A Strategy to Measure the Dark Energy Equation of State using the HII galaxy Hubble Function & X-ray AGN Clustering: Preliminary Results.

M. Plionis\textsuperscript{1,2}, R. Terlevich\textsuperscript{2}, S. Basilakos\textsuperscript{3}, F. Bresolin\textsuperscript{4}, E. Terlevich\textsuperscript{2}, J. Melnick\textsuperscript{5}, R. Chavez\textsuperscript{2}

\textsuperscript{1} Institute of Astronomy & Astrophysics, National Observatory of Athens, Palaia Penteli 152 36, Athens, Greece.
\textsuperscript{2} Instituto Nacional de Astrofísica Optica y Electrónica, AP 51 y 216, 72000, Puebla, México.
\textsuperscript{3} Academy of Athens, Research Center for Astronomy and Applied Mathematics, Soranou Efesiou 4, 11527, Athens, Greece
\textsuperscript{4} Institute for Astronomy of the University of Hawaii, 2680 Wooldaen Drive, 96822 Honolulu, HI USA
\textsuperscript{5} European Southern Observatory, Alonso de Cordoba 3107, Santiago, Chile

ABSTRACT

We explore the possibility of setting stringent constraints to the Dark Energy equation of state using alternative cosmic tracers like: (a) the Hubble relation using HII galaxies, which can be observed at much higher redshifts ($z \lesssim 3.5$) than those currently traced by SNIa samples, and (b) the large-scale structure using the clustering of X-ray selected AGN, which have a redshift distribution peaking at $z \sim 1$.

In this paper we use extensive Monte-Carlo simulations to define the optimal strategy for the recovery of the dark-energy equation of state using the high redshift ($z \sim 2$) Hubble relation, but accounting also for the effects of gravitational lensing, which for such high redshifts can significantly affect the derived cosmological constraints. We investigate the size of the sample of high-$z$ HII-galaxies needed to provide useful constraints in the Dark Energy equation of state. Based on a “Figure of Merit” analysis, we provide estimates for the number of $2 \lesssim z \lesssim 3.5$ tracers needed to reduce the cosmological solution space, presently provided by the SNIa set, by a desired factor. The analysis is given for any level of rms distance modulus uncertainty and we find that an expected reduction (i.e. by $\sim 20\%-40\%$) of the current level of HII-galaxy based distance modulus uncertainty does not provide a significant improvement in the derived cosmological constraints. It is much more efficient to increase the number of tracers than to reduce their individual uncertainties.

Finally, we propose a framework to put constraints on the dark energy equation of state by using the joint likelihood of the X-ray AGN clustering and of the Hubble relation cosmological analyses. A preliminary joint analysis using the X-ray AGN clustering of the 2XMM survey and the Hubble relation of the Constitution SNIa set provide: $\Omega_m = 0.31 \pm 0.01$ and $w = -1.06 \pm 0.05$. We also find that the joint SNIa-2XMM analysis provides significantly more stringent cosmological constraints, increasing the Figure of Merit by a factor $\sim 2$, with respect to that of the joint SNIa-BAO analysis.

1 INTRODUCTION

We live in a very exciting period for our understanding of the Cosmos. Over the past decade the accumulation and detailed analyses of high quality cosmological data (eg., supernovae type Ia, CMB temperature fluctuations, galaxy clustering, high $z$ clusters of galaxies, etc.) have strongly suggested that we live in a flat and accelerating universe, which contains at least some sort of cold dark matter to explain the clustering of extragalactic sources, and an extra component which acts as having a negative pressure, as for example the energy of the vacuum (or in a more general setting the so called dark energy), to explain the observed accelerated cosmic expansion (eg. Riess, et al. 1998; 2004; Perlmutter et al. 1999; Spergel et al. 2003, 2007, Tonry et al. 2003; Schuecker et al. 2003; Tegmark et al. 2004; Seljak et al. 2004; Allen et al. 2004; Basilakos & Plionis 2005; 2006; 2009; Blake et al. 2007; Davis et al. 2007; Kowalski et al. 2008, Komatsu et al. 2009; Hicken et al. 2009, Amanullah et al. 2010, etc).

Due to the absence of a well-motivated fundamental theory, there have been many theoretical speculations regarding the nature of the dark energy (hereafter DE), on whether it is a cosmological constant or a field that provides a time varying equation of state, usually parametrized by:
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with $p_Q$ and $\rho_Q$ the pressure and density of the exotic dark energy fluid. For a large class of DE models, we have:

$$w(z) = w_0 + w_1 f(z),$$

with $w_0 = w(z = 0)$ and $f(z)$ an increasing function of redshift. A particular example of $w(z)$ is its 1st order Taylor’s expansion around $w(0)$, which provides $f(z) = z/(1+z)$, i.e., the so-called CPL form of the DE equation of state (Chevallier & Polarski 2001, Linder 2003; see also Peebles & Ratra 2003, Dicus & Repko 2004; Wang & Mukherjee 2006). Of course, it could also be conceived that the equation of state parameter does not evolve cosmologically (quintessence Dark Energy model; QDE).

It is clear that one of the most important questions in Cosmology and cosmic structure formation is related to the nature of dark energy (as well as whether it is the sole explanation of the observed accelerated expansion of the Universe) and its interpretation within a fundamental physical theory (eg., Albrecht et al. 2006; Peacock et al. 2006). To this end, a large number of very expensive experiments are proposed and/or are at various stages of development, viz the Dark Energy Survey: http://www.darkenergysurvey.org/, the Joint Dark Energy Mission: http://jdem.gsfc.nasa.gov/, HETDEX http://www.as.utexas.edu/hetdex/, Pan-STARRS: http://pan-starrs.ifa.hawaii.edu, Euclid: http://sci.esa.int/euclid/, Wfirst: http://wfirst.gsfc.nasa.gov, etc.

Therefore, the paramount importance of the detection and quantification of DE for our understanding of the cosmos and for fundamental theories implies that the results of the different experiments should not only be scrutinized, but alternative, even higher-risk, methods to measure DE should be developed and applied as well. It is within this paradigm that our current work falls. Indeed, we wish to constrain the DE equation of state using, individually and in combination, the Hubble relation and large-scale structure (clustering) methods, but utilizing alternative cosmic tracers for both of these components.

