# The galaxy-dark matter connection: A cosmological perspective

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**Abstract.** We have presented a method that uses observations of galaxies to simultaneously constrain cosmological parameters, and the galaxy-dark matter connection (aka halo occupation statistics). The latter describes how galaxies are distributed over dark matter haloes, and is an imprint of the poorly understood physics of galaxy formation. A generic problem of using galaxies to constrain cosmology is that galaxies are a biased tracer of the mass distribution, and this bias is generally unknown. The great advantage of simultaneously constraining cosmology and halo occupation statistics is that this effectively allows cosmological constraints marginalized over the uncertainties regarding galaxy bias. We have used a combination of the analytical halo model and the conditional luminosity function to describe the galaxy-dark matter connection, which we have used to model the abundance, clustering and galaxy-galaxy lensing properties of the galaxy population. We have used a Fisher matrix analysis to gauge the complementarity of these different observables, and presented some preliminary results from an analysis based on data from the Sloan Digital Sky Survey. Our results are complementary to and perfectly consistent with the results from the WMAP mission, strengthening the case for a true 'concordance' cosmology.

## 1. Introduction

In the concordance cosmological picture, dark matter and dark energy dominate the energy density of the Universe, while stars in galaxies form a negligible component. However, unlike dark matter or dark energy, we can observe galaxies directly, and use them as tracers of the underlying matter density field to investigate the properties of the Universe. Unfortunately, this connection between galaxies and matter is complicated by the fact that galaxies are biased tracers of the mass distribution. Although this 'galaxy bias' is generally considered a nuisance when trying to use galaxies to constrain cosmology, it also contains a wealth of information regarding galaxy formation. After all, it is the physics of galaxy formation that determines where, how and with what efficiency galaxies form within the dark matter density field. Therefore, ideally one would like to *simultaneously* solve for cosmology and galaxy bias.

It is crucial to understand why and how galaxies are biased with respect to the matter distribution in order to break the degeneracy between galaxy bias and the cosmological parameters. Since dark matter halos, in which galaxies reside, form preferentially at the peaks of matter density field, they are biased tracers of the underlying matter density field. Galaxies inherit the bias of their parent halos. Observations of the abundance of galaxies [1, 2], the clustering of galaxies on small scales [3], the gravitational lensing signal due to the dark matter around galaxies [4], and the kinematics of satellite galaxies around halos [5, 6, 7] can all provide important clues regarding this "galaxy-dark matter connection" (i.e., what galaxies resides in what halo). Using this information, one can predict the galaxy bias, both as function of scale and as function of galaxy properties (e.g., luminosity). This allows one to break (some of) the degeneracies between galaxy bias and cosmology, and thus, to use the observed distribution of galaxies to constrain cosmology.

In this paper, we have demonstrated the strength and complementarity of a variety of galaxy observations from the SDSS to constrain cosmological parameters. In particular, we have shown how observations of galaxy abundances [1], galaxy clustering [3] and galaxy-galaxy lensing [4], can be used to constrain cosmological parameters such as the matter density in units of the critical density $\Omega_{\rm m}$, and the amplitude of the power spectrum of matter fluctuations, as characterized by $\sigma_8$. We rely on the framework of the halo model to analytically predict these observations. The halo model assumes that all the dark matter in the Universe is partitioned over dark matter halos of different sizes and masses [8]. The abundance and clustering of these halos of dark matter is set by the underlying cosmological parameters, and this dependence has been well calibrated with the use of numerical simulations [9, 10]. A parametric form of how galaxies populate halos, called the *halo occupation distribution function*, can then be used to predict the abundance and clustering of galaxies using the abundance and clustering of halos [11]. In this paper, we have used a Fisher matrix analysis to highlight the complementarity of using these different data sets, and presented some preliminary results from an analysis based on existing data.

We have used the conditional luminosity function (CLF) to specify the halo occupation distribution of galaxies [12]. The CLF describes the average number of galaxies with a given luminosity that reside in a halo of mass $M$. We have used a total of 9 parameters to describe the CLF. Given the parameters of the CLF, and the cosmological parameters which set the abundance and clustering of halos, we can predict all the observables that we wish to model. Because of the page-limits of these proceedings, we cannot provide the detailed expressions that we have used to calculate the observables for a given model (i.e., cosmology plus CLF). These have been presented in [13]. We have emphasized, though, that our implementation of the 'halo model' properly accounts for (i) the scale dependence of halo bias, (ii) halo exclusion, and (iii) residual redshift space distortions that can affect the determinations of galaxy bias [14].

