¿Qué variables gobiernan la cantidad de materia oscura dentro de las galaxias de tipo temprano?

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Aim

The aim of this work is to study the luminous mass as function of the dynamical mass inside the effective radius (r_e) of early-type galaxies (ETGs) to search for differences between these masses. We consider Newtonian dynamics and assume that any difference between the masses is due to the presence of dark matter and/or a non Universal IMF.

The samples of ETGs

We use a sample of approximately **98000 ETGs** from the Nine Data Release of the Sloan Digital Sky Survey (SDSS-DR9. York et al. 2000) in the g and r filters. **This sample is distributed in a redshift interval $0.0024 < z < 0.3500$. This sample shall be called hereafter, "Total-SDSS-Sample".**

The selection criteria of the Total-SDSS-Sample are similar to those used in Hyde & Bernardi (2009) and Nigoche-Netro et al. (2010); i.e.:

- ***1) The brightness profile of the galaxy must be well adjusted by a de Vaucouleurs profile.***
- ***2)The de Vaucouleurs magnitude of the galaxies must be contained in the interval $14.5 < m_{r,dev} < 17.5$.***
- ***3)The quotient of the semi axes (b/a) for the galaxies must be larger than 0.6.***
- ***4) The galaxies must have a velocity dispersion of $\sigma_o > 60$ km/s and a signal-to-noise ratio (S/N) > 10.***

The samples of ETGs

- In the DR9 we find a new morphological classification (Zoospec catalogue, Lintott et al. 2008). The total number of galaxies considering this morphological classification and the criteria 1-4 listed before is approximately **27,000 ETGs**. We shall refer to it as "**The-Morphological-Sample**".

- In addition, we extract a volume-limited sample ($0.04 < z < 0.08$) of approximately **19 000 ETGs** from the DR9. This subsample is approximately complete for $M_g > -20.0$ (Nigoche- Netro et al. 2010; 2011). We shall refer to it as "**The-Homogeneous-SDSS-Sample**".

Correction of the photometric and spectroscopic data

- The photometry and spectroscopy of the samples of galaxies drawn from the DR9 require a series of corrections that are listed as follows (Nigoche-Netro et al. 2010):
  - *Seeing correction*
  - *Extinction correction*
  - *K correction*
  - *Cosmological dimming correction*
  - *Evolution correction*
  - *Effective radius correction to the rest reference frame*
  - *Aperture correction to the velocity dispersion*

Calculation of the stellar mass of the ETGs considering an universal IMF

- **i) de Devaucouleurs Salpeter IMF stellar mass.** We use de Devaucouleurs profiles, a equation for stellar mass-to-light (M/L) ratios obtained from fits of optical-near infrared galaxy data with simple stellar population synthesis models and considering a universal Salpeter IMF (Bell et al. 2003). The equation is as following.

$$\boxed{\mathrm{M_g} \sim \mathrm{L_g} 10^{\mathrm{a_g}+\mathrm{b_g}(M_g-M_r)}} \qquad \mathbf{1}$$

where $\mathbf{M_g}$ is the mass obtained from the luminosity in the *g* filter ($\mathrm{L_g}$), M_g and M_r are the magnitudes in the *g* and *r* filters, $\mathrm{a_g}$ and $\mathrm{b_g}$ are scale factors.

- **ii) Sérsic Salpeter-IMF stellar mass.** The stellar masses were obtained considering equation 1, Sérsic parameters and a universal Salpeter IMF. The Sérsic parameters were obtained from the SDSS-DR9 Petrosian parameters following Graham et al. (2005).

Calculation of the stellar mass of the ETGs

- **iii) Kroupa IMF stellar mass.** In this case the stellar masses have been obtained directly from the GalSpec catalogue of the SDSS-DR9. These were calculated using a Bayesian methodology, a universal Kroupa IMF (Kroupa 2001) and stellar population model grids described in Kauffmann et al. (2003).

- According to Schulz et al. (2010), the luminous mass inside a sphere of radius r_e, corresponds approximately to 42% of the mass calculated using the two procedures mentioned above.