Thus, we will trace the Hubble relation using HII galaxies, which can be observed at higher redshifts than reached by current SN Ia surveys to distances where the Hubble relation is more sensitive to the cosmological parameters. The HII galaxies can be used as standard candles (Melnick, Terlevich & Terlevich 2000, Melnick 2003; Siegel et al. 2005; Plionis et al. 2009) due to the correlation between their velocity dispersion, $H_\beta$ luminosity and metallicity (Melnick 1978, Terlevich & Melnick 1981, Melnick, Terlevich & Moles 1988). Furthermore, the use of such alternative high z tracer will enable us to check the SN Ia results and lift any doubts that arise from the fact that they are the only tracers of the Hubble relation used to-date (for possible usage of GRBs see for example, Ghirlanda et al. 2006, 2009; Basilakos & Perivolaropoulos 2008 and references therein).

Additionally, we use X-ray selected AGN at a median redshift of $\sim 1$, which is roughly the peak of their redshift distribution (see Basilakos et al. 2004; 2005, Miyaji et al. 2007), in order to determine their clustering pattern and compare it with that predicted by different cosmological models (see Matsubara 2004).

Although each of the previously discussed components of our project (Hubble relation using HII galaxies and angular/spatial clustering of X-ray AGN) will provide interesting and relatively stringent constraints on the cosmological parameters, especially under our anticipation that we will reduce significantly the corresponding random and systematic errors, it is the combined likelihood of these two type of analyses that enables us to break the known degeneracies between cosmological parameters and determine with great accuracy the DE equation of state (see Basilakos & Plionis 2005; 2006; 2009).

Below we present the basic methodology and expectations of the two components of our method. In section 2 we present the details of the first component where we develop a Monte-Carlo simulation approach designed to ultimately provide a rule of thumb of how many HII galaxies we need to obtain a particular level of the DE equation of state parameter uncertainty. We also develop a method to account for the effects of gravitational lensing, which at such high redshifts are significant. In section 3 we present the details of the second component and in section 4 we present an example of joining the two components to provide cosmological constraints. The conclusions are listed in section 5.

2 COSMOLOGICAL PARAMETERS FROM THE HUBBLE RELATION

In the matter dominated epoch and in flat universes, the Hubble relation depends on the cosmological parameters via the following equation:

$$H(z) = H_0 E(z)$$

and

$$E^2(z) = \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_Q \exp \left[ 3 \int_0^z \frac{1 + w(x)}{1 + x} dx \right].$$

which is simply derived from Friedman’s equation. We remind the reader that $\Omega_m$, $\Omega_k$ and $\Omega_Q (\equiv 1 - \Omega_m - \Omega_k)$ are the present fractional contributions to the total cosmic mass-energy density of the matter, the spatial curvature and dark energy source terms, respectively.

Supernovae SN Ia are considered standard candles at peak luminosity and therefore they have been used not only...
Figure 1. Left Panel: The expected distance modulus difference between the DE models shown and the reference $\Lambda$-model ($w= -1$) with $\Omega_m = 0.27$. Right Panel: The expected distance modulus differences once the $\Omega_m$-$w(z)$ degeneracy is broken (imposing the same $\Omega_m$ value as in the comparison model).

2.1 Theoretical Expectations:

To appreciate the magnitude of the Hubble relation variations due to the different DE equation of states, we plot in Figure 1 the relative deviations of the distance modulus, $\Delta \mu$, of different dark-energy models from a nominal standard (w= -1) $\Lambda$-cosmology (with $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$), with the relative deviations defined as:

$$\Delta \mu = \mu_{\Lambda} - \mu_{\text{model}}.$$  (8)

The parameters of the different models used are shown in Figure 1. As far as the dark-energy equation of state parameter is concerned, we present the deviations from the standard model of two models with a constant $w$ value and of two models with an evolving equation of state parameter, utilizing the form of eq.(2). In the left panel of Figure 1 we present results for selected values of $\Omega_m$, while in the right panel we use the same dark-energy equations of state parameters but for the same value of $\Omega_m (= 0.27)$ (ie., we avoid the $\Omega_m$-$w(z)$ degeneracy).

Three important observations should be made from Figure 1:

(i) The relative magnitude deviations between the different dark-energy models are quite small (typically $\lesssim 0.1$ mag), which puts severe pressure on the necessary photometric accuracy of the relevant observations.

(ii) The largest relative deviations of the distance moduli occur at redshifts $z \gtrsim 1.5$, quite larger than those currently traced by SN Ia samples, and

(iii) There are strong degeneracies between the different cosmological models at redshifts $z \lesssim 1$, and in some models even up to much higher redshifts (eg., between the models with $(\Omega_m, w_0, w_1) = (0.31, -1, 0)$ and $(0.29, -1, 0.3)$; see Figure 1).

Luckily, as discussed already in the introduction, such degeneracies can be broken by using other cosmological probes (eg., the clustering of extragalactic sources, the CMB shift pa-
rameter, BAO’s, etc). Indeed, current evidence overwhelm-
ingly show that the total matter content of the universe is
within the range: $0.2 \lesssim \Omega_m \lesssim 0.3$, a fact that reduces sig-
nificantly the degeneracies between the cosmological param-
eters.

2.2 Gravitational Lensing Effects on High $z$
Distance Moduli

A potentially important systematic effect that could hin-
der attempts to put stringent cosmological constraints via
the Hubble relation, especially when using high $z$ standard
candles (which as we saw are those precisely that differen-
tiate between DE equations of state) is related to gravita-
tional lensing by structures intervening between source and
receptor. It is indeed known that the gravitational poten-
tial of large-scale structure affects the propagation of light
from high redshift sources and thus also the distance modu-
lus of similarly high redshift standard candles (eg., Holz &
Wald 1998; Holz & Linder 2005; Brouzakis & Tetradis 2008
and references therein). These studies assume a Robertson-
Walker background superimposing a locally inhomogeneous
universe and take into account both strong and weak lensing
effects. The resulting magnification distribution of a single
source over different paths is non-Gaussian and therefore
has a non-trivial effect on its distance modulus, especially
so for the high $z$ standard candles.

