosts. The best-fitting slopes and normalizations at the median mass are: $-0.35 \pm 0.29$ and $c(5 \times 10^{12}) = 8.5 \pm 3.6$ (red hosts), $-0.91 \pm 0.95$ and $c(10^{12} M_{\odot}) = 10.0_{-5.5}^{+9.9}$ (blue hosts). Comparing the profiles at $M_{100} = 2.5 \times 10^{12} M_{\odot}$, which is a common mass scale of red and blue hosts in the sample, we find that the concentration parameter for blue galaxies is smaller than that for the red: $c = 4.4_{-1.8}^{+3.5}$ (blue hosts), $c = 10.9_{-4.3}^{+5.2}$ (red hosts). This finding is significant at the 2$\sigma$ level.

Fig. 6 shows the concentration parameter as a function of the stellar mass. Fitting power-law profiles yields the slopes $-0.44 \pm 0.47$ ($-0.59 \pm 0.7$) and the normalizations $c(10^{11} M_{\odot}) = 7.6_{-2.3}^{+3.4}$ [$c(2 \times 10^{12} M_{\odot}) = 7.7_{-3.5}^{+4.2}$] for the blue (red) hosts. Concentration

Table 2. Constraints on the parameters of the DM density profile and the number density of galaxy satellites in all bins of stellar mass $M_*$ and both types of host galaxies (red and blue): the range of stellar mass $M_*$, the median $r$-band absolute magnitude, the DM halo mass $M_{100}$ (or $M_{200}$), the concentration parameter $c_{100}$ (or $c_{200}$) and the ratio of tracer-to-DM scale radius $r_s^{\text{sat}}/r_{DM}$.

| $\log_{10}(M_*/M_{\odot})$ | $M_*$ (mag) | $\log_{10}(M_{100}/M_{\odot})$ | $c_{100}$ | $\log_{10}(M_{200}/M_{\odot})$ | $c_{200}$ | $r_s^{\text{sat}}/r_{DM}$ | $N_{\text{sat}}/N_{\text{host}}$ |
|---------------------------|-------------|-------------------------------|----------|-------------------------------|---------|--------------------------|-----------------------------|
| 10.00–10.50 (red)         | -20.3       | 12.26_{-0.22}^{+0.03}          | 11.9_{-7.4}^{+19.0} | 12.19_{-0.30}^{+0.03} | 8.9_{-5.8}^{+14.7} | 1.7_{-1.2}^{+3.0} | 128_{-105}^{+115} |
| 10.50–10.75 (red)         | -21.3       | 12.40_{-0.08}^{+0.05}          | 16.7_{-4.9}^{+8.5}  | 12.34_{-0.08}^{+0.04} | 12.7_{-6.9}^{+6.6} | 4.0_{-1.6}^{+3.7} | 303_{-242}^{+297} |
| 10.75–11.00 (red)         | -21.8       | 12.58_{-0.05}^{+0.02}          | 10.6_{-3.6}^{+5.5}  | 12.51_{-0.05}^{+0.03} | 7.9_{-2.8}^{+4.3} | 3.4_{-1.4}^{+1.6} | 740_{-524}^{+567} |
| 11.00–11.25 (red)         | -22.3       | 12.87_{-0.07}^{+0.03}          | 5.6_{-2.4}^{+5.3}   | 12.78_{-0.10}^{+0.06} | 4.1_{-1.8}^{+4.1} | 1.4_{-0.6}^{+1.3} | 1072_{-645}^{+703} |
| 11.25–11.50 (red)         | -22.7       | 13.19_{-0.10}^{+0.07}          | 2.6_{-1.4}^{+5.1}   | 13.04_{-0.12}^{+0.09} | 1.8_{-0.9}^{+1.1} | 0.8_{-0.4}^{+0.9} | 726_{-357}^{+407} |
| 11.50–11.80 (red)         | -23.2       | 13.68_{-0.40}^{+0.06}          | 6.9_{-5.6}^{+15.5}  | 13.60_{-0.30}^{+0.09} | 5.1_{-4.2}^{+12.1} | 1.5_{-1.2}^{+4.3} | 248_{-72}^{+126} |
| 9.50–10.00 (blue)         | -20.3       | 11.82_{-0.43}^{+0.13}          | 16.1_{-15.0}^{+16.6} | 11.76_{-0.42}^{+0.02} | 12.2_{-1.6}^{+12.9} | 1.9_{-1.7}^{+2.3} | 44_{-42}^{+44} |
| 10.00–10.50 (blue)        | -21.0       | 12.07_{-0.13}^{+0.06}          | 7.4_{-4.3}^{+4.5}   | 11.99_{-0.31}^{+0.06} | 5.5_{-3.3}^{+3.5} | 1.6_{-1.0}^{+1.0} | 159_{-142}^{+167} |
| 10.50–11.00 (blue)        | -21.9       | 12.41_{-0.12}^{+0.05}          | 4.5_{-2.6}^{+5.7}   | 12.30_{-0.10}^{+0.06} | 3.3_{-2.0}^{+2.8} | 1.3_{-0.7}^{+1.4} | 323_{-263}^{+304} |
Figure 5. Concentration–mass relation for galaxy-size haloes. The points with the error bars show constraints on the halo mass and the concentration parameter of the DM density profile inferred from the kinematics of the satellite galaxies (red circles for red hosts and blue triangles for blue hosts). The purple dash–dotted line is the best-fitting power-law fit and the shaded region is the 1σ confidence area calculated by bootstrapping from MCMC models. The red (dashed) and blue (dotted) line show the best-fitting profile (±1σ) with the data comprising red and blue hosts. The black solid line represent the median concentration–mass relation from cosmological simulations of a standard ΛCDM model (the Bolshoi Simulation; Klypin et al. 2011).