Calculation of the virial mass of the ETGs

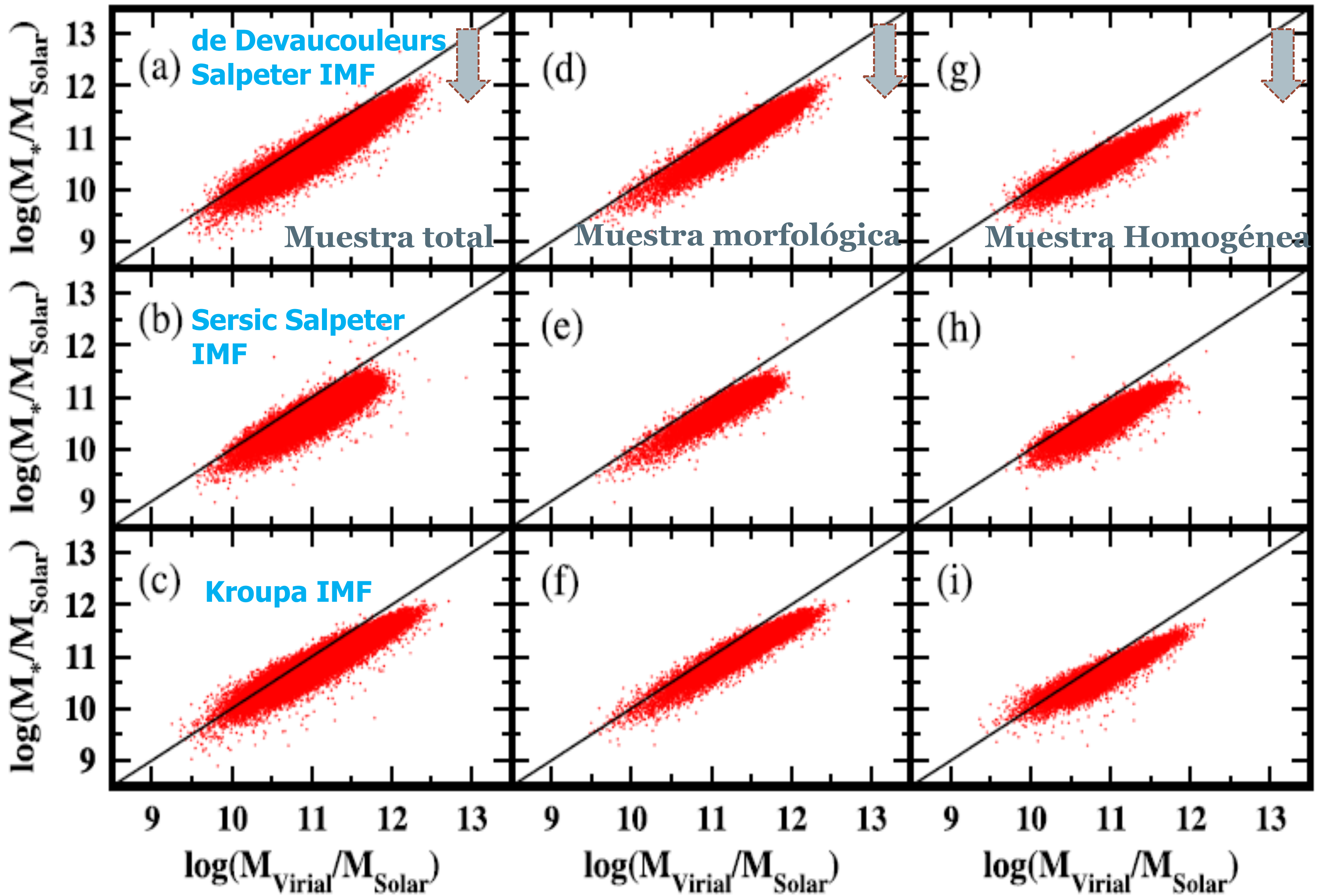
- This method necessitates the value of the velocity dispersion, and assumes that the galaxies are in virial equilibrium. It uses the following equation:

$$\boxed{\mathbf{M}_{\mathbf{virial}} \sim K \frac{r_e \sigma_e^2}{G}} \qquad 3$$

where $\mathbf{M}_{\mathbf{virial}}$ is the virial mass, r_e is the effective radius, σ_e is the velocity dispersion inside r_e, G is the gravitational constant and K is a scale factor that for the case of the de Vaucouleurs profile takes the value of 5.953 (Cappellari et al. 2006).

- The mass calculated using equation 3 gives the approximate value of the dynamic mass inside a sphere of radius equal to the effective radius r_e (see Schulz et al. 2010). **This mass may be luminous or not.** We will now perform an analysis of the behaviour of the masses calculated by means of both methods listed above. We shall only consider the region internal to r_e.

Distribution of the stellar mass with respect to the virial mass



The geometric effect in the parameters of the linear regressions performed on the observed distributions of virial vs. stellar mass.

In Nigoche-Netro et al. (2008, 2009, 2010) it has been demonstrated that for linear fits to sets of data with a high intrinsic dispersion, the value of the parameters of the linear fits performed to these points depend on the geometric form of the point distribution. **This geometric form may depend on physical properties of the galaxies as well as on observational biases and arbitrary cuts performed in the observed samples. This effect has been called the geometric effect.** In the following section we shall quantify the geometric effect on the values of the parameters of the linear regressions performed to the virial and stellar mass distribution.