The main characteristics of the magnification proba-
bility density function, $P(\mu_a)$, as derived from a variety
of studies based on Monte-Carlo analyses and ray-tracing
techniques, is that $P(\mu_a)$ resembles a log-normal distribu-
tion with zero mean (the mean flux of each source over all
possible different paths is conserved, since lensing does not
affect photon numbers), with a mode shifted towards the
de-magnified regime and a long tail to high magnification.
This implies that most sources will be de-magnified, induc-
ing an apparently enhanced accelerated expansion, while a
few will be highly magnified. The effect is obviously stronger
for higher redshift sources since the lower the redshift the
less the optical depth of lensing. Note that although the de-
tailed shape of $P(\mu_a)$ is a function of the underlying cosmo-
logy, density profile and evolutionary phase of the interven-

![Figure 2. Probability density function of the lensing magnification (left), flux (middle) and magnitude (right) distributions for a source with intrinsic magnitude uncertainty of $\sigma_{\text{int}} = 0.1$ at two different redshifts (thin line corresponds to $z = 1$, while the thick line to $z = 3$).](image-url)
with $S^2$ the variance of $\ln \mu_\text{a}$. The mean magnification is given by $\langle \mu_\text{a} \rangle = \exp (\langle \ln \mu_\text{a} \rangle + S^2/2) = 1$, implying that $\langle \ln \mu_\text{a} \rangle = -S^2/2$. Therefore, the probability function is skewed ($\langle \ln \mu_\text{a} \rangle < 0$) and determined by only the $S$ parameter. From eq.(9) HL05 derived the corresponding flux distribution, which is also log-normal, and then the corresponding magnitude distribution, which is given by:

$$P(m) = \frac{1}{\sigma_m \sqrt{2\pi}} \exp \left[ \frac{-(m - m_0 + b\langle \ln \mu_\text{a} \rangle)^2}{2\sigma^2_\text{m}} \right] \quad (10)$$

with $b = 2.5/\ln 10$ and $\sigma^2_\text{m} = \sigma^2_{\text{obs}} + (bS)^2$. Therefore, we re-capitulate that the effects of lensing are:

(a) an offset of the mean, given by:

$$\langle m \rangle = m_0 + \delta m \quad (11)$$

where $m_0$ is the intrinsic (demagnified) magnitude, and $\delta m = -b\langle \ln \mu_\text{a} \rangle = bS^2/2$, and,

(b) an increase of the variance for which we have that $\sigma^2_\text{eff} = (bS)^2$ and thus $S^2 = \sigma^2_\text{eff}/b^2$.

Recalling that for large enough sources ($N$), in relatively small $z$-bins ($\sim 0.1z$), we have that $\sigma^2_{\text{eff}} = N\sigma^2_\text{N}$, we obtain that the magnitude offset of sources within the redshift bin is given by:

$$\delta m(z) = \frac{\sigma^2_\text{eff}}{2bN} = \frac{(0.093z)^2}{2bN} \quad (12)$$

and the total source variance:

$$\sigma^2_m(z) = \sigma^2_{\text{obs}} + (0.093z)^2/N \quad (13)$$

In Figure 2 we plot as an example the magnification, flux and magnitude probability distributions for the case of a single source placed at two different redshifts ($z = 1$ and $3$) and for an intrinsic observational magnitude uncertainty of $\sigma_{\text{obs}} = 0.1$. The intrinsic flux of the source is assumed to be $10^{-17}$ erg $s^{-1}$ cm$^{-2}$ and the intrinsic apparent magnitude $m = 18$. The main effects discussed previously are clearly seen, i.e., a mode offset towards the demagnification (fainter) regime and an enhanced variance, both increasing with redshift. In Figure 3 we plot the expected increase of both the mode offset and variance (in magnitudes) as a function of redshift for a single source (left panel). In the right panel of the same Figure we plot the suppression of both quantities as we increase the source sampling (the case shown corresponds to a source located at a redshift $z = 3$).

We will therefore correct statistically the distance moduli of observed standard candles (SNIa, GRBs, HII-galaxies, etc) by subtracting an offset $\delta m(z)$ from their raw distance modulus (according to eq.12), within redshift bins of $\sim 0.1z$ width and using as the total distance modulus uncertainty that given by eq.(13).

### 2.3 Best Strategy to Determine the DE Equation of State

#### 2.3.1 Fitting Models to the Data

We can now proceed with our investigation to find an efficient strategy to put more stringent constraints on the dark-energy equation of state. To this end we have decided to re-analyse two recently compiled SNIa samples, the Davis et al. (2007) [hereafter D07] compilation of 192 SNIa (based on data from Wood-Vasey et al. 2007, Riess et al. 2007 and Astier et al. 2007) and the Constitution compilation of 397 SNIa (Hicken et al. 2009). Note that the two samples are not independent since most of the D07 is included in the Constitution sample.

Firstly, we present in the left panel of Figure 4 the Constitution SNIa distance moduli overplotted (red-continuous line) with the theoretical expectation of a flat cosmology with $(\Omega_m, w) = (0.27, -1)$. In the inset we plot the distance moduli difference between the SNIa data and the pre-

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**Figure 3.** The mode offset ($\delta m$) and effective variance ($\sigma_{\text{eff}}$) (a) of a source as a function of redshift (left panel) and (b) as a function of the number of sources, $N$, tracing the same redshift (for this example $z = 3$).
The corresponding difference between the reference (red-continuous line) and the two best fit models (see Table 1) is presented in Figure 4. The distance modulus difference between the best fit model and the theoretical models is given by eq. (5), where $\sigma$ is the distance modulus uncertainty, which includes the observational uncertainty and the gravitational lensing variance (see eq. 13). Since in occasional cases the observational distance modulus uncertainty has the form: $\mu_{\text{obs}} - \mu_{\text{th}}$, i.e., it is non-symmetric (due to its logarithmic dependence on the flux), we will use a slightly different weighting scheme in the minimization function that takes into account the asymmetric observational uncertainty. Following Barlow (2004), and assuming that the likelihood function of the observed $\mu$, derived from the theoretical $\mu(p)$, is a Gaussian, we can use the following weighting scheme of the $\chi^2$ function:

$$\sigma_1 = \sigma_1 + \sigma_2 \left[ \mu_{\text{th}}(p) - \mu_{\text{obs}} \right]$$

with $\sigma_1 = 2\sigma_p\sigma_n/(\sigma_p + \sigma_n)$ and $\sigma_2 = (\sigma_p - \sigma_n)/(\sigma_p + \sigma_n)$. Obviously, when $\sigma_p = \sigma_n$ we recover the usual symmetric error weighting.

In what follows we will constrain our analysis within the framework of a flat ($\Omega_m + \Omega_Q = 1$) cosmology and therefore $p \equiv (\Omega_m, w_0, w_1)$. Note that we sample the various parameters on a grid as follows: the matter density $\Omega_m \in [0.04, 0.64]$, the equation of state parameter $w \in [-2.0, -0.5]$, while when using a time-dependent equation of state: $w_0 \in [0, -2]$ and $w_1 \in [-3, 3]$. The typical step size that we use is 0.0015. Note that the uncertainty of each fitted parameter will be estimated after marginalizing one parameter over the other, providing as its uncertainty the range for which $\Delta \chi^2 \leq 2.3$ (2$\sigma$). Such a definition, however, may hide the extent of a possible degeneracy between the two fitted parameters and therefore it is important to visualize the 2D solution space, as indicated in the relevant contour plots.