Throughout, we have adopted a 'standard' flat ΛCDM cosmology (i.e., gravity is described by the standard general relativity, neutrino mass is neglected, initial power spectrum is a single power-law, and dark energy is modelled as Einstein's cosmological constant), which is described by 5 cosmological parameters: The matter density parameter $\Omega_{\rm m}$, the baryon density parameter $\Omega_{\rm b}$, the hubble parameter $h$, the power law index $n_{\rm s}$, and the parameter $\sigma_8$. Our goal is to constrain (subsets) of these cosmological parameters, fully marginalizing over the galaxy-dark matter connection as parameterized by our 9-parameter CLF model.

## 2. Results

### *2.1. Fisher information analysis*

In this section, we have used the Fisher information matrix in order to gauge the accuracy with which constraints on the cosmological parameters $\Omega_{\rm m}$ and $\sigma_8$ can be obtained, given the current accuracy of the observables that we wish to model. Since, we have three different

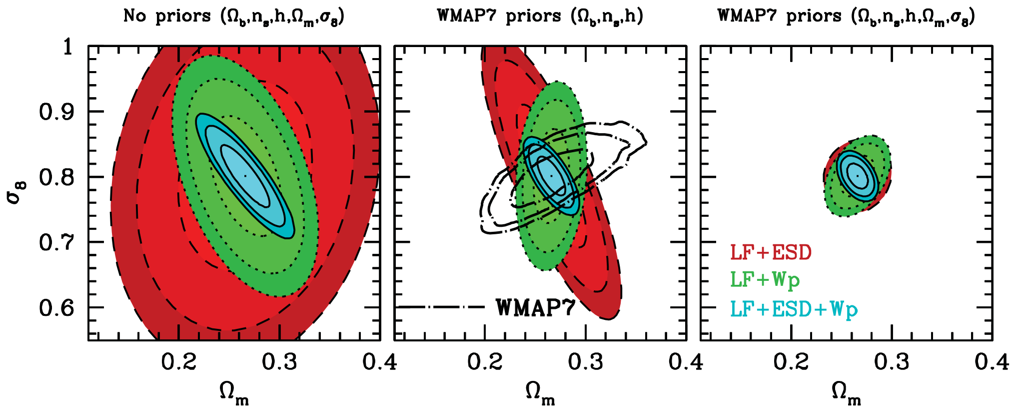


**Figure 1.** Fisher forecasts of 68, 95 and 99 per cent confidence constraints on the cosmological parameters $\Omega_{\rm m}$ and $\sigma_8$ when different combinations of the luminosity function (LF), galaxy clustering (Wp), and the galaxy-galaxy lensing (ESD) data are analysed. Different panels show the effect of varying priors on cosmological parameters from analysis of the cosmic microwave background data. (For a definitive version, see [15].)

observables: the luminosity function, galaxy-galaxy clustering, and galaxy-galaxy lensing, we have started by investigating how each of these different data sets contributes to our constraining power. The different panels of Figure 1 show the 68, 95 and 99 per cent confidence intervals that can be placed on the cosmological parameters $\Omega_{\rm m}$ and $\sigma_8$ under varying assumptions of prior information from the analysis of the WMAP-7 mission [16]. The left-hand panel assumes uninformative priors on all of the cosmological parameters in our model. The dashed contours are used to indicate the confidence levels when we perform a joint analysis of the abundance of galaxies and the galaxy-galaxy lensing signal around them. The constraints are fairly weak, in particular, because the galaxy-galaxy lensing signal has only been measured on fairly small scales ($r_{\rm p} \lesssim 2h^{-1}$Mpc). This results in a number of degeneracies between the cosmological parameters, and the CLF parameters such that $\Omega_{\rm m}$ and $\sigma_8$ are only weakly constrained. The dotted contours show the confidence contours obtained by combining the luminosity function with the galaxy-galaxy clustering data. The constraints are significantly tighter, and the improvement is largely due to the addition of information on intermediate scales ($2\ h^{-1}$ Mpc $\lesssim r_{\rm p} \lesssim 40\ h^{-1}$ Mpc). Finally, the solid contours show the result of a joint analysis of all three observables. Even in the absence of prior information, this joint analysis breaks a number of degeneracies that are present in our model. The resulting cosmological constraints are competitive with the existing constraints on these parameters, demonstrating the potential power of this method. The middle panel of Figure 1 shows the effect of adding prior information on the secondary cosmological parameters $\Omega_b$, $n_s$ and $h$ from the WMAP-7 results and the right panel shows the effect of adding all the prior information from WMAP-7.