Mean value of stellar mass with respect to the mean value of virial mass

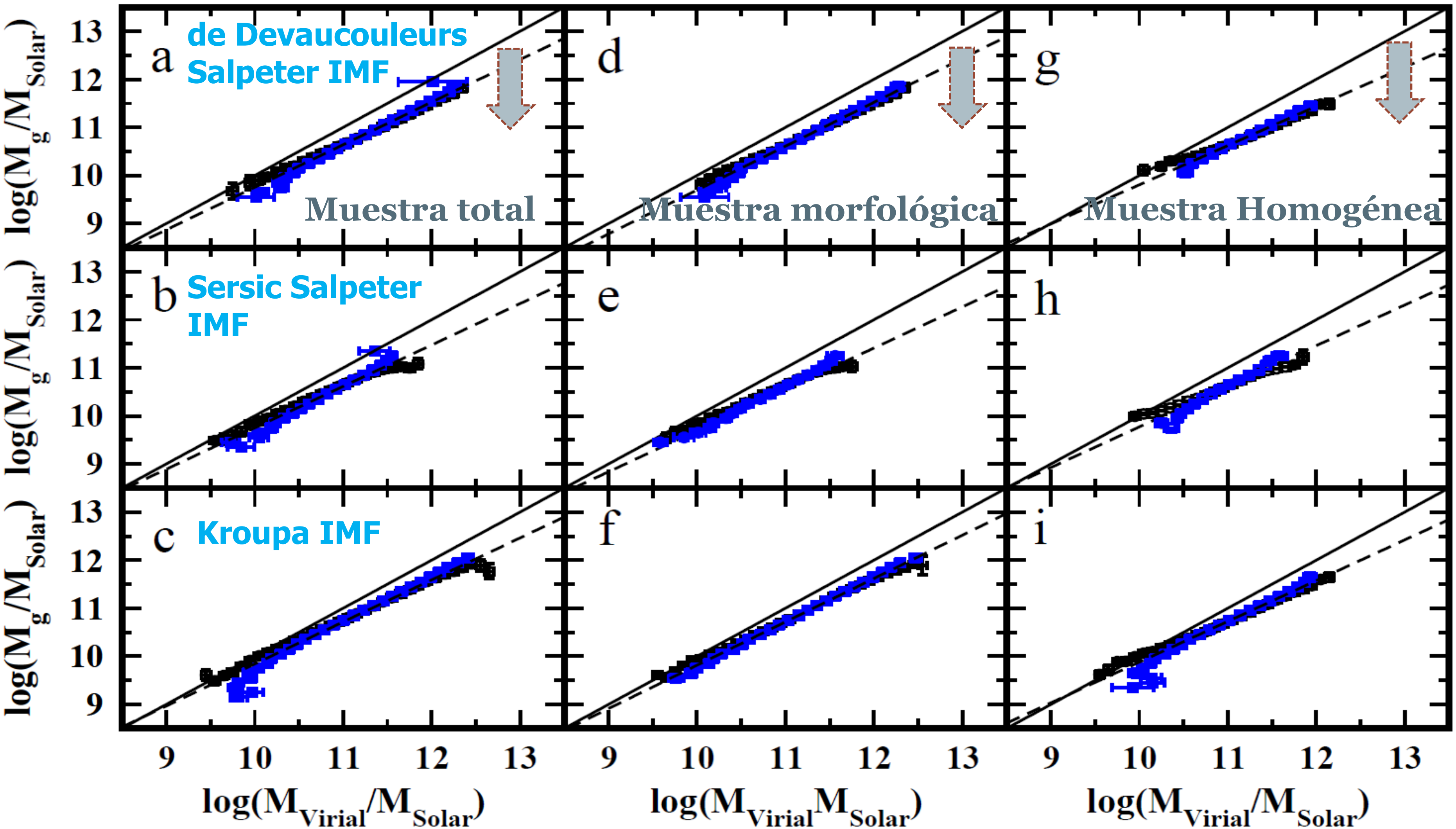


Fig. 1. Distribution of the mean values of the virial and stellar mass from the Total (column 1), Morphologic (column 2) and Homogeneous (column 3) samples. The first row corresponds to the Salpeter IMF stellar mass, the second one corresponds to the Sérsic Salpeter stellar mass and the third one corresponds to the Kroupa IMF stellar mass. The black dots represent the mean values of the stellar mass at quasi-constant virial mass and the blue squares represent the mean values of the virial mass at quasi-constant stellar mass. The dashed line corresponds to the WBQ fit. The solid line is the one-to-one line.