### 2.3.2 Larger Numbers?

The first issue that we wish to address is how better have we done in imposing cosmological constraints by increasing the available SNIa sample from 181 to 366 (excluding the $z < 0.02$ SNIa)\(^\dagger\), i.e., more than doubling the sample. Table 1 presents various solutions using each of the two previously

\(^\dagger\) We use only SNIa with $z \geq 0.02$ in order to avoid redshift uncertainties due to the local bulk flow (eg. Hudson et al. 1999 and references therein).
the whole range of the 1... beyond inspecting the relevant contour plots, is to also present... the extent of the degeneracy between the two... the reader that the definition we use (see above) cannot... Hubble constant, see for example Wei 2008).

ternally derived Hubble constant (for methods that do not... for both data sets. However, there is a reduction of the size of the solution space when using the Constitution SNIA compilation (see also Table 1) at roughly the level expected from Poisson statistics.

A first conclusion is therefore that the increase by ~100% of the Constitution sample has not broken the degeneracy in the \( (\Omega_m, w) \) plane and thus has not provided significantly more stringent constraints to the cosmological parameters. We have further verified that the larger number of SNIA's in the Constitution sample are not preferentially located at low-z's (see inset panel of Fig.5) - in which case we would not have expected more stringent cosmological constraints using the latter SNIA sample, but they have very similar z-distributions.

We already have a strong hint, from the previously presented comparison between the D07 and Constitution results, that increasing the number of Hubble relation tracers, covering the same redshift range and with the current level of uncertainties, as in the available SNIA samples, does not appear to be an efficient avenue for providing stringent constraints of the cosmological parameters.

2.3.3 Lower uncertainties or higher z’s:

We now resort to a Monte-Carlo procedure to investigate which of the following two directions, that bracket many different possibilities, provide the required more stringent cosmological constraints:

- Reduce significantly the distance modulus uncertainties of SNIA, tracing however the same redshift range as the currently available samples, or
- use tracers of the Hubble relation located at redshifts where the models show their largest relative differences (z ≥ 2), with distance modulus uncertainties comparable to that of the highest redshift SNIA’s (\( \sigma_m \) ≃ 0.4). At such large redshifts however we expect that the gravitational lensing magnification/de-magnification effects will be significant and therefore we will also use the algorithm presented in section 2.2 to statistically degrade the intrinsic source flux and investigate its effects on the derived cosmological parameters.

The Monte-Carlo procedure is based on using the observed high z SNIA distance modulus uncertainty distribution (\( \sigma_m \)) and a model to assign random \( \mu \)-deviations from a reference \( H(z) \) function, that reproduces exactly the original banana-shaped contours of the \( (\Omega_m, w) \) solution space of Figure 5, or in the case of the CPL model of the DE...
degradation (right panel) the relevant uncertainty, the reference model (with the corresponding reduction of the random deviations of the SNIa distance moduli from the questions posed previously. Firstly, we reduce to half their uncertainties (central panel of Figure 7), which shows that indeed by inserting statistically the expected lensing degradation (right panel). For clarity we show only contours corresponding to the 1 and 3σ confidence levels.

Table 1. Cosmological parameter fits using the SNIa data for a flat prior cosmology. Note that for the case where \( p = (\Omega_m, w) \), the indicated uncertainties are estimated by fixing one parameter at its best value and allowing the other to vary, providing as its uncertainty the range for which \( \Delta \chi^2 \leq 2.3 \).

|        | \( D07 \)          | \( Constitution \) |
|--------|--------------------|----------------------|
|        | \( w \) \( \Omega_m \) \( \chi^2_{\text{min}}/\text{dof} \) | \( w \) \( \Omega_m \) \( \chi^2_{\text{min}}/\text{dof} \) |
| Raw    | \( -1 \) 0.287 ± 0.020 186.721/180 | \( -1 \) 0.285 ± 0.015 439.745/365 |
|        | \( -1.005 \pm 0.076 \) 0.289 ± 0.030 186.721/179 | \( -1.038 \pm 0.053 \) 0.300 ± 0.022 439.703/364 |
| Lensing corrected | \( -1 \) 0.288 ± 0.020 184.775/180 | \( -1 \) 0.284 ± 0.014 438.263/365 |
|        | \( -0.995 \pm 0.075 \) 0.286 ± 0.030 184.775/179 | \( -1.036 \pm 0.053 \) 0.299 ± 0.022 438.229/364 |

Figure 7. Comparison of the model Constitution SNIa constraints (black contours) with those (filled contours) derived by reducing to half their uncertainties (left panel), with those derived by adding a sample of 76 high \( z \) tracers (\( 2 \leq z \leq 3.5 \)) with a distance modulus mean uncertainty of \( \langle \sigma_\mu \rangle \simeq 0.5 \) and no lensing degradation (central panel), and with those by including statistically the expected lensing degradation (right panel). For clarity we show only contours corresponding to the 1 and 3σ confidence levels.

equation of state the corresponding contours in the \( w_0, w_1 \) solution-space. Indeed, after a trial and error procedure we have found that by assigning to each SNIa (using their true redshift) a distance modulus deviation \( (\delta \mu) \) from a reference model having a Gaussian distribution with zero mean and variance given by the observed \( (\sigma_\mu)^2 \), and using as the relevant individual distance modulus uncertainty the following: \( \sigma_\mu^2 = (1.25\delta \mu)^2 + \phi^2 \) (with \( \phi \) a random Poisson deviation within \([-0.01, 0.01]\)) we reproduce exactly the banana-shaped solution range of the reference model. This can be clearly seen in Figure 6, where we plot the original Constitution SNIa solution space (red shaded contours) and the model solution space (black contours). In the inset panel we show the distribution of the true SNIa deviations from the best fitted model as well as a random realization of the corresponding model deviations.