Figure 6. Same as Fig. 5, but as a function of the stellar mass. Parameters of the blue hosts tend to be smaller by factor of ≈2 than the red with the same stellar mass. Both c–M* relations have comparable slopes. The stellar masses of the red hosts are typically larger by 0.7 dex than those of the blue with the same concentration of DM.

Fig. 7 shows the probability distribution for r_sat/r_DM combined from all bins of the stellar mass, where r_sat and r_DM are the scale radii of the satellite number density profile and DM density profile. The red, blue and black colours (dashed, dotted and solid lines, respectively) correspond to the red and blue host galaxies, and both types of the central galaxies.

4.2 Halo–stellar mass relation

Fig. 8 shows the halo mass as a function of the stellar mass of both types of host galaxies. The halo mass is measured with an accuracy of up to 0.05 dex for red galaxies with stellar masses log_{10}(M_*/M_☉) = 10.75−11.25 for which the number of satellites per stellar mass bin reaches maximum. Our constraints on the halo–stellar mass relation reveal a change of the slope between low and high stellar masses, with the transition mass log_{10}(M_*/M_☉) ≈ 11.
Following Dutton et al. (2010), we find that a reasonable fit to the data is achieved using the following function:

$$M_{200} = M_{h,0} \left( \frac{M}{M_{\odot}} \right) \left[ \frac{1}{2} + \frac{1}{2} \left( \frac{M}{M_{\odot}} \right)^{\gamma} \right]^{(b-a)/\gamma},$$

where $\alpha$ and $\beta$ are the logarithmic slopes at small and large stellar masses, respectively, $M_{\odot}$ and $M_{h,0}$ are the stellar and halo mass at the transition point, and $\gamma$ is a parameter controlling the sharpness of the transition. Fitting this function to the data of red galaxies yields $a = 0.29$, $b = 2.91$, $\gamma = 1.24$, log$_{10}(M_{h,0}/M_{\odot}) = 11.3$ and log$_{10}(M_{\odot}/M_{\odot}) = 13.1$. Our constraints on the halo–stellar mass relation for blue galaxies cover approximately one order of magnitude in the stellar mass and are consistent with a power law with the logarithmic slope 0.66 ± 0.07 and normalization log$_{10}(M_{200}/M_{\odot}) = 12.0$ at the stellar mass log$_{10}(M_{h}/M_{\odot}) = 10.3$. These best-fitting relations of the halo–stellar mass relation are also shown in Fig. 8.

