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BREAKING THE $\sigma_8-\Omega_m$ DEGENERACY USING THE CLUSTERING OF HIGH-z X-RAY ACTIVE GALACTIC NUCLEI

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ABSTRACT

The clustering of X-ray selected active galactic nuclei (AGNs) appears to be a valuable tool for extracting cosmological information. Using the recent high-precision angular clustering results of ∼30,000 *XMM-Newton* soft (0.5–2 keV) X-ray sources, which have a median redshift of $z \sim 1$, and assuming a flat geometry, a constant in comoving coordinates AGN clustering evolution, and the AGN bias evolution model of Basilakos et al., we manage to break the σ_8–Ω_m degeneracy. The resulting cosmological constraints are $\Omega_m = 0.27^{+0.03}_{-0.05}$, $\mathrm{w} = -0.90^{+0.10}_{-0.16}$, and $\sigma_8 = 0.74^{+0.14}_{-0.12}$, while the dark matter host halo mass, in which the X-ray selected AGNs are presumed to reside, is $M = 2.50^{+0.50}_{-1.50} \times 10^{13}\, h^{-1}\, M_\odot$. For the constant Λ model ($\mathrm{w} = -1$) we find $\Omega_m = 0.24 \pm 0.06$ and $\sigma_8 = 0.83^{+0.11}_{-0.16}$, in good agreement with recent studies based on cluster abundances, weak lensing, and the cosmic microwave background, but in disagreement with the recent bulk flow analysis.

Key words: cosmological parameters – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

A large variety of cosmologically relevant data, based on the combination of galaxy clustering, the supernova Ia'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, such as 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 case, the dark-energy component is described by an equation of state $p_Q = \mathrm{w}\rho_Q$ with $\mathrm{w} < -1/3$ (dubbed "quintessence," e.g., Peebles & Ratra 2003, and references therein). The traditional cosmological constant (Λ) model corresponds to $\mathrm{w} = -1$. 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 et al. 2009, and references therein).

Another important cosmological parameter is the normalization of the CDM power spectrum in the form of the rms density fluctuations in spheres of radius $8h^{-1}$ Mpc, the so-called σ_8. There is a degenerate relation between σ_8 and Ω_m (e.g., Eke et al. 1996; Wang & Steinhardt 1998; Henry et al. 2009; Rozo et al. 2010, 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 σ_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 et al. (2009).

In this Letter, 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 (AGNs; 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, have 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

$$w(\theta) = 2\frac{H_0}{c}\int_0^\infty \left(\frac{1}{N}\frac{dN}{dz}\right)^2 E(z)dz \int_0^\infty \xi(r,z)\, du, \quad (1)$$

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

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

with w the dark-energy equation of state parameter given by $p_Q = \mathrm{w}\rho_Q$ with $\mathrm{w} < -1/3$. The source spatial correlation function is

$$\xi(r,z) = (1+z)^{-(3+\epsilon)} b^2(z)\xi_{\rm DM}(r), \quad (3)$$

where $b(z)$ is the evolution of the linear bias factor, ϵ is a parameter related to the model of AGN clustering evolution (e.g., de Zotti et al. 1990),[4] and $\xi_{\rm DM}(r)$ 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:

$$\xi_{\rm DM}(r) = \frac{1}{2\pi^2}\int_0^\infty k^2 P(k)\frac{\sin(kr)}{kr}dk. \quad (4)$$

We use the nominal functional form of the CDM power spectrum, $P(k) = P_0 k^n T^2(k)$, with $T(k)$ the CDM transfer function (Bardeen et al. 1986; Sugiyama 1995) and $n \simeq 0.96$, following the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) results (Komatsu et al. 2010) and a baryonic density of $\Omega_b h^2 = 0.022(\pm 0.002)$. The normalization of the power spectrum, P_0, can be parameterized by the rms mass fluctuations on $R_8 = 8\,h^{-1}$ Mpc scales (σ_8), according to

$$P_0 = 2\pi^2\sigma_8^2\left[\int_0^\infty T^2(k)k^{n+2}W^2(kR_8)dk\right]^{-1}, \quad (5)$$

where $W(kR_8) = 3(\sin kR_8 - kR_8\cos kR_8)/(kR_8)^3$. Regarding the Hubble constant, we use either $H_0 \simeq 71$ km s^{-1} Mpc^{-1} (Freedman et al. 2001; Komatsu et al. 2010) or $H_0 \simeq 74$ km s^{-1} Mpc^{-1} (Riess et al. 2009). Note that in the current analysis we also utilize the nonlinear corrections introduced by Peacock & Dodds (1994).