Armed with the above procedure we can now address the questions posed previously. Firstly, we reduce to half the random deviations of the SNIa distance moduli from the reference model (with the corresponding reduction of the relevant uncertainty, \( \sigma_i \)). The results of the likelihood analysis can be seen in the left panel of Figure 7. There is a reduction of the range of the solution space, but indeed quite a small one. Secondly, we add to the Constitution SNIa sample, a mock subsample of 76 high \( z \) tracers with a distance modulus mean uncertainty of \( \langle \sigma_\mu \rangle \simeq 0.5 \) (corresponding to that of the current HII-galaxy data) randomly distributed between \( 2 \leq z \leq 3.5 \), i.e., in a range where the largest deviations between the different cosmological models occur (see Figure 1). We now find a significantly reduced solution space (central panel of Figure 7), which shows that indeed by increasing the \( H(z) \) tracers by a few tens, at those redshifts where the largest deviations between models occur, can have a significant impact on the recovered cosmological parameter solution space. If we include the expected lensing degradation of the distance modulus (according to eq.12), then we observe (right panel of Figure 7) a slightly worsening of the solution space, but still significantly smaller than that of the left panel of Fig.7.

The main conclusion of the previous analysis is that a more efficient strategy to decrease the uncertainties of the cosmological parameters, based on the Hubble relation, is...
to use standard candles which trace also the redshift range $2 < z < 3.5$. However, in such a case the effects of gravitational lensing can be severe, especially for small number of high-$z$ tracers, and therefore it is necessary to be taken into account.

### 2.3.4 Figure of Merit Analysis

In order to study the relation between the number of high-$z$ tracers used and the corresponding reduction of the cosmological parameter solution space, we will use the Figure of Merit (FoM; Bassett 2005; Albrecht et al. 2006; Bueno Sanchez, Nesseris & Perivolaropoulos 2009), defined as the reciprocal area of the $2\sigma$ contour (i.e., where $-2\ln L/L_{\text{max}} = 6.14$) in the parameter space of any two degenerate cosmological parameters [e.g., $(\Omega_m, w)$ for the QDE model or $(w_0, w_1)$ for the CPL model], and which has been found to be a useful measure of the effectiveness of a data set in constraining cosmological parameters. A larger figure of merit indicates a greater accuracy in constraining the cosmological parameters.

Here we will use a slightly different quantity, which we call “reduction factor” and is indicated by $S$, defined as the ratio of the FoM of the SNIa+high-$z$ Hubble relation solution to that of only the SNIa (in both cases we use the Constitution set), in order to study the question of how better we can constrain the cosmological parameter space, when adding $N_{\text{high}_z}$ high-$z$ tracers of the Hubble relation, with respect to the best current SNIa data set as a function of the number of high-$z$ tracers. For example a value $S = 2$ indicates that the FoM based on the SNIa+high-$z$ Hubble relation is half of that based on the Constitution SNIa data set, i.e., the $2\sigma$ range of the solution space is reduced by a factor of 2.

In Figure 8 we present the results of our analysis as a function of the number of high-$z$ tracers for the QDE model. We present results only for the realistic lensing degradation case and for two different values of the distance modulus mean observational uncertainty, ranging between a pessimistic $(\langle \sigma_\mu \rangle = 0.5$; open circles) and an optimistic $(\langle \sigma_\mu \rangle = 0.25$; filled points) value.

It is evident that including even a small number of high-$z$ tracers we can reduce significantly the cosmological parameter solution space. There is a roughly linear relation between $S$ and the number of high-$z$ tracers used, $N_{\text{high}_z}$, which depends obviously on the distance modulus mean uncertainty, $(\langle \sigma_\mu \rangle$ and on whether one uses in addition to the high-$z$ tracers also the lower redshift SNIa data.

It is also interesting to note that the high-$z$ HII galaxies could constrain cosmological parameters with the level of accuracy provided by current SNIa data sets (for $N_{\text{high}_z} \sim 200$) and thus lift any doubts that arise from the fact that SNIa are the only reliable tracers of the Hubble relation to date. Of course the above relatively large number of high-$z$ HII galaxies can be significantly reduced by including an intermediate population of HII galaxies, i.e., tracing similar depths as the current SNIa samples ($z \sim 1$). In such a case the expected values of $S$ will be intermediate between the only high-$z$ and SNIa-high-$z$ curves of Figure 8. For example, a realistic case of a sample with $80 \ 0.2 < z < 1$ and $60 \ z > 2$ HII galaxies and a rms distance modulus uncertainty of $\sim 0.35$ will provide similar constraints as the current SNIa based analyses ($S \sim 1$).

In order to quantify the previous results and provide a tool to estimate the number of high-$z$ tracers necessary to reduce the current SNIa solution space by a given factor, taking into account the whole parameter space, we first normalize the S values by that given for, say, $N_{\text{high}_z} = 100$ ($S_{100}$). We then quantify how $S_{100}$ depends on $(\sigma_\mu)$, which is shown in the inset panel of Figure 8. The continuous curves are logarithmic fits to the data, which are given by the following equations:

$$S_{100}^\text{QDE} \simeq \begin{cases} 187 \log_{10}(\langle \sigma_\mu \rangle^{-1} + 0.74) + 1.28 & \text{SNIa+high}_z \\ 0.44 \log_{10}(\langle \sigma_\mu \rangle^{-1} + 0.15) + 0.30 & \text{only high}_z \end{cases} \quad (17)$$

Then, in order to obtain the number of high-$z$ tracers, $N_{\text{high}_z}$, necessary to reduce the cosmological solution space (in the QDE model) by a factor $S$, we fit the normalized value, $S/S_{100}$ and find:

$$N_{\text{high}_z} \simeq \begin{cases} 187 \ S/S_{100} - 88 & \text{SNIa+high}_z \\ 139 \ S/S_{100} - 39 & \text{only high}_z \end{cases} \quad (18)$$

which has a typical uncertainty of $\sigma_{N_{\text{high}_z}} = \pm 5$ for both the SNIa+high$_z$ and only high$_z$ cases. The continuous (red) lines in the left panel of Fig.8 are derived from eq.(17) and eq.(18) for $(\langle \sigma_\mu \rangle = 0.25$ and 0.5, and it is evident that they reproduce extremely well the observed $S$ values (points). As an example, we can ask how many high-$z$ tracers, with say $(\langle \sigma_\mu \rangle = 0.4$, do we need to add to the current SNIa data set in order to reduce by a factor of 2 ($S = 2$) the current SNIa QDE solution space. Using eq.(17) and eq.(18) we find

![Figure 8](image-url)
$N_{\text{high}} \approx 80$, which drops to $\sim 60$ for $\langle \sigma_\mu \rangle = 0.25$. It is therefore interesting to point out that a reduction by a factor of 2 in the distance modulus uncertainty, of the high-$z$ tracers (which is really a non-trivial aim) can be compensated by a relatively small increase in the number of high-$z$ tracers.

