BREAKING THE $\sigma_8 - \Omega_M$ DEGENERACY USING THE CLUSTERING OF HIGH-Z X-RAY AGN

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ABSTRACT

The clustering of X-ray selected AGN appears to be a valuable tool for extracting cosmological information. Using the recent high-precision angular clustering results of $\sim 30000$ XMM-Newton soft (0.5-2 keV) X-ray sources, we manage to break the $\Omega_m - \sigma_8$ degeneracy. The resulting cosmological constraints are: $\Omega_m = 0.27^{+0.03}_{-0.05}$, $w = -0.90^{+0.16}_{-0.14}$ and $\sigma_8 = 0.74^{+0.14}_{-0.12}$, while the dark matter host halo mass, in which the X-ray selected AGN are presumed to reside, is $M = 2.50^{+0.50}_{-1.50} \times 10^{13} h^{-1} M_\odot$. For the constant $\Lambda$ model ($w = -1$) we find $\Omega_m = 0.24 \pm 0.06$ and $\sigma_8 = 0.82^{+0.11}_{-0.16}$ in good agreement with recent studies based on cluster abundances, weak lensing and the CMB, but in disagreement with the recent bulk flow analysis.

Keywords: cosmology: cosmological parameters, large scale structure of the universe

1. INTRODUCTION

A large variety of cosmologically relevant data, based on the combination of galaxy clustering, the supernova $\Lambda$'s Hubble relation, the cosmic microwave background (CMB) fluctuations and weak-lensing strongly support a flat universe, containing cold dark matter (CDM) and “dark energy” which is necessary to explain the observed accelerated cosmic expansion (e.g., Komatsu et al. 2010; Hicken et al. 2009; Fu et al. 2008 and references therein).

The nature of the mechanism that is responsible for the late-time acceleration of the Hubble expansion is a fundamental problem in modern theoretical physics and cosmology. Due to the absence of a physically well-motivated fundamental theory, various proposals have been suggested in the literature, among which a cosmological constant, a time varying vacuum quintessence, $k$-essence, vector fields, phantom, tachyons, Chaplygin gas, etc (e.g., Weinberg 1989; Peebles & Ratra 2003; Boehmer & Harko 2007; Padmanabhan 2008 and references therein). Note that the simplest pattern of dark energy corresponds to a scalar field having a self-interaction potential with the associated field energy density decreasing with a slower rate than the matter energy density. In such a case the dark energy component is described by an equation of state $p = w \rho$ with $w < -1/3$ (dubbed “quintessence”, e.g., Peebles & Ratra 2003 and references therein). The traditional cosmological constant ($\Lambda$) model corresponds to $w = -1$. The viability of the different dark-energy models in reproducing the current excellent cosmological data and the requirements of galaxy formation is a subject of intense work (e.g., Basilakos, Plionis & Solá 2009 and references therein).

Another important cosmological parameter is the normalization of the cold dark matter power spectrum in the form of the rms density fluctuations in spheres of radius $8 h^{-1}$ Mpc, the so-called $\sigma_8$. There is a degenerate relation between $\sigma_8$ and $\Omega_m$ (e.g. Eke, Cole & Frenk 1996; Wang & Steinhardt 1998; Henry et al. 2009; Rozo et al. 2009 and references therein) and it is important to improve current constraints in order to break such degeneracies. Furthermore, there are also apparent inconsistencies between the values of $\sigma_8$ provided by different observational methods, among which the most deviant and problematic for the concordance cosmology, is provided by the recent bulk flow analysis of Watkins, Feldman & Hudson (2009).

In this paper we extend our previous work (Basilakos & Plionis 2009; hereafter BP09), using the angular clustering of the largest sample of high-z X-ray selected active galactic nuclei (Ebrero et al. 2009a), in an attempt to break the $\sigma_8 - \Omega_m$ degeneracy within spatially flat cosmological models.

2. BASIC METHODOLOGY

The main ingredients of the method used to put cosmological constraints based on the angular clustering of some extragalactic mass-tracer, has been already presented in our previous papers (see also Matsubara 2004; BP09 and references therein). It consists in comparing the observed angular clustering with that predicted by different primordial fluctuations power-spectra, using Limber’s equation to invert from spatial to angular clustering. By minimizing the differences of the observed and predicted angular correlation function, one can constrain the cosmological parameters that enter in the power-spectrum determination as well as in Limber’s inversion. Below we present only the main steps of the procedure.