Fig. 9 shows a comparison with other constraints on the halo–stellar mass relation selected from the literature. In particular, we refer to the existing constraints based on satellite kinematics (Conroy et al. 2007; More et al. 2011) and the empirical halo–stellar mass relation obtained by Dutton et al. (2010) as a compilation of all available results based on both stellar kinematics (Conroy et al. 2007; More et al. 2011) and weak lensing (Mandelbaum et al. 2006b, 2008; Schulz, Mandelbaum & Padmanabhan 2010). Stellar masses were converted to a common standard consistent with the Chabrier (2003) IMF, as described in Dutton et al. (2010). We find that the halo–stellar mass relation from our analysis of red hosts is fairly consistent with other measurements. Compared to the results obtained by More et al. (2011), it exhibits a slightly sharper transition between low and high stellar mass regimes. This tension seems to be alleviated when comparing with results obtained by Conroy et al. (2007). But at the high end, our halo masses are typically 0.2 dex lower than found in the literature (Dutton et al. 2010).

Our constraints for blue hosts agree with those from More et al. (2011). On the other hand, halo masses appear to be offset by 0.1 dex with respect to the compiled profile obtained by Dutton et al. (2010). This trend occurs for the measurements from Conroy et al. (2007) and More et al. (2011), suggesting that the weak lensing technique leads to preferentially lower halo masses in late-type galaxies than the stellar kinematics.

Fig. 10 shows the DM fraction at $1R_\odot$, $2R_\odot$ and $5R_\odot$ as a function of the stellar mass for red host galaxies (for details of the calculation of the stellar mass distribution, see Section 5). While the DM within the virial radius is least important for $10.75 < \log M_\ast < 11$. Fig. 10 indicates that the DM fraction at several effective radii is minimized at a larger mass interval $11.25 < \log M_\ast < 11.5$, which happens to be the one for which DM haloes have the lowest DM concentrations (Fig. 5).

### 4.3 Anisotropy of the satellite orbits

Constraints on the anisotropy parameter obtained in individual bins of the stellar mass are not tight enough to draw any solid conclusion. For example, working in separate bins of host stellar mass, we cannot differentiate between an isotropic velocity distribution ($\beta = 0$) and the typical anisotropy profile found in simulated DM haloes where $\beta$ increases with radius from 0.1 in the halo centre to 0.3–0.5 at the virial radius (Wojtak et al. 2005; Ascasibar & Gottlöber 2008; Cuesta et al. 2008). Since there is no theoretical hint that the anisotropy may depend on the halo mass and results obtained in different stellar mass bins do not reveal any trend with the stellar mass, it is advisable to combine constraints from all bins into one.

Fig. 11 shows the contours of the resulting joint probability distribution of two parameters determining the anisotropy profile, $\beta_0 = \beta(r < r_{\text{vir}})$ and $\beta_\infty = \beta(r > r_{\text{vir}})$. When we combine all host galaxy mass bins, we find that the satellite orbits are mildly radially anisotropic with $\beta_0 = 0.2 \pm 0.1$ and $\beta_\infty = 0.3 \pm 0.2$. These constraints on the $\beta(r)$ profile are not significantly different from typical anisotropy profiles of $\Lambda$CDM haloes (red square; Ascasibar & Gottlöber 2008; Wojtak et al. 2008), neither from the universal relations between the anisotropy and the logarithmic slope of an underlying DM density profile (Hansen & Moore 2006; Hansen, Juncher & Sparre 2010). The shift between the marginal probability distributions for $\beta_\infty$ and $\beta_0$ may indicate a tendency for the anisotropy to increase with radius. This effect, however, is of a marginal statistical significance and the data still permit a flat anisotropy profile.
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Figure 11. Constraints on the asymptotic values of the anisotropy profile parameter $\beta(r) = \beta(r < r_0)$ and $\beta_\infty = \beta(r \gg r_0)$. The contours are the confidence regions containing 68 and 95 per cent of the probability combining results from the stellar mass bins. Red, blue and both types of host galaxies are shown as red shaded regions, (wide) blue shaded regions and black contours, respectively. The green filled and empty squares indicate the typical $\beta(r)$ profile of $\Lambda$CDM haloes (based on Ascasibar & Gottlöber 2008; Wojtak et al. 2008) and the universal relation between the anisotropy and DM density slope (Hansen & Moore 2006; Hansen et al. 2010) applied to our best-fitting NFW model.