Repeating the previous analysis for the case of an evolving DE equation of state (CPL; as in eq. 2), and after marginalizing with respect to $\Omega_m$, we also find a reduction of the $(w_0, w_1)$ solution space, when we include the high-$z$ tracer subsample (Fig. 9), but significantly smaller than that of the QDE parametrization. We can again estimate what is the necessary number of high-$z$ tracers, $N_{\text{high}}$, having a mean distance modulus error of $\langle \sigma_\mu \rangle$, in order to reduce the cosmological $(w_0, w_1)$ solution space by a factor $S$. Again using a parametrization based on the value of $S$ for $N_{\text{high}} = 100$, we have that:

\[
S_{100}^{\text{CPL}} \approx \begin{cases} 
0.49 \log_{10}(\langle \sigma_\mu \rangle^{-1} + 0.65) + 1.09 & \text{SNIIa+high}_z \\
0.20 \log_{10}(\langle \sigma_\mu \rangle^{-1} + 0.69) + 0.22 & \text{only high}_z 
\end{cases} \quad (19)
\]

and

\[
N_{\text{high}} \approx \begin{cases} 
404 S/S_{100} - 300 & \text{SNIIa+high}_z \\
211 S/S_{100} - 106 & \text{only high}_z 
\end{cases} \quad (20)
\]

with a typical uncertainty of $\sigma_N \approx \pm 7$ for the SNIIa+high-$z$ and only high-$z$ cases, respectively. These results imply that in order to reduce by a factor of 2 ($S = 2$) the current SNIa CPL solution space using high-$z$ tracers with $\langle \sigma_\mu \rangle \approx 0.35$, one needs $N_{\text{high}} \approx 300$ and 1200 for the SNIIa+high-$z$ and only high-$z$ tracers case, respectively. The latter value can be significantly reduced if we include an intermediate redshift ($0.2 \lesssim z \lesssim 1$) HI1 sample, as discussed also for the QDE case previously. For example, using a sample of 80 such intermediate $z$ HI1 galaxies reduces this number by a factor of 2. In any case, the large number of high-$z$ tracers of the Hubble expansion, needed to effectively constrain the CPL equation of state, renders this task rather unrealistic. Therefore, in order to provide stringent cosmological constraints for the CPL model (ie., the values of $w_0$ and $w_1$), it would be necessary (a) to combine the high-$z$ Hubble relation with that of current SNIa data, and (b) to join the Hubble relation analysis with other cosmological tests, like the one that is an integral part of our proposal, ie., the clustering of X-ray AGN. Of course other cosmological probes, like BAOs, can and should be used as well.

We now draw the main conclusions of our Monte-Carlo analysis:

- Even a small number of high-$z$ ($2 \lesssim z \lesssim 3.5$) tracers of the Hubble expansion can reduce significantly the QDE model parameter solution space.
- For the case of the CPL model, in order to reduce the $(w_0, w_1)$ solution space, provided by the current Constitution SNIa set, by the same amount as in the corresponding QDM model, one needs three or more as many high-$z$ Hubble expansion tracers.
- It appears that the effort to reduce significantly the current level of random distance modulus scatter of HI1 galaxies is not as important as it is to increase the number of high-$z$ HI1 galaxies, unless one is able to reduce it to $\langle \sigma_\mu \rangle \lesssim 0.1 - 0.2$ (as can be seen in the inset panel of Fig.8).

![Figure 9](image)

**Figure 9.** As in Figure 8 but for an evolving DE equation of state (CPL model) and after marginalizing with respect to $\Omega_m$. The input cosmological model has $(\Omega_m, w_0, w_1) = (0.3, -0.98, -0.48)$. The axes scale has been kept as in Figure 8 in order to appreciate the significant reduction of efficiency of the high-$z$ Hubble relation in providing cosmological constraints for the CPL model.

### 2.4 A High $z$ Hubble Relation tracer: HI1 galaxies

HI1 galaxies, compact extragalactic objects experiencing massive bursts of star formation, have a high luminosity per unit mass, in large part concentrated in a few strong emission lines in the optical rest frame. This ensures that the first, obvious, requirement for a standard candle to be usable at very large distances is met.

The potential use of HI1 galaxies as distance indicators stems from the fact that as one increases the mass of the young stellar component, not only the ionizing output increases, but also the turbulent velocity of the gas, which is indicative of supersonic motions in the gas in the stellar gravitational potential, becomes larger. This effect induces a correlation between the integrated luminosity in a nebular hydrogen recombination line, e.g. $L(H\beta)$, which is proportional to the number of ionizing photons, and the line width $\sigma$.

Terlevich & Melnick (1981) found the first observational confirmation of a correlation between $H\beta$ luminosity and line profile width for giant extragalactic HI1 regions and HI1 galaxies, with residuals that are correlated with the nebular metallicity. Subsequent work by Melnick et al. (1987; 1988) was devoted to obtain a calibration of this correlation in order to make it suitable for distance measurements.

The distance indicator, defined as $M_z = \sigma^2/(O/H)$ with $O/H$ the oxygen abundance of the nebular gas, provides the predicted luminosity from the relation:

\[
\log L(H\beta) = \log M_z + P_0 \, , \quad (21)
\]

where the zero-point $P_0 = 29.60$ was originally defined from a sample of 14 giant extragalactic HI1 regions (Melnick et al. 1988) and from which they obtained $H_0 = 80 \pm 5$ km sec$^{-1}$ Mpc$^{-1}$. Obviously, a critical prerequisite for using such scal-
ing relations as distance estimators is an accurate calibration of their zero-points. Note that a semi-empirical upper limit of $\sigma = 65$ km/s has been proposed for suitable galaxies, which can be explained by the requirement that HII galaxies are powered by clusters of coeval starbursts with their dynamics dominated by pressure and not rotation.

The $L(H_{\beta}) - \sigma$ relation has been shown to hold also at large redshifts (Koo et al. 1996, Pettini et al. 2001, Erb et al. 2003). Melnick et al. (2000) showed that HII-like starburst galaxies up to $z \simeq 3$, satisfy the $L(H_{\beta})-\sigma$ relation, opening the possibility of using the relation to measure cosmological parameters. They derived the following distance modulus relation for HII galaxies:

$$
\mu = 2.5 \log(\sigma^2/F_{H\beta}) - 2.5 \log(O/H) - A_{H\beta} + Z_0 ,
$$

(22)

where $F_{H\beta}$ and $A_{H\beta}$ are the flux and extinction in $H_{\beta}$, respectively. The originally determined zero-point was $Z_0 = -26.18$ and the rms distance modulus dispersion was found to be $\sim 0.52$ mag. Although, such an rms uncertainty is larger than what is obtained with SNIa, the advantage of using HII galaxies is that we can reach a much larger redshift limit ($z \sim 4$ vs $z \sim 1.7$).