2.1. Theoretical Angular and Spatial Clustering

Using the well known Limber’s inversion equation (Limber 1953), we can relate the angular and spatial clustering of any extragalactic population under the assumption of
power-law correlations and the small angle approximation (see details in BP09). After some algebraic calculations and within the context of flat spatial geometry, we can easily write the angular correlation function as:

\[ w(\theta) = \frac{2}{c} H_0 \int_0^\infty \left( \frac{dN}{dz} \right)^2 E(z) dz \int_0^\infty \xi(r, z) du, \]  

(1)

where \( dN/dz \) is the source redshift distribution, estimated by integrating the appropriate source luminosity function (in our case that of Ebrero et al. 2009b), folding in also the area curve of the survey. We also have

\[ E(z) = \left[ \Omega_m (1 + z)^3 + (1 - \Omega_m)(1 + z)^{3(1+w)} \right]^{1/2}, \]  

(2)

with \( w \) the dark-energy equation of state parameter given by \( p_Q = w \rho_Q \) with \( w < -1/3 \). The source spatial correlation function is:

\[ \xi(r, z) = (1 + z)^{(3+\epsilon)} b^2(z) \xi_{\text{DM}}(r), \]  

(3)

where \( b(z) \) is the evolution of the linear bias factor, \( \epsilon \) is a parameter related to the model of AGN clustering evolution (eg. de Zotti et al. 1990) and \( \xi_{\text{DM}}(r) \) is the corresponding correlation function of the underlying dark matter distribution, given by the Fourier transform of the spatial power spectrum \( P(k) \) of the matter fluctuations, linearly extrapolated to the present epoch:

\[ \xi_{\text{DM}}(r) = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k) \frac{\sin(kr)}{kr} dk. \]  

(4)

We use the nominal functional form of the CDM power spectrum, \( P(k) = P_0 k^{n-1} T^2(k) \), with \( T(k) \) the CDM transfer function (Bardeen et al. 1986; Sugiyama 1995) and \( n \simeq 0.96 \), following the 5 (and 7)-year WMAP results (Komatsu et al. 2010), and a baryonic density of \( \Omega_h^2 = 0.022(\pm 0.002) \). The normalization of the power-spectrum, \( P_0 \), can be parametrized by the rms mass fluctuations on \( R_s = 8h^{-1}\text{Mpc} \) scales (\( \sigma_8 \)), according to:

\[ P_0 = 2\pi^2 \sigma_8^2 \left[ \int_0^\infty T^2(k) k^{n+2} W^2(kR_s) dk \right]^{-1}, \]  

(5)

where \( W(kR_s) = 3(\sin kR_s - kR_s \cos kR_s)/(kR_s)^3 \). Regarding the Hubble constant we use either \( H_0 \simeq 71 \text{km}\text{s}^{-1}\text{Mpc}^{-1} \) (Freedman 2001; Komatsu et al. 2010) or \( H_0 \simeq 74 \text{km}\text{s}^{-1}\text{Mpc}^{-1} \) (Riess et al. 2009). Note, that in the current analysis we also utilize the non-linear corrections introduced by Peacock & Dodds (1994).

2.2. X-ray AGN bias evolution

The notion of the bias between mass-tracers and underlying DM mass is an essential ingredient for CDM models in order to reproduce the observed extragalactic source distribution (eg. Kaiser 1984; Davis et al. 1985; Bardeen et al. 1986).Although a large number of models have been proposed in the literature to model the evolution of the bias factor, in the current analysis we use our own approach, which was described initially in Basilakos & Plionis (2001; 2003) and extended in Basilakos, Plionis & Ragone-Figueroa (2008; hereafter BP08).

For a benefit of the reader we remind that our bias model is based on linear perturbation theory and the Friedmann-Lemaître solutions of the cosmological field equations, while it also allows for interactions and merging of the mass tracers. Under the usual assumption that each X-ray AGN is hosted by a dark matter halo of the same mass, we can present analytically its bias evolution behavior. A more realistic view, however, of the AGN host halo having a spread of masses around a given value, with a given distribution that does not change significantly with redshift, should not alter the predictions of our bias evolution model.

For the case of a spatially flat cosmological model, our bias evolution model predicts:

\[ b(M, z) = C_1(M) E(z) + C_2(M) I(z) + y(z) + 1, \]  

(6)

where

\[ y(z) = E(z) \left[ \int_0^z \frac{K(z)f(z)dz}{1 + x} - I(z) \int_0^z \frac{K(x)dz}{1 + x^3} \right], \]  

(7)

with \( K(z) = f(z) E^2(z), I(z) = \int_0^z (1 + x)^3dx/E^3(x), \)

\[ f(z) = A(m - 2)(1 + z)^m E(z)/D(z), \]  

(8)

\[ C_{1,2}(M) \simeq a_{1,2}(M/10^{13}h^{-1}M_\odot)^{b_{1,2}}, \]  

(9)

The various constants are given in BP08.\(^4\) Note that \( D(z) \) is the linear growth factor (scaled to unity at the present time), useful expressions of which can be found for the dark energy models in Silveira & Waga (1994) and in Basilakos (2003).