Virial mass vs. stellar mass at constant redshift

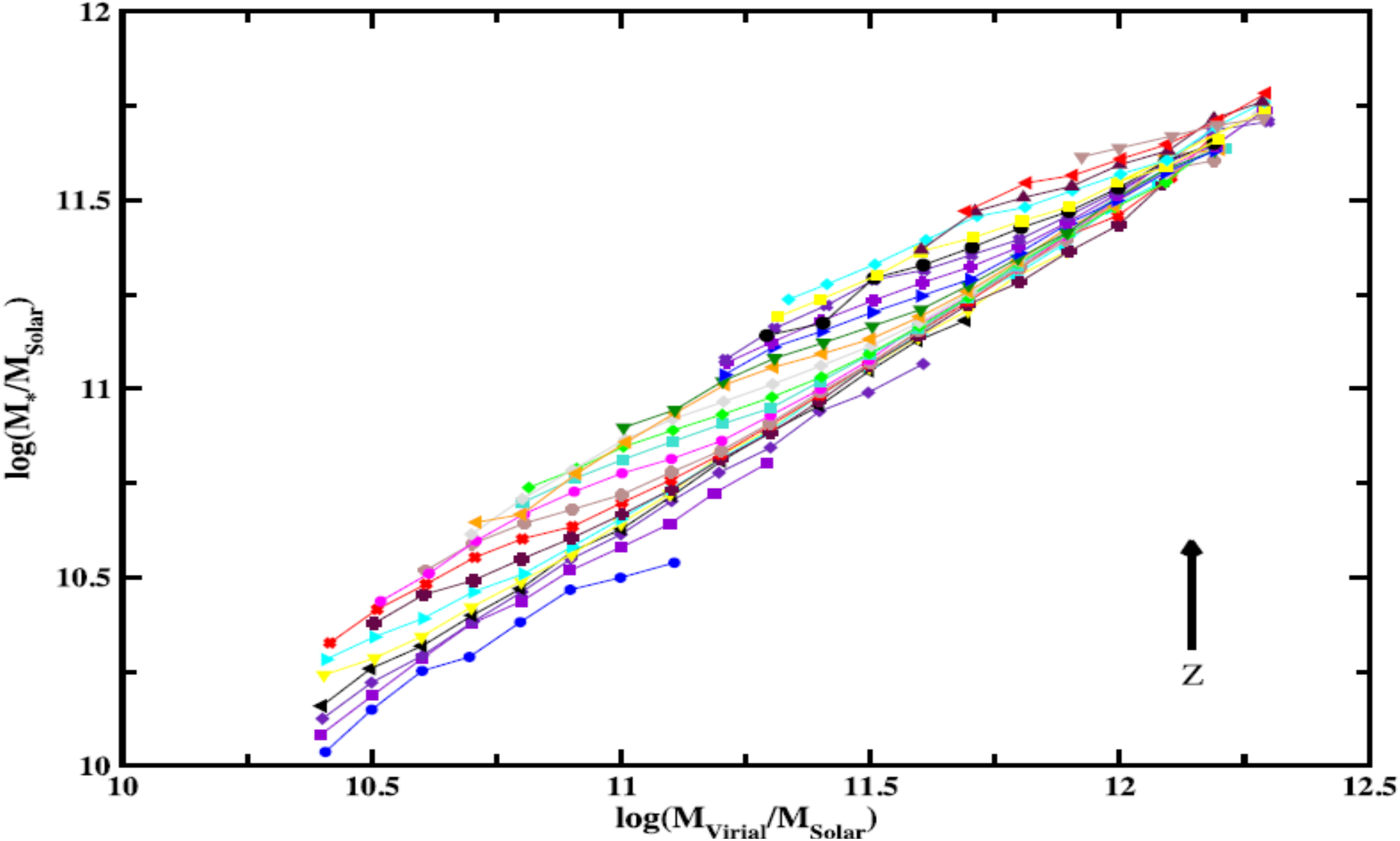


Figure 4. Behaviour of stellar mass as function of virial mass for constant redshift. Each colour and symbol represents a constant redshift. The lower-left part of the graph (blue dots) corresponds to $z \sim 0.025$, while the upper-right part of the graph (brown triangles) corresponds to $z \sim 0.26$. The difference in redshift between consecutive symbols is approximately 0.01. The mean errors for $\log(M_{\text{virial}}/M_\odot)$ and $\log(M_*/M_\odot)$ are approximately 0.052 and 0.065, respectively.

Differences between virial and stellar mass as function of virial mass at constant redshift