Our measurement of the anisotropy parameter relies mostly on the data for red galaxies (compare the red and black probability distributions in Fig. 11). Combining results for red galaxies yields $\beta_0 = 0.26^{+0.10}_{-0.08}$ and $\beta_\infty = 0.38^{+0.20}_{-0.23}$ which are statistically consistent with the constraints obtained for both types of central galaxies. Measurement of the orbital anisotropy around blue galaxies is much weaker due to significantly smaller number of the satellites and it does not allow us to differentiate between an isotropic velocity distribution and the anisotropy profile motivated by cosmological simulations (see the blue probability distribution in Fig. 11).

The analysis of the combined probability distribution results in $\beta_0 = -0.2^{+0.5}_{-0.4}$ and $\beta_\infty = 0.2^{+0.3}_{-0.2}$.

5 SUMMARY AND DISCUSSION

We made use of satellite kinematics compiled from the redshift catalogue of the SDSS to measure the physical properties of DM haloes and the orbital anisotropy of the satellites orbiting fairly isolated galaxies. Our data analysis was carried out in the framework of the PPS density based on an anisotropic model of the DF for equilibrated spherical systems (Wojtak et al. 2008). This approach avoids arbitrary binning the data. It furthermore allows us to break the mass–anisotropy degeneracy (Wojtak et al. 2009).

We found that the relation between halo masses and stellar masses of galaxies matched, to first order, the previous measurements through satellite kinematics (Conroy et al. 2007; More et al. 2011) and weak lensing (compiled together by Dutton et al. 2010). In particular, we confirm that the halo masses of red hosts are significantly greater than those of blue hosts of the same stellar mass. However, at the high end of our red hosts, our halo masses are typically 0.2 dex lower than found in the literature (Dutton et al. 2010). This might be the consequence of a stricter isolation criterion applied to our host galaxies, thus avoiding better host galaxies at the centres of groups.

The concentration parameter of DM density profiles has a typical value of $\approx 9$, in full consistency with the results from cosmological simulations (Klypin et al. 2011). Our constraints on the concentration–mass relation are not tight enough to determine its slope over the range of galactic halo masses. However, a more robust measurement of the $c\sim M_{\text{100}}$ slope may be achieved by means of complementing these results by similar constraints at higher halo masses available in the literature. Combining the normalization of the $c\sim M_{\text{100}}$ resulting from satellite kinematics with that obtained by Wojtak & Łokas (2010) from galaxy kinematics in clusters ($c_{\text{100}} = 6.8 \pm 0.7$ at $M_{\text{100}} = 4.9 \times 10^{14} M_\odot$) yields the slope $-0.05 \pm 0.04$, in fair agreement with $-0.07$ from cosmological simulations (Klypin et al. 2011).

We found that red hosts have significantly more concentrated DM haloes than blue hosts of the same stellar or halo mass. Naively, one would conclude that the haloes of red hosts assembled earlier than those of blue hosts, since halo concentrations tend to be greater at higher redshift (Zhao et al. 2003). However, if red galaxies are built by mergers of blue galaxies, the halo mass of the merger remnant will be close to the sum of the original ones, while the concentration will remain the same if the merger keeps the DM density profile self-similar, as found in binary major mergers of NFW models (Kazantzidis, Zentner & Kravtsov 2006). Given the negative slope of the $c\sim M$ relation, this would explain why red galaxies have higher halo concentration than blue galaxies of the same halo mass. However, the offset seen in Fig. 5 between the red and blue host galaxy $c\sim M$ relations is roughly a factor of 3 at a given halo mass, so one would have to conclude that red galaxies are the products of more than a single major merger of blue galaxies.