### *2.2. Cosmological constraints*
We have carried out a joint analysis of all the three observables, and obtained the posterior distribution of our model parameters given these data. We have used a Monte Carlo Markov Chain to sample from the posterior probability distribution of the parameters. For our fiducial analysis, we have imposed priors on the secondary cosmological parameters $\Omega_{\rm b}$, $n_{\rm s}$ and $h$, and completely uninformative priors on the parameters $\Omega_{\rm m}$ and $\sigma_8$. Our model is able to fit the data sufficiently well with $\chi^2$ per degree of freedom of the order of 2. The fits to the data have been presented in [17]. Preliminary results of our analysis, in the form of 68, 95 and 99 per cent

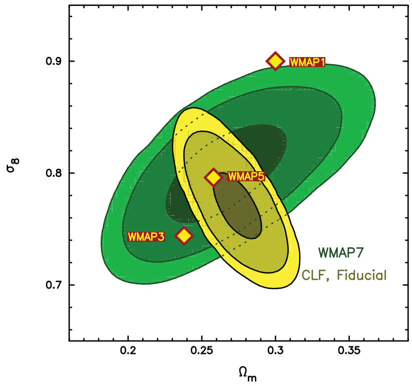


**Figure 2.** 68, 95 and 99 per cent confidence limits on the cosmological parameters $\Omega_m$ and $\sigma_8$ from our analysis (shown in chrome yellow) compared with the confidence limits obtained by the analysis of the WMAP-7 experiment (shown in green). (For a more definitive version, see [17].)

confidence contours, are shown in Figure 2 and compared to the WMAP-7 results.

There are two points worth making: First of all, the constraints obtained from our analysis are in remarkably good agreement with the WMAP-7 results, even though we have used no prior information on $\Omega_{\rm m}$ and $\sigma_8$. The WMAP-7 results are based on observations of the microwave background at a very early time in the Universe ($z \sim 1080$), and primarily rest on the physics of perturbations that can be treated with the help of linear perturbation theory. The results from our analysis derived from galaxy observations at redshift $z \sim 0.1$ and are obtained by modelling extremely non-linear scales, properly marginalizing over the uncertainties related to galaxy bias (i.e., the galaxy-dark matter connection). The agreement in cosmological constraints obtained from these two completely disjunct analyses is extremely striking, and provides strong support for the notion of a true 'concordance' cosmology: Clearly ΛCDM provides an excellent description of data over a large range of scales and cosmic epochs. Secondly, the constraints obtained from our analysis are both competitive with, and complementary to those obtained by the WMAP-7 analysis. This is also in agreement with the complementarity expected from the Fisher analysis presented in the previous subsection.

## 3. Summary
Observations of galaxies are an excellent way of probing the underlying matter distribution in the Universe and thereby, obtaining precise constraints on the cosmological model. We have shown that a joint analysis of the abundance of galaxies, the clustering of galaxies, and the galaxy-galaxy lensing signal in the framework of the halo model can be a useful way to constrain the cosmological parameters.

Using a Fisher matrix analysis, we have shown that the cosmological information contained in the three observables described above is complementary to each other and a joint analysis of these datasets is able to break a number of degeneracies between the CLF parameters and the cosmological parameters. We have followed up the Fisher analysis, by constraining our model parameters using the actual data. We have shown that the resulting constraints on the cosmological parameters $\Omega_{\rm m}$ and $\sigma_8$ are in remarkable agreement with constraints from the analysis of the WMAP-7 data. This is yet another jewel in the crown of the ΛCDM model, which continues to reign king.

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