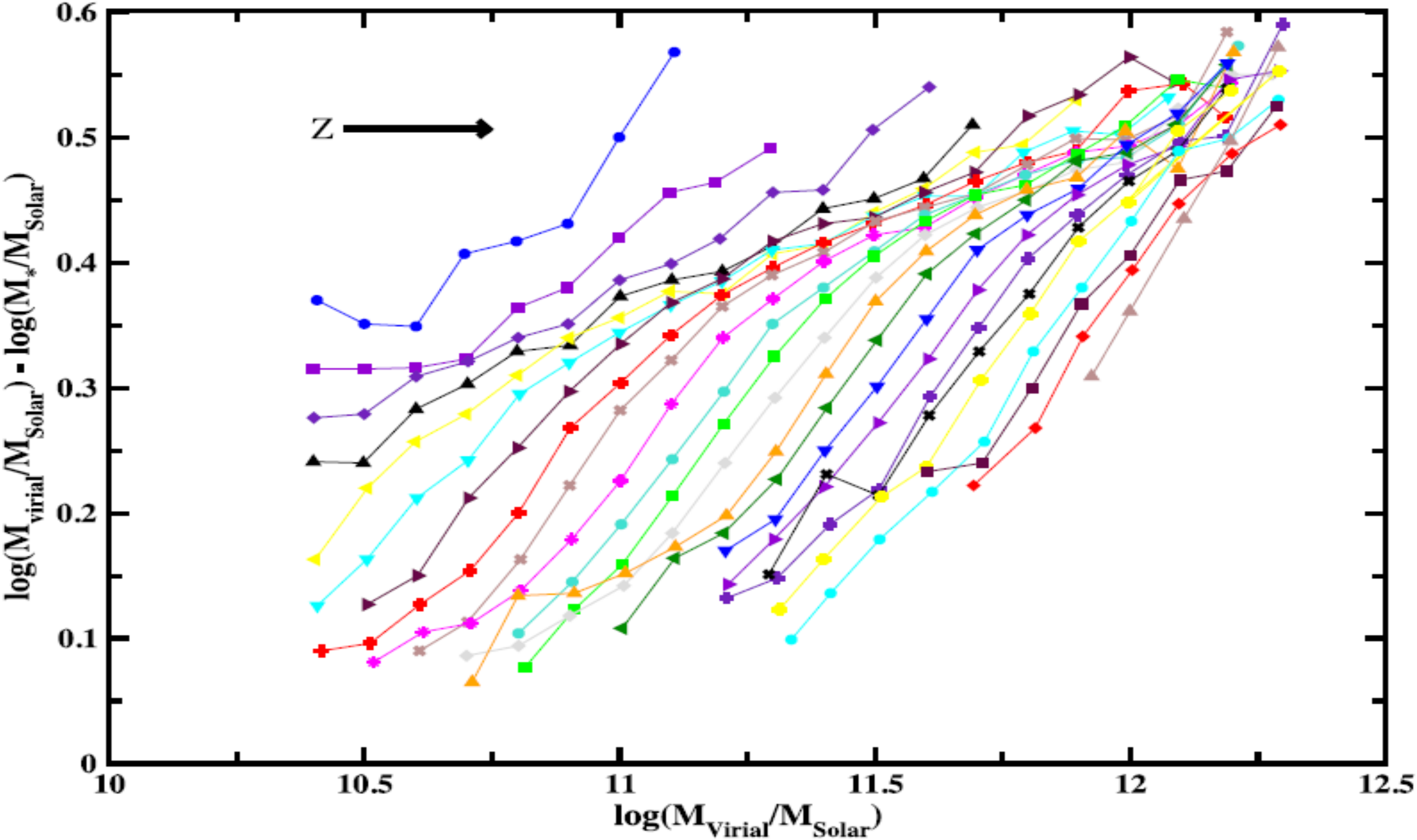


Figure 5. Difference between virial and stellar mass as function of virial mass for the ETGs samples. Each colour and symbol represents a constant redshift. The upper-left part of the graph (blue dots) corresponds to $z \sim 0.025$, while the lower-right part of the graph (brown triangles) corresponds to $z \sim 0.26$. The difference in redshift between consecutive symbols is approximately 0.01. The mean error of the difference between $\log(M_{\rm virial}/M_\odot)$ and $\log(M_*/M_\odot)$ is approximately 0.12.

Density of galaxies

The projected density of galaxies was computed following the method described in Aguerri et al. (2009). They used the projected co-moving distance to the Nth nearest neighbour (d_N) of the target galaxy as follows:

$$\Sigma_N \sim \frac{N}{\pi(d_N)^2}, \qquad (3)$$

The nearest neighbours were calculated using two different samples which are defined as follows:

i) Spectroscopic sample. This sample was selected considering only those galaxies with spectroscopic redshift located in a velocity range of ± 1000 km/s from the target galaxy and within a magnitude range of ± 2 mag. These two constraints are similar to those used by Balogh et al. (2004) and allow us to limit the contamination by background/foreground galaxies even if we are working with projected distances.

ii) Photometric sample. This sample was selected considering only those galaxies with photometric redshifts located within ± 0.1 of the target galaxy (see Baldry et al. 2006). This range roughly corresponds to the typical photometric redshift error in SDSS. In addition, we also imposed the magnitude limitation of ± 2 mag as for the spectroscopic sample.