Mass modelling of elliptical galaxies using stellar kinematics is usually limited to $3\sim4R_e$, beyond which the signal-to-noise ratios of spectra are too low to properly infer LOS velocity dispersions. Our analysis of the satellite kinematics allows us to probe down to $5R_e$. We find (top broken line of Fig. 10) that, at this radius, the DM component always dominates, but less so for stellar masses $11.25 < \log M_e < 11.5$. If we extrapolate our analysis to lower radii, we obtain the same trend with stellar mass (bottom two broken lines of Fig. 10). In particular, at $2R_e$, the DM component should dominate at all stellar masses except for $11.25 < \log M_e < 11.5$. It will be worth confronting this (extrapolated) prediction with forthcoming observational studies of elliptical galaxy internal kinematics out to $2R_e$ in a large range of stellar masses.

Although our analysis relies on a specific parametrization of the density profile, the existence of a well-constrained DM scale radius $r_{\text{DM}} < r_{\text{100}}$ suffices to conclude that the observed satellite kinematics is fully compatible with the NFW density profile of DM and can hardly be reconciled with an isothermal sphere model suggested in several studies based on lensing analyses of massive elliptical galaxies (Koopmans et al. 2006, 2009; Gavazzi et al. 2007). An isothermal density profile of DM would noticeably affect the measurement of the concentration parameter resulting in $r_{\text{DM}} \approx r_{\text{100}}$. Note that the weak lensing measurements of Leauthaud et al. (2010) are consistent with both power laws and NFW DM profiles (see their Fig. 4). So the apparent flattening of the density profile at large radii implied by isothermal profiles should probably be attributed to a projection effect of the local dense environment rather than to DM haloes. This finding confirms and complements a number of tests showing consistency of satellite kinematics with...
the NFW profile of DM density (Prada et al. 2003; Klypin & Prada 2009).

In our analysis, by adopting a single NFW model for the host mass distribution, we have neglected the contribution of the stellar component. Since elliptical galaxies are known to be dominated by their stellar component within the effective radius (Mamon & Łokas 2005a; Humphrey et al. 2006), one may worry that our DM concentrations will be overestimated, even though we only considered satellites further than 5 R_e from the host galaxy. For example, the total density profile of a two-component NFW+Sérsic model is very close to a singular isothermal in the range 0.1 R_e → 1 R_e (see the upper-left panel of fig. 4 of Mamon & Łokas 2005b), thus explaining the isothermal profile found in this fairly low range of radii by Koopmans et al. (2006). Since the mass distribution returned from our model is most sensitive to the LOS velocity dispersion profile, σ_los(R), we asked ourselves how much lower would the DM concentration be if we incorporated a Sérsic (1968) model to the mass distribution.

We performed this test for our red host galaxies. For each of our bins of stellar mass, we determined the median r-band absolute magnitude. We then obtained from table 3 of Simard et al. (2011) the effective radii, R_e, and Sérsic indices, n, for these absolute magnitudes, after restricting the SDSS sample of Simard et al. to the red sequence (using the same cut as we did in our mass analysis) and our adopted redshift range. We then computed σ_los(R) for the satellite population with a two-component NFW+Sérsic mass model, adopting the central stellar mass of our mass bin with the values of R_e and n that we obtained above, the satellite scale radius that we previously measured (derived from Table 2), adopting β(r) = 0.2 for the satellites (consistent with Fig. 6), as well as the DM normalization derived from our one-component mass model (Table 2). The DM concentration, c_100, is a free parameter. We iterated on c_100 until our profile of σ_los(R) matched the profile expected for a one-component NFW model. For each of the six mass bins, we were then able to match σ_los(R) to better than 1 per cent typically (5 per cent in the worst case of stellar mass and radius) between 5 R_e and the virial radius r_100. In the end, we found that the concentration of the DM component was 7–20 per cent lower than in the one-component model. This suggests that our derived values of c_100 are overestimated by 7–20 per cent. Note that if we allowed for adiabatic contraction (e.g. Gnedin et al. 2011), the DM concentration would be greater; hence, our overestimate would be lower. This simple analysis suggests that our choice of a single NFW model for the mass distribution of isolated galaxies beyond 5 R_e is reasonable, as the predicted LOS velocity dispersion profiles match those of more realistic two-component models and our concentration is typically overestimated by only 10 per cent.