\(^4\) Following Kündic (1997) and Basilakos & Plionis (2005; 2006) we use the constant in comoving coordinates clustering model, ie., \( \epsilon = -1.2 \).

\(^5\) For the reader of the paper we present the values of the constants for a few selected cases: \( a_1 = 3.29, b_1 = 0.34, a_2 = -0.36, b_2 = 0.32 \), while in eq.(5) we have \( A = 5 \times 10^{-5} \) and \( m = 2.62 \) for \( 1 \times 10^{13} \leq M/h^{-1}M_\odot \leq 3 \times 10^{13} \), and \( A = 6 \times 10^{-5} \) and \( m = 2.54 \) for the case of \( 1 \times 10^{13} < M/h^{-1}M_\odot \leq 6 \times 10^{13} \).

Fig. 1.— The observed evolution of AGN bias (different points) compared with the BPR08 model predictions (curves). Optically selected SDSS and 2dF quasars are represented by empty dots and crosses, respectively, while X-ray selected AGN by filled (blue) squares. In the insert we plot the most recent optical QSO bias values of optical and X-ray selected AGNs with the solid (red) lines corresponding to a DM halo mass of \( M = 10^{13} h^{-1}M_\odot \) and the dashed line to \( M = 2.5 \times 10^{13} h^{-1}M_\odot \).

In order to provide an insight on the success or failure of our bias evolution model, we compare in Fig. 1 the measured bias values of optical and X-ray selected AGNs with our \( b(z) \) model. The bias of optical quasars by Croom et al. (2005), Myers et al. (2007), Shen et al. (2007) and Ross et al. (2009) based on the 2dF QSOs (open circles), SDSS DR4 (crosses), SDSS DR5 (solid points) and the SDSS quasar uniform sample (insert panel), are...
well approximated by our $b(z)$ model for a DM halo of $10^{13} h^{-1} M_{\odot}$ (solid red line) in agreement with previous studies (Porciani, Magliocchetti, Norberg 2004; Croom et al. 2005; Negrello, Magliocchetti & de Zotti 2006; Hopkins et al. 2007). However, what is worth stressing is that our model is (to our knowledge) the only one that can simultaneously fit the lower redshift ($z < 2.5$) optical AGN bias with the higher ($z > 3$) results of Shen et al. (2007) for the same halo mass of $10^{13} h^{-1} M_{\odot}$. The solid (blue) squares represent the bias of the soft X-ray selected AGNs, based on a variety of X-ray surveys (eg. Basilakos et al. 2005; Puccetti et al. 2006; Gilli et al. 2009; Ebrero et al. 2009a). The model $b(z)$ curve (dashed line) that fits these results correspond to halo masses $M = 2.5 \times 10^{13} h^{-1} M_{\odot}$, strongly indicating that X-ray and optically selected AGN do not inhabit the same DM halos.

3. COSMOLOGICAL PARAMETER ESTIMATION

We use the most recent measurement of the angular correlation function of X-ray selected AGN (Ebrero et al. 2009a). This measurement is based on a sample (hereafter 2XMM) constructed from 1063 XMM-Newton observations at high galactic latitudes and includes $\sim 30000$ soft (0.5-2 keV) point sources within an effective area of $\sim 125.5$ deg$^2$ and an effective flux-limit of $f_x \geq 1.4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (for more details see Mateos et al. 2008). Notice that the redshift selection function of the X-ray sources, obtained by using the soft-band luminosity function of Ebrero et al. (2009b), that takes into account the realistic luminosity dependent density evolution of the X-rays sources, predicts a characteristic depth of $z \sim 1$.

In BP09, using the 2XMM clustering, we already provided stringent cosmological constraints in the $\Omega_m - w$ plane, using as a prior a flat cosmology and the WMAP7 power-spectrum normalization value of Komatsu et al. (2010). In the current analysis we relax the latter prior and allow $\sigma_8$ to be a free parameter to be fitted by the data. Therefore the corresponding free-parameter vector that enters the standard $\chi^2$ likelihood procedure, which compares the observed and predicted clustering, is: $\mathbf{p} \equiv (\Omega_m, w, \sigma_8, M)$, with $M$ the AGN host dark matter halo mass, which enters in our BPR08 biasing evolution scheme.