Difference between virial and stellar mass as function of density **Kroupa IMF**

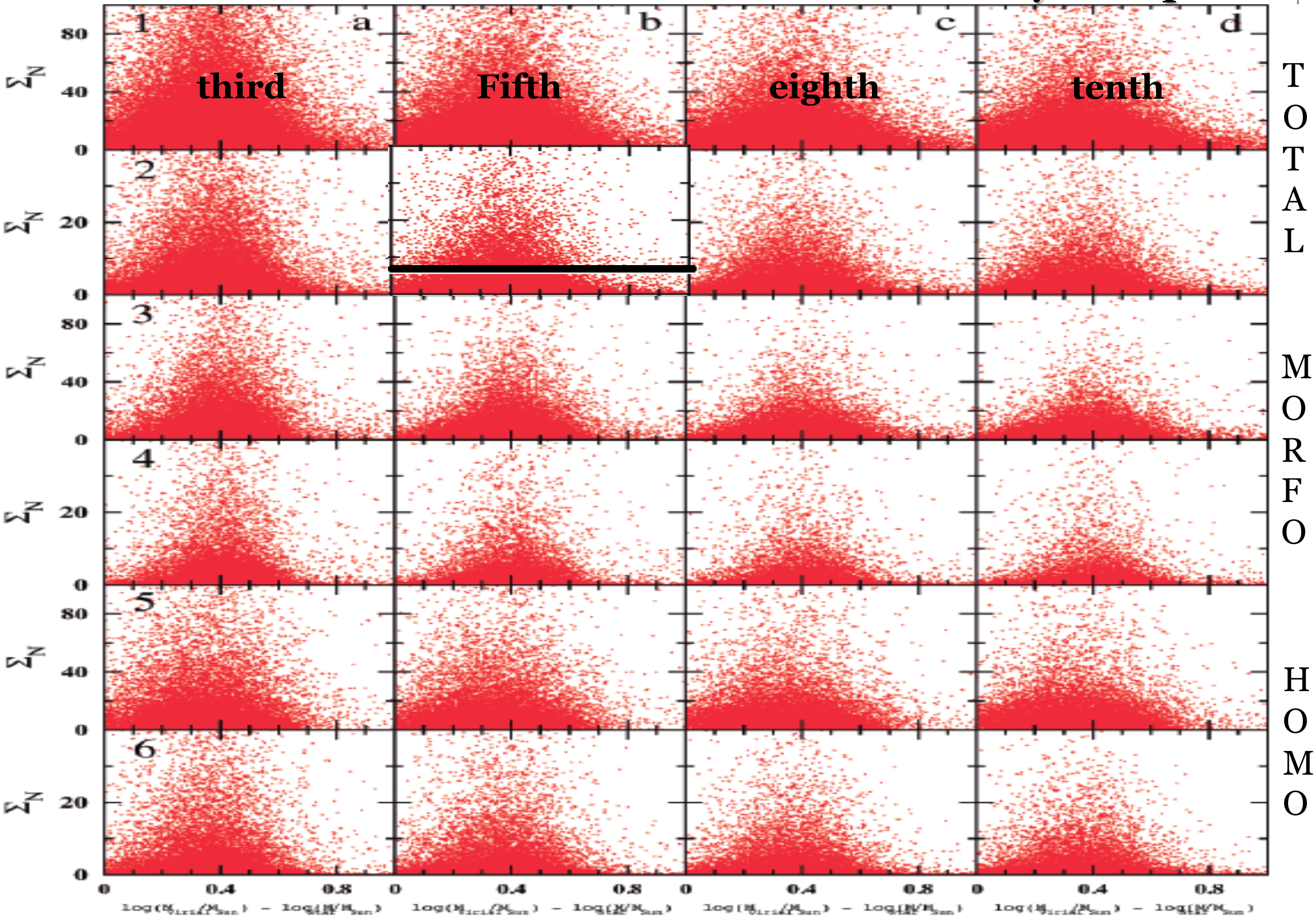


Figure 4. Distribution of the logarithmic difference between dynamical and stellar mass inside r_e as function of density of galaxies for different samples of ETGs considering a Kroupa-IMF stellar mass. Rows 1-2, 3-4 and 5-6 correspond to the total, morphological, and homogeneous SDSS samples, respectively. Rows 1, 3, and 5 are data from the photometric sample. Rows 2, 4 and 6 are data from the spectroscopic sample. Columns a, b, c, d are the data considering the third, fifth, eight, and tenth nearest neighbours respectively.

Difference between virial and stellar mass as function of density

A different way to make comparisons of structural properties of galaxies is making cuts in density, for example, Aguerri et al. 2009 consider very low-density environments (field) (Sigma_{5} < 1 Mpc^{-2}), loose groups (Sigma_{5} > 1 Mpc^{-2}) and compact galaxy groups/clusters (Sigma_{5} ~ 10 Mpc^{-2}) to analyze if the environment plays a role in the fraction of barred galaxies. Using these considerations they find that the fraction of barred galaxies does not depend of the environment.

Following the environmental definition of \cite{ague09} we analyze here the possible effects of the environment on the virial and stellar mass difference inside of ETGs. We calculate the mean values of the logarithmic mass difference for Sigma_{N} < 1 Mpc^{-2} (field), Sigma_{N} > 1 Mpc^{-2} (loose groups) and 9.9 Mpc^{-2} < \Sigma_{N} < 10.1 Mpc^{-2} (compact groups/clusters) where N is the third, fifth, eighth, and tenth nearest neighbours. we find that the mean value of the mass difference for the field, loose and compact clusters within the same sample has a variation less than 0.03 dex which, considering the associated errors is not significant. This result agrees with other papers in the literature Tortora et al. 2012 where they find that there are no differences in dark matter content inside ETGs due to the environment. However it appears to be opposed to the results of the visual inspection of the distribution that was shown previously.