Using recent galaxy distance determinations we should be able to better determine the zero-point of the distance indicator, $Z_0$. To this end we have repeated the original analysis of Melnick et al. (1988; 2000), using Cepheid and RR Lyrae distance determinations and indeed the rms scatter of the distance indicator relation is reduced by $\sim 7\%$ while $P_0 = 29.44$. This results in a reduction by $\sim 0.42$ mags of the zero-point (i.e., $Z_0 = -26.60$), which provides results consistent with $H_0 = 73$ km sec$^{-1}$ Mpc$^{-1}$ (Chávez et al. 2012 in preparation).

It should also be mentioned that there are some systematic effects than can bias distances obtained with the $L(H_{\beta}) - \sigma$ relation, in particular differences in the ages of the stellar populations, contamination from underlying old stellar components, or different extinction laws. To some extent these effects can be mitigated by using the equivalent widths of the lines to select only very young objects, and the use of modern instrumentation that allows a precise control of the size, orientation, and location of the spectrograph slits. Still the observations remain challenging and require a high level of planning and control.

We are at the process of completing an investigation of these effects by using high-resolution spectroscopy of a relatively large number of SDSS low-z HII galaxies with a wide range of relevant parameters ($H_{\beta}$ equivalent widths and luminosities, metal content, and local overdensity) in an attempt to understand systematics and to reduce the scatter of the distance estimator (Chávez et al. 2011 in preparation).

Most high-z HII galaxies known until recently were found in broad-band searches aimed mostly to search for Lyman break galaxies, which means that they generally have relatively strong continua. Still, a substantial fraction present strong emission lines making them ideal for our distance estimator (see for example Erb et al. 2006a; 2006b). Furthermore, deep slit-less surveys using WFC3 on HST and Narrow band filters at SUBARU have revealed substantial numbers of HII galaxies with large equivalent widths (i.e. strong emission lines and weak continua) at intermediate and high redshifts (Yamada et al. 2005; Kakazu, Cowie, & Hu 2007; Xia et al. 2011; Atek et al. 2010; Nestor et al. 2011).

Table 2. Cosmological parameter fits using the Siegel et al. HII-galaxies and the newly derived zero-point $Z_0$ (eq. 22). The QDE equation of state parameter, $w$, remains completely unconstrained by the current analysis.

| $w$ | $\Omega_m$ | $\chi^2_{\text{min}}$/dof |
|-----|-----------|--------------------------|
| -1  | 0.198$^{+0.051}_{-0.044}$ | 53.057/14 |
| unconstrained | 0.280$^{+0.048}_{-0.038}$ | 53.849/13 |

excluding 2 galaxies with tilted emission lines

| $w$ | $\Omega_m$ | $\chi^2_{\text{min}}$/dof |
|-----|-----------|--------------------------|
| -1  | 0.224$^{+0.063}_{-0.026}$ | 43.119/12 |
| unconstrained | 0.310$^{+0.052}_{-0.046}$ | 42.954/11 |

Figure 10. The HII-galaxy QDE constraints (in the $\Omega_m$, w plane), based on the Siegel et al. sample after excluding two HII galaxies showing strong indications for a rotational velocity component. Although the constraints are weak, leaving completely unconstrained the value of w, they are consistent at a $\sim 1\sigma$ level with the SNIa results (thin red contours).

Straughn et al., 2011). In all, the present sample has more than 400 HII galaxies covering the redshift range 0.5$<z<$3.7 with about 100 in the range 3.0$<z<$3.7 and about 150 at $z\sim2$.

Summarizing, the use of HII galaxies to trace the Hubble relation, as an alternative to the traditionally used SN Ia, is based on the following facts:

(a) local and high z HII galaxies define a phenomenological relation between $H_{\beta}$ luminosity, velocity dispersion, and metallicity as traced by $O/H$ that holds out to cosmological distances. Thus, HII galaxies can be used as alternative tracers of the Hubble expansion;
(b) HII galaxies can be readily observed at much larger redshifts than those currently probed by SNIa samples, and;
(c) it is at such higher redshifts that the differences between...
the predictions of the different cosmological models appear more vividly (see Fig. 1).

A more recent application using 15 starburst galaxies with redshift in the range $z = 2.17-3.39$ has been carried out by Siegel et al. (2005) in an attempt to constrain cosmological parameters, but the resulting constraints are rather weak. They found $\Omega_m = 0.21^{+0.30}_{-0.12}$ for a $\Lambda$-dominated Universe. Clearly, the errors are still large, and up to this point the results are not competitive with SNIa.

We have performed our own re-analysis of this data-set, following a similar procedure to that applied to the SNIa data in the previous sections, but using the newly derived value of $Z_0$ in eq. (22), allowing for the asymmetric uncertainties of the HII-galaxy distance moduli and correcting for the effects of gravitational lensing, according to section 2.2. Furthermore, we have updated the values of the stellar velocity dispersion and its uncertainty, for some of the galaxies in the Siegel et al. sample, according to Erb et al. (2006a).

The resulting constraints on the $(\Omega_m, w)$ plane are indicated in the first two rows of Table 2, while in the last two rows (and in Figure 10) we present results after excluding two HII galaxies (Q1700-MD103 and SSA22a-MD41) that show indications of a significant rotational velocity component (derived from the tilted emission lines; Erb et al. 2006a), which contaminates the estimate of their velocity dispersion.

Our results show that the derived $\Omega_m$ values, independent of the value of $w$, are towards the lower end of the generally accepted range, while when excluding the two rotating galaxies the fitted $\Omega_m$ parameter moves towards higher values, while there is also a decrease of the value of the corresponding reduced $\chi^2$.

In any case, the main qualitative result of our HII-galaxy based analysis is that although the constraints in the $(\Omega_m, w)$ plane are consistent with those of the Constitution SNia analysis, as can be seen in Fig. 10, the provided cosmological parameter uncertainties are significantly larger and the degeneracy between $\Omega_m$ and $w$ is even more exacerbated. These results clearly indicate that the distance indicator for HII galaxies is highly competitive provided:

- We increase the number of available high-$z$ ($z \gtrsim 2$) HII galaxies, but it is important to cover also the $0.2 < z < 1$ range (as shown in section 2.3.4).
- We apply the estimator to a significant sample of bona-fide high redshift HII galaxies selected by the strength of their emission lines to ensure no contamination by rotation and/or underlying old stellar populations.
- We minimize all possible sources of systematic and random errors.