The likelihood estimator is defined as: $\mathcal{L}_{\mathrm{AGN}}(\mathbf{p}) \propto \exp[-\chi^2_{\mathrm{AGN}}(\mathbf{p})/2]$ with:

$$\chi^2_{\mathrm{AGN}}(\mathbf{p}) = \sum_{i=1}^{n} \frac{[w_{\mathrm{th}}(\theta_i, \mathbf{p}) - w_{\mathrm{obs}}(\theta_i)]^2}{\sigma^2_{\mathrm{th}} + \sigma^2_{\mathrm{obs}}}, \quad (10)$$

where $n$ and $\sigma_i$ is the number of logarithmic bins ($n = 13$) and the uncertainty of the observed angular correlation function respectively, while $\sigma_{\theta_i}$ corresponds to the width of the angular separation bins.

We sample the various parameters in a grid as follows: the matter density $\Omega_m \in [0.01, 1]$ in steps of 0.01; the equation of state parameter $w \in [-1.6, -0.34]$ in steps of 0.01; the rms matter fluctuations $\sigma_8 \in [0.4, 1.4]$ in steps of 0.01 and the parent dark halo mass $M/10^{13} h^{-1} M_{\odot} \in [0.1, 4]$ in steps of 0.1. Note that we have allowed the parameter $w$ to take values below $-1$.

Our main results are listed in Table 1, where we quote the best fit parameters with the corresponding 1$\sigma$ uncertainties, for two different values of the Hubble constant.

Small variations around $\sim 71$ km$^{-1}$Mpc$^{-1}$ (which is the value used in the rest of the paper), appear to provide statistically indistinguishable results. The likelihood function of the soft X-ray sources peaks at $\Omega_m = 0.27^{+0.03}_{-0.05}$, $w = -0.90^{+0.11}_{-0.19}$, $\sigma_8 = 0.74^{+0.14}_{-0.12}$ and $M = 2.5^{+0.5}_{-1.5} \times 10^{13} h^{-1} M_{\odot}$, with a reduced $\chi^2$ of $\sim 4$. Such a large $\chi^2$/df value is caused by the measured small $w(\theta)$ uncertainties in combination with the observed $w(\theta)$ sinusoidal modulation (see BP09). Had we used a $2\sigma$ $w(\theta)$ uncertainty in eq. (10) we would have obtained roughly the same constraints and a reduced $\chi^2$ of $\sim 1$. The apparent sinusoidal $w(\theta)$ modulation is a subject of further investigation.

**Fig. 2.** Likelihood contours ($1\sigma$, $2\sigma$ and $3\sigma$) in the following planes: $(\Omega_m, w)$ (upper left panel), $(\Omega_m, \sigma_8)$ (upper right panel), $(\sigma_8, w)$ (bottom left panel) and $(\sigma_8, M)$ (bottom right panel). In the upper two panels we show for clarity our current solution with thick (red) contours, while the dashed contours correspond to our previous analysis, based on the shallower XMM/2dF survey (Basilakos & Plionis 2006).

In Fig.2 we present the $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels (corresponding to where $-2\ln \mathcal{L}/\mathcal{L}_{\max}$ equals 2.30, 6.16 and 11.83) in the $(\Omega_m, w)$, $(\Omega_m, \sigma_8)$, $(\sigma_8, w)$ and $(\sigma_8, M)$ planes, by marginalizing the first one over $M$ and $\sigma_8$, the second one over $M$ and $w$, the third one over $M$ and $\Omega_m$ and the last one over $\Omega_m$ and $w$. We also present, with dashed lines, our previous solution of Basilakos & Plionis (2006), which we derived by using the shallower (effective flux-limit of $f_x \geq 2.7 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) and significantly smaller ($\sim 2.3$ deg$^2$) XMM/2dF survey (Basilakos et al. 2005). Comparing our current results with our previous analysis it becomes evident that with the current high-precision X-ray AGN correlation function of Ebrero et al. (2009a) we have achieved to break the $\Omega_m - \sigma_8$ degeneracy and to substantially improve the constraints on $\Omega_m$, $w$ and $\sigma_8$. However, there are still degeneracies, the most important of which is in the $w - \sigma_8$ plane.