Difference between virial and stellar mass as function of density

The explanation to this contradiction can be reasoned as follows: the distribution of galaxies in the log$({\bf M_{Virial}/{\bf M_{Sun}}})$ - log$({\bf M_{Star}/{\bf M_{Sun}}})$ vs. density plane for all the samples appears to be symmetric but non-homogeneous (galaxies do not populate the plane uniformly), these properties cause that the distribution inside each one of the considered areas is also symmetric but non-homogeneous. Given the symmetry of the distributions, the mean of those distributions have to be similar, that is to say, the results for the mean values for the field, loose, and compact groups of galaxies must be similar, but this result does not represent the geometric differences in the distribution that we can see in each one of the samples due to the non-homogeneous distribution. To characterize the differences between samples we have to consider other parameters to make comparisons. One parameter that can give us appropriate results is the intrinsic dispersion of the distribution because this parameter can characterize the shape of the mentioned distribution. This result is similar to that found in Nigoche et al. 2010, named ``geometrical effect'', where they showed that a good parameter to analyze structural properties of galaxies is the intrinsic dispersion of the distribution of galaxies on the plane that involves the parameters of interest. In this paper we define the intrinsic dispersion as the standard deviation of the density of galaxies at quasi-constant mass difference and/or the standard deviation of the mass difference at quasi-constant density of galaxies.

Intrinsic dispersion of density as function of mass difference

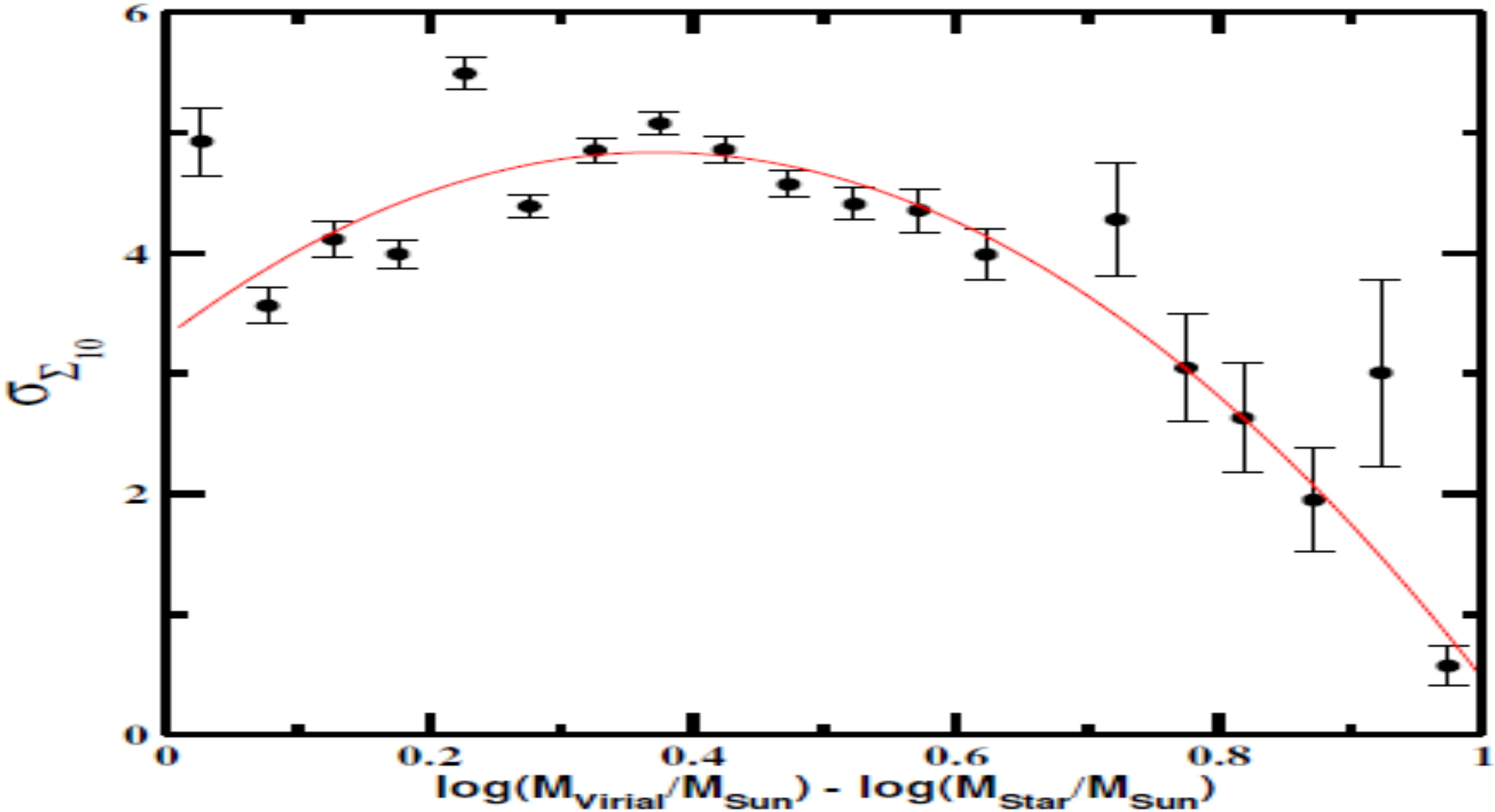


Figure 6. Intrinsic dispersion of the density of galaxies distribution (black dots) as a function of the logarithmic difference between dynamical and stellar mass (quasi-constant mass) inside r_e for the spectroscopic-homogeneous-SDSS sample (Kroupa-IMF stellar mass) considering the tenth nearest neighbour. The red continuous line is a second degree polynomial least square fit to the data.