2.2. X-ray AGN Bias Evolution

The notion of the bias between mass tracers and underlying dark matter (DM) mass is an essential ingredient for CDM models in order to reproduce the observed extragalactic source distribution (e.g., 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 et al. (2008, hereafter BPR08).

For the benefit of the reader, we remind that our bias model is based on linear perturbation theory and the Friedmann–Lemaitre 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

$$b(M,z) = \mathcal{C}_1(M)E(z) + \mathcal{C}_2(M)E(z)I(z) + y(z) + 1, \quad (6)$$

where

$$y(z) = E(z)\left[\int_0^z \frac{\mathcal{K}(x)I(x)dx}{(1+x)^3} - I(z)\int_0^z \frac{\mathcal{K}(x)dx}{(1+x)^3}\right], \quad (7)$$

with $\mathcal{K}(z) = f(z)E^2(z)$, $I(z) = \int_z^\infty (1+x)^3 dx/E^3(x)$,

$$f(z) = A(m-2)(1+z)^m E(z)/D(z), \quad (8)$$

$$\mathcal{C}_{1,2}(M) \simeq \alpha_{1,2}(M/10^{13}\,h^{-1}\,M_\odot)^{\beta_{1,2}}. \quad (9)$$

The various constants are given in BPR08.[5] 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 Basilakos (2003).

In order to provide an insight on the success or failure of our bias evolution model, we compare in Figure 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 Two-Degree Field (2dF) QSOs (open circles), Sloan Digital Sky Survey Data Release 4 (SDSS DR4; crosses), SDSS DR5 (solid points), and the SDSS quasar uniform sample (inset 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 et al. 2004; Croom et al. 2005; Negrello et al. 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 (e.g., 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 AGNs (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 ∼30,000 soft (0.5–2 keV) point sources within an effective area of ∼125.5 deg^2 and an effective flux limit of $f_x \geqslant 1.4\times 10^{-15}$ erg cm^{-2} s^{-1} (for more details, see

[4] Following Kúndic (1997) and Basilakos & Plionis (2005, 2006), we use the constant in the comoving coordinates clustering model, i.e., $\epsilon = -1.2$.

[5] For the benefit of the reader, we present the values of the constants for a few selected cases: $\alpha_1 = 3.29$, $\beta_1 = 0.34$ and $\alpha_2 = -0.36$, $\beta_2 = 0.32$, while in Equation (8) we have $A = 5\times 10^{-3}$ and $m = 2.62$ for $1\times 10^{13} \leqslant M/h^{-1}\,M_\odot \leqslant 3\times 10^{13}$, and $A = 6\times 10^{-3}$ and $m = 2.54$ for the case of $1\times 10^{13} < M/h^{-1}\,M_\odot \leqslant 6\times 10^{13}$.

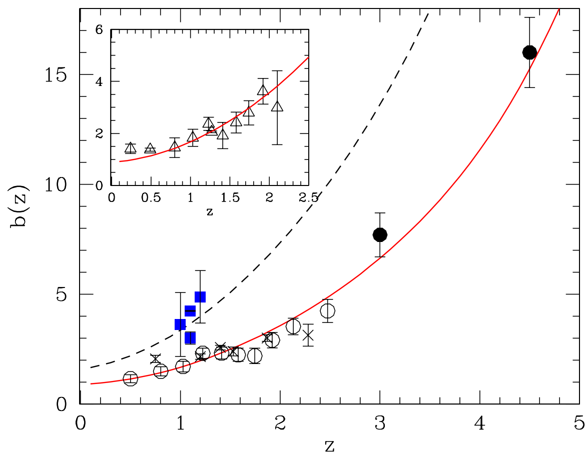

Figure 1. Observed evolution of AGN bias (different points) compared with the BPR08 model predictions (curves). Optically selected SDSS and 2dF quasars are represented by empty dots and crosses, respectively, while X-ray selected AGNs by filled (blue) squares. In the inset, we plot the most recent optical QSO bias values based on the SDSS quasar uniform sample (Ross et al. 2009). The curves represent the expectations of the BPR08 model, with the solid (red) lines corresponding to a DM halo mass of $M = 10^{13}\,h^{-1}\,M_\odot$ and the dashed line to $M = 2.5 \times 10^{13}\,h^{-1}\,M_\odot$.

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Mateos et al. 2008). Note 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-ray sources, predicts a characteristic depth of $z \sim 1$.

In BP09, using the 2XMM clustering, we already provided stringent cosmological constraints in the Ω_m–w plane, using as a prior a flat cosmology and the *WMAP* power-spectrum normalization value (Komatsu et al. 2010). In the current analysis, we relax the latter prior and allow σ_8 to be a free parameter to be fitted by the data. Therefore, the corresponding free-parameter vector that enters the standard χ^2 likelihood procedure, which compares the observed and predicted clustering, is $\mathbf{p} \equiv (\Omega_m, \mathrm{w}, \sigma_8, M)$, with M the AGN host dark matter halo mass, which enters in our BPR08 biasing evolution scheme.