Satellite kinematics reveals a bias between the spatial distributions of DM and satellite galaxies. The scale radius of the satellite number density profile is typically larger by factor of 1.6 than that of DM. This finding is consistent with the estimate of a counterpart bias between DM particles and subhaloes found in cosmological simulations (see e.g. Sales et al. 2007; Klypin et al. 2011). We did not find any statistically significant difference between the bias of red and blue galaxies.

The orbital anisotropy of satellite galaxies exhibits a mild excess of radial orbits with typical anisotropy parameter β = 0.2 ± 0.1 in the inner regions and β = 0.3 ± 0.2 in the outer regions of their hosts. These constraints on the inner and outer asymptotic values of the anisotropy profile are statistically consistent with the values found in the haloes in ΛCDM cosmological simulations. The difference between inner and outer anisotropies is too weak to reveal any statistically significant trend of the anisotropy with radius.

Due to the substantial difference between the numbers of satellites around red and blue hosts, our constraints on the orbital anisotropy come principally from the satellites around red hosts. This radial anisotropy around red (giant elliptical) galaxies has been predicted from hydrodynamical simulations of binary mergers (Dekel et al. 2005). Some giant elliptical galaxies show signs of such radial outer anisotropy (Das et al. 2008; de Lorenzi et al. 2008), while others do not (Napolitano et al. 2011). The velocity distribution of the satellites orbiting blue galaxies is less well constrained and is consistent with an isotropic model, contrary to the case for the satellites orbiting red hosts.

In general, fitting an anisotropic (β ≠ 0) model of galaxy kinematics leads to different mass profiles than when isotropic velocities (β = 0) are forced. For example, the same velocity dispersion profile may be equally well fitted by a steep mass profile with isotropic orbits or a shallow mass profile with radially biased orbits (see Merritt 1987). In order to assess the impact of the anisotropy on our results, we reanalysed the data assuming an isotropic model of the phase-space density (β_0 = β_∞ = 0). We found that the new constraint on the virial masses and the scale radii r_los^sat remained the same within the errors. On the other hand, concentration parameters of DM profiles and r_los^sat/r_DM ratios for red hosts tended to be larger by typically 17 per cent, which is comparable to the error on the normalization of the mass–concentration relation. This steepening of DM mass profiles is the only effect of ignoring the anisotropy of satellite orbits.

ACKNOWLEDGMENTS

The authors thank an anonymous referee for the comments and help in improving the manuscript. RW warmly thanks Aaron Dutton for sharing his data compilation with constraints on the halo–stellar mass relation. The Dark Cosmology Centre is funded by the Danish National Research Foundation. RW is grateful for the hospitality of Institut d’Astrophysique de Paris where part of this work was done. RW also thanks Steen Hansen for fruitful discussions and Anna Gallazzi for her useful advice about stellar masses of galaxies from SDSS. GAM thanks Andrea Cattaneo for insightful comments. The computations were performed on the facilities provided by the Danish Center for Scientific Computing.

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Our roughly linear trend of halo vs. stellar mass for blue host galaxies is consistent with the observed linearity of the Tully. Fisher relation (Tully & Fisher 1977) observed in spiral galaxies (assuming a roughly constant ratio of maximum rotational velocity to circular velocity at the virial radius, see Dutton 2010). The curvature of the analogous relation for red host galaxies is a consequence of the limit of massive galaxies at increasing halo mass. Also, the halo to stellar mass ratio vs. stellar mass relation obtained from abundance matching (references in Dutton 2010) is very similar to our relation for red hosts, with the same strong curvature, except that ours is shifted to 0.5 dex higher stellar masses.

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