Intrinsic dispersion of mass difference as function of density

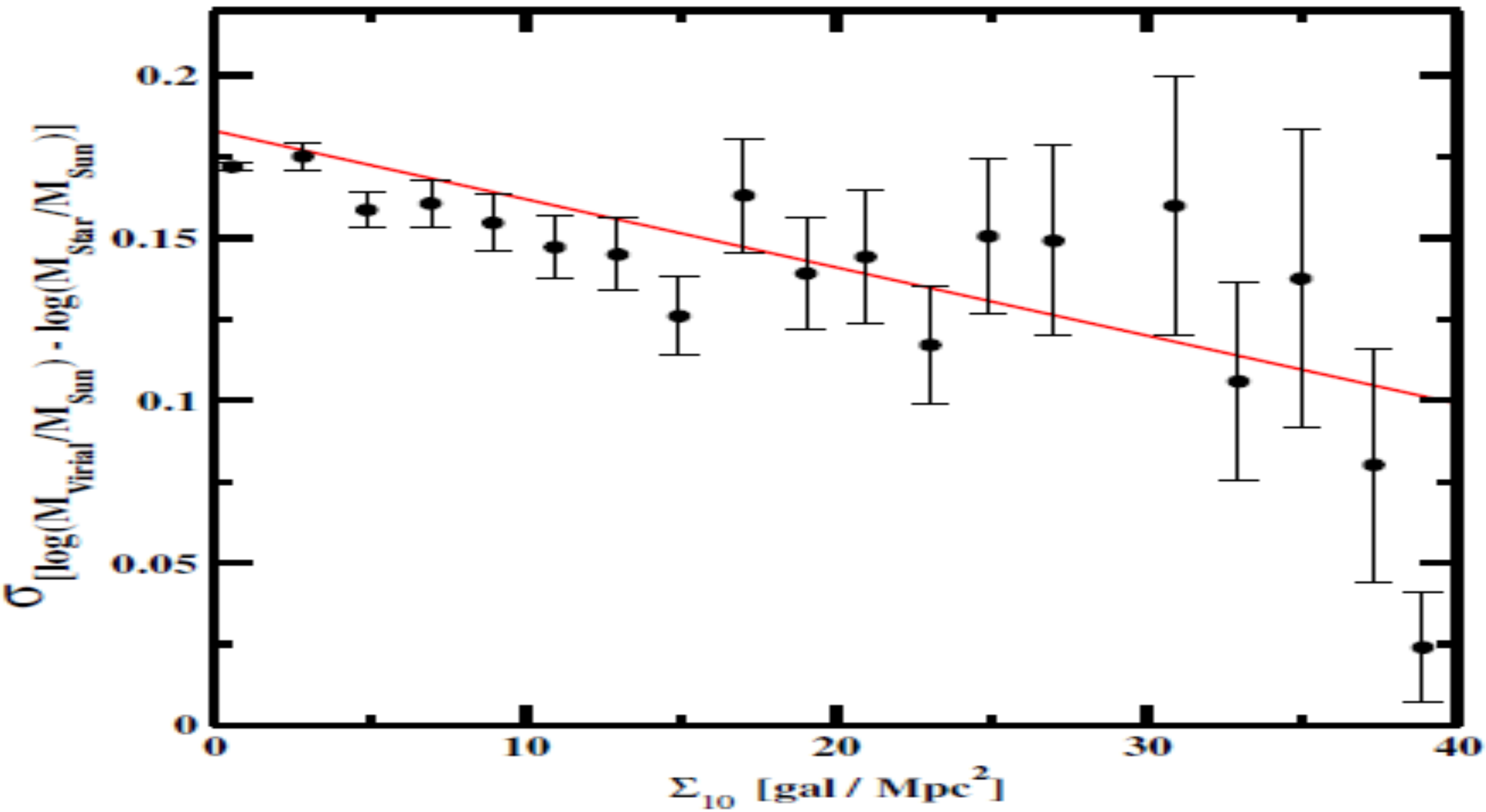


Figure 7. Intrinsic dispersion of the logarithmic difference between dynamical and stellar mass (black dots) inside r_e as function of density of galaxies (quasi-constant density) for the spectroscopic-homogeneous-SDSS sample (Kroupa-IMF stellar mass) considering the tenth nearest neighbour. The red continuous line is a first degree polynomial least square fit to the data.

Results

The main results are the following:

i) The difference between dynamical and stellar mass depends on dynamical mass.

ii) The difference between dynamical and stellar mass depends on redshift.

iii) The difference between dynamical and stellar mass inside ETGs goes from 0% to 70% depending on mass and redshift.

iv) The difference between dynamical and stellar mass depends on environment.

Results

The main results are the following:

iv)The difference between dynamical and stellar mass inside ETGs in the most dense environments is approximately 50% - 70% of the dynamical mass.

v) These differences are due to dark matter or a non Universal IMF or a combination of both.

vi) This amount of dark matter is an upper limit, the accurate value depends on the impact of the IMF on the stellar mass estimation.

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