The likelihood estimator,[6] is defined as $\mathcal{L}_{\rm AGN}(\mathbf{p}) \propto \exp[-\chi^2_{\rm AGN}(\mathbf{p})/2]$, with

$$\chi^2_{\rm AGN}(\mathbf{p}) = \sum_{i=1}^{n} [w_{\rm th}(\theta_i, \mathbf{p}) - w_{\rm obs}(\theta_i)]^2 \Big/ \left(\sigma_i^2 + \sigma_{\theta_i}^2\right) , \qquad (10)$$

where n and σ_i are the number of logarithmic bins ($n = 13$) and the uncertainty of the observed angular correlation function, respectively, while σ_{θ_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 $\mathrm{w} \in [-1.6, -0.34]$ 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 matter halo $M/10^{13}\,h^{-1}\,M_\odot \in [0.1, 4]$ 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 1σ uncertainties, for two different values of the Hubble constant. Small variations

[6] Likelihoods are normalized to their maximum values.

Table 1
The Best-fit Cosmological Parameters from the Likelihood Analysis

H_0 (km s^{-1} Mpc^{-1})	Ω_m	w	σ_8	M ($10^{13}\,h^{-1}\,M_\odot$)
71	$0.27^{+0.03}_{-0.05}$	$-0.90^{+0.10}_{-0.16}$	$0.74^{+0.14}_{-0.12}$	$2.50^{+0.50}_{-1.50}$
74	$0.26^{+0.04}_{-0.05}$	$-0.92^{+0.08}_{-0.14}$	$0.72^{+0.16}_{-0.14}$	$2.50^{+0.50}_{-1.50}$
71	0.24 ± 0.06	-1	$0.83^{+0.11}_{-0.16}$	2.50

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

around $\sim$71 km s^{-1} Mpc^{-1} (which is the value used in the rest of the Letter) appear to provide statistically indistinguishable results. The likelihood function of the soft X-ray sources peaks at $\Omega_m = 0.27^{+0.03}_{-0.05}$, $\mathrm{w} = -0.90^{+0.11}_{-0.19}$, $\sigma_8 = 0.74^{+0.14}_{-0.12}$, and $M = 2.5^{+0.5}_{-1.5} \times 10^{13}\,h^{-1}\,M_\odot$, with a reduced χ^2 of $\sim$4. Such a large χ^2/(degrees of freedom) 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 2σ $w(\theta)$ uncertainty in Equation (10) we would have obtained roughly the same constraints and a reduced χ^2 of $\sim$1. The apparent sinusoidal $w(\theta)$ modulation is a subject of further investigation.

In Figure 2, we present the 1σ, 2σ, and 3σ confidence levels (corresponding to where $-2\ln\mathcal{L}/\mathcal{L}_{\rm max}$ equals 2.30, 6.16, and 11.83) in the (Ω_m, w), (Ω_m, σ_8), (σ_8, w), and (σ_8, M) planes, by marginalizing the first one over M and σ_8, the second one over M and w, the third one over M and $\Omega_{\rm m}$, and the last one over Ω_m and w. We also present, with dashed lines, our previous solution of Basilakos & Plionis (2006), which was derived by using the shallower (effective flux limit of $f_x \geqslant 2.7 \times 10^{-14}$ erg cm^{-2} s^{-1}) and significantly smaller ($\sim$2.3 deg^2) *XMM-Newton*/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 the breaking of the $\sigma_8-\Omega_m$ degeneracy and substantially improved the constraints on Ω_m, w, and σ_8. However, there are still degeneracies, the most important of which is in the w–σ_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 σ_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 σ_8 normalization which is a factor of $\sim$2 larger than what is expected in the *concordance* cosmology. On the high σ_8 side are also the results of Reichardt et al. (2009), based on the secondary Sunyaev–Zel'dovich anisotropies in the CMB, providing $\sigma_8 \simeq 0.94$, 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 σ_8 value consistent with the *concordance* cosmology and in agreement with a variety of other studies. In particular, for $\mathrm{w} = -1$ (Λ cosmology) and $M = 2.5^{+0.3}_{-0.2} \times 10^{13}\,h^{-1}\,M_\odot$, we find $\Omega_m = 0.24 \pm 0.06$ and $\sigma_8 = 0.83^{+0.11}_{-0.16}$ (see Table 1). Our results are in agreement with those of recent cluster abundance studies, providing (for $\mathrm{w} = -1$) $\sigma_8 = 0.86 \pm 0.04(\Omega_m/0.32)^{-0.3}$ (Henry et al. 2009) and $\sigma_8 = 0.83 \pm 0.03(\Omega_m/0.25)^{-0.41}$ (Rozo et al. 2010). Furthermore, Mantz et al. (2009), using as a new cosmological tool the simultaneous fit of the cosmological parameter space and the cluster X-ray luminosity–mass relation, also broke the $\sigma_8-\Omega_m$ degeneracy and found $\Omega_m = 0.23 \pm 0.04$, $\sigma_8 = 0.82 \pm 0.05$, and $\mathrm{w} = -1.01 \pm 0.20$ (see their Table 2 and Figure 4), which