It should be mentioned that some recent works, based on the large-scale bulk flows, strongly challenge the concordance ΛCDM cosmology by implying a very large $\sigma_8$ value. Indeed, Watkins et al. (2009), using a variety of tracers to measure the bulk flow on scales of $\sim 100 h^{-1}$Mpc, found a value of $\sim 400$ km s$^{-1}$ that implies a $\sigma_8$ normalization.
which is a factor of ~2 larger than what expected in the concordance cosmology. On the high $\sigma_8$ side are also the results of Reichardt et al. (2009), based on the secondary SunayeV-Zeldovich anisotropies in the CMB, providing $\sigma_8 \approx 0.94$, as well as a novel analysis based on the integrated Sachs-Wolfe effect (Ho et al. 2008).

Contrary to the above results, our X-ray AGN clustering analysis provides a $\sigma_8$ value consistent with the concordance cosmology and in agreement with a variety of other studies. In particular, for $w = -1$ (Λ cosmology) and $M = 2.5_{-0.3}^{+0.1} \times 10^{13} h^{-1} M_{\odot}$, we find $\Omega_m = 0.24 \pm 0.06$ and $\sigma_8 = 0.83_{-0.16}^{+0.2}$ (see Table 1). Our results are in agreement with those of recent cluster abundances studies, providing (for $w = -1$): $\sigma_8 = 0.86 \pm 0.04 (\Omega_m/0.3)^{-0.3}$ (Henry et al. 2009) and $\sigma_8 = 0.83 \pm 0.03 (\Omega_m/0.25)^{-0.41}$ (Rozo et al. 2009). Furthermore, Mantz et al. (2009) using as a new cosmological tool the simultaneous fit of the peculiar velocities statistical analysis, Pike & Hudson (2005) and Cabr´e & Gaztañaga (2009) obtained $\sigma_8 = 0.88 \pm 0.05 (\Omega_m/0.25)^{-0.53}$ and $\sigma_8 = 0.85 \pm 0.06$ (for $\Omega_m = 0.245$), respectively. The consistency of all the (seven) previously mentioned works (including the current study) can be also appreciated from their average $\sigma_8$ value which is (for $w = -1$ and ignoring the different $\Omega_m$ values): $\langle \sigma_8 \rangle = 0.84 \pm 0.009$, where the quoted uncertainty is the $1\sigma$ scatter of the mean. Note that the combined WMAP 7-years+SNIa+BAO analysis of Komatsu et al. (2010) provide a slightly lower value of $\sigma_8 = 0.809 \pm 0.024$ (with $\Omega_m = 0.272 \pm 0.015$ and $w = -0.98 \pm 0.05$).

4. Conclusions

We have used the recent angular clustering measurements of high-$z$ X-ray selected AGN, identified as soft (0.5-2 keV) XMM point sources (Ebrero et al. 2009a), in order to break the degeneracy between the rms mass fluctuations $\sigma_8$ and $\Omega_m$. Applying a standard likelihood procedure, assuming a constant in comoving coordinates AGN clustering evolution, the bias evolution model of Basilakos et al. (2008) and a spatially flat geometry, we put relatively stringent constraints on the main cosmological parameters, given by: $\Omega_m = 0.27^{+0.03}_{-0.05}$, $w = -0.90^{+0.10}_{-0.16}$ and $\sigma_8 = 0.74^{+0.14}_{-0.11}$. We also find that the dark matter host halo mass, in which the X-ray selected AGN are assumed to reside, is $M = 2.50^{+0.50}_{-1.50} \times 10^{13} h^{-1} M_{\odot}$. Finally, if we marginalize over the previous host halo mass and $w = -1$ (Λ cosmology), we find $\Omega_m = 0.24 \pm 0.06$ and $\sigma_8 = 0.83_{-0.16}^{+0.11}$.

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Breaking the $\sigma_8 - \Omega_m$ degeneracy

Table 1

| $H_0$/kms$^{-1}$Mpc$^{-1}$ | $\Omega_m$    | $w$      | $\sigma_8$ | $M/10^{13}h^{-1}M_\odot$ |
|---------------------------|---------------|----------|-------------|--------------------------|
| 71                        | $0.27^{+0.03}_{-0.05}$ | $-0.90^{+0.16}_{-0.14}$ | $0.74^{+0.12}_{-0.14}$ | $2.50^{+0.10}_{-0.10}$ |
| 74                        | $0.26^{+0.04}_{-0.05}$ | $-0.92^{+0.08}_{-0.14}$ | $0.72^{+0.16}_{-0.14}$ | $2.50^{+0.10}_{-1.50}$ |
| 71                        | $0.24 \pm 0.06$    | $-1$     | $0.83^{+0.11}_{-0.16}$ | $2.50$                  |

*Errors of the fitted parameters represent 1σ uncertainties.*