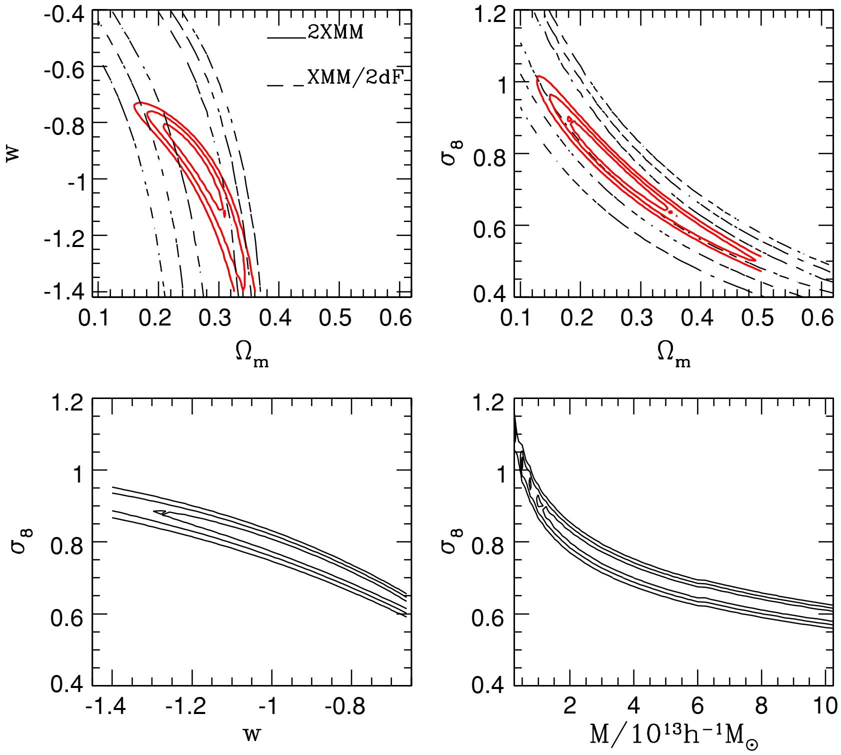

Figure 2. Likelihood contours (1σ, 2σ, and 3σ) in the following planes: (Ω_m, w) (upper left panel), (Ω_m, σ_8) (upper right panel), (σ_8, w) (bottom left panel), and (σ_8, M) (bottom right panel). In the upper two panels we show for clarity our current solution with thick (red) contours, while the dashed contours correspond to our previous analysis, based on the shallower *XMM-Newton*/2dF survey (Basilakos & Plionis 2006).

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are in excellent agreement with our $w = -1$ results (see the last row in Table 1). Note that their combined analysis (utilizing also the CMB, baryonic acoustic oscillations, and gas mass fraction) provides $\Omega_m = 0.27 \pm 0.02$, $w = -0.96 \pm 0.06$, and $\sigma_8 = 0.79 \pm 0.03$. Moreover, Fu et al. (2008) based on a weak-lensing analysis found the degenerate combination $\sigma_8 = 0.837 \pm 0.084(\Omega_m/0.25)^{0.-53}$. From the peculiar velocities statistical analysis, Pike & Hudson (2005) and Cabré & 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 σ_8 value which is (for $w = -1$ and ignoring the different Ω_m values) $\langle\sigma_8\rangle = 0.844 \pm 0.009$, where the quoted uncertainty is the 1σ scatter of the mean. Note that the combined *WMAP* 7-years+SNIa+BAO analysis of Komatsu et al. (2010) provides 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 AGNs, identified as soft (0.5–2 keV) *XMM-Newton* point sources (Ebrero et al. 2009a), in order to break the degeneracy between the rms mass fluctuations σ_8 and Ω_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 $\sigma_8 = 0.74^{+0.14}_{-0.12}$. We also find that the dark matter host halo mass, in which the X-ray selected AGNs 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 $\sigma_8 = 0.83^{+0.11}_{-0.16}$.

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