3 COSMOLOGICAL PARAMETERS FROM THE CLUSTERING OF X-RAY AGN

The method used to put cosmological constraints, based on the clustering of some extragalactic mass-tracer (Matsubara 2004, Basilakos & Plionis 2009 - hereafter BP09 - and references therein), consists in comparing the observed spatial or angular clustering with that predicted by different primordial fluctuations power-spectra, in the latter case using also Limber’s integral equation (Limber 1953) to invert the spatial to angular clustering. By minimizing the differences of the observed and predicted correlation function, one can constrain the cosmological parameters that enter in the power-spectrum determination as well as in Limber’s inversion. Using the latter we can relate the angular and spatial clustering of any extragalactic population under the assumption of power-law correlations and the small angle approximation.

We have chosen X-ray selected AGN as a tracer of the large-scale structure, in order to perform the previously described analysis, for the following reasons:

(a) X-ray selected AGN can be detected out to high redshifts (the peak of their $z$-distribution is $\sim 1$) and thus trace the distant density fluctuations providing a further anchor of the evolution parameter at a redshift other than $z \sim 0$, which most galaxy samples trace to-date.

(b) AGN selected through their X-ray emission (and not in the optical) provide a relatively unbiased census of the AGN phenomenon, since obscured AGN, largely missed in optical surveys, are included in X-ray surveys.

(c) Furthermore, determining the clustering at $z \sim 1$ and $z \sim 0$, one can put better constraints on the cosmic evolution of the AGN phenomenon and the evolution of the relation between AGN activity and Dark Matter (DM) halo hosts (eg. Mo & White 1996, Sheth et al. 2001), and finally also on the cosmological parameters and the dark-energy equation of state (eg. Basilakos & Plionis 2005; 2006; 2009; 2010).

3.1 Clustering of X-ray AGN: Biases and Systematics

The earlier ROSAT-based analyses (eg. Boyle & Mo 1993; Vikhlinin & Forman 1995; Carrera et al. 1998; Akylas, Georgantzopoulos & Plionis; 2000; Mullis et al. 2004) provided conflicting results on the nature and amplitude of high $z$ AGN clustering. With the advent of the XMM and Chandra X-ray observatories, many groups have attempted to settle this issue, but in vain. Different surveys have provided again a multitude of conflicting results, intensifying the debate (eg. Yang et al. 2003; Manners et al. 2003; Basilakos et al. 2004; Gilli et al. 2005; Basilakos et al 2005; Yang et al. 2006; Puccetti et al. 2006; Miyaji et al. 2007; Gandhi et al. 2006; Carrera et al. 2007; Coil et al. 2009; Starikova et al. 2010). However, strong indications exist for a flux-limit dependent clustering, interpreted as an X-ray luminosity dependent clustering, which appears to remove most of the above inconsistencies (Plionis et al. 2008). Such a luminosity dependent clustering trend was recently reported also by Cappelluti et al. (2010) and Krumei, Miyaji & Coil (2010).

Furthermore, there are indications for a quite large high $z$ AGN clustering length, reaching values $\gtrsim 10 \ h^{-1} \ Mpc$ at the brightest flux-limits (eg., Basilakos et al 2004; 2005, Puccetti et al. 2006, Plionis et al. 2008; Cappelluti et al. 2010), which, if verified, has important consequences for the AGN bias evolution and therefore for the evolution of the AGN phenomenon (eg. Miyaji et al. 2007; Basilakos, Plionis & Ragone-Figueroa 2008 - BPR08 hereafter). An independent test of these results would be to establish that the environment of high $z$ AGN is associated with large DM haloes, which being massive should be more clustered (work in progress).
It is also important to understand and overcome the shortcomings and problems that one is facing in order to reliably and unambiguously determine the clustering properties of the X-ray selected AGN. Such a list of problems includes the effects of Cosmic Variance, the so-called amplification bias, the reliability of the log N – log S distribution of the X-ray AGN luminosity function, etc. (see discussion in Plionis et al. 2009).

Recently, Ebrero et al. (2009a) derived the angular correlation function of the soft (0.5-2 keV) X-ray sources using 1063 XMM-Newton observations at high galactic latitudes (2XMM survey). A full description of the data reduction, source detection and flux estimation are presented in Mateos et al. (2008). Note, that the survey contains ~ 30,000 soft-band point sources within an effective area of ~ 125.5 deg² (for f_s ≥ 1.4×10⁻¹⁵ erg cm⁻² s⁻¹). The large area covered and the corresponding large number of X-ray sources ensure that the previously mentioned cosmic variance effects are minimized. However, further details regarding the various biases that should be taken into account (the amplification bias and integral constraint), the survey luminosity and selection functions as well as issues related to possible non-AGN contamination, which are estimated to be ≲ 10%, can be found in Ebrero et al (2009b).

3.2 Cosmology from the 2XMM angular Clustering

An optimal approach to unambiguously determine the clustering pattern of X-ray selected AGN would be to determine both the angular and spatial clustering pattern. The reason being that various systematic effects or uncertainties enter differently in the two types of analyses. On the one side, using the angular two-point correlation function, w(θ), and its Limber inversion, one bypasses the effects of redshift-space distortions and uncertainties related to possible misidentification of the optical counter-parts of X-ray sources. On the other side, using spectroscopic or accurate photometric redshifts to measure the spatial, ξ(r), or projected, w_p(θ), 2-point correlation function one by-passes the inherent necessity, in Limber’s inversion of w(θ), of assuming a source redshift-selection function (for the determination of which one uses the integrated X-ray source luminosity function, different models of which exist).

The basic integral equation relating the angular and spatial correlation functions is:

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

(23)

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. Note that to derive the spatial correlation length from eq. (23), it is necessary to model the spatial correlation function as a power law, assume the small angle approximation as well as a cosmological background model. The latter is provided by the function E(z) (eq. 4), which for a flat background and the QDM equation of state, it takes the form:

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

(24)

The AGN spatial correlation function can be written as:

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

(25)

where \( \beta(z) \) is the evolution of the linear bias factor (e.g. Mo & White 1997; Matarrese et al. 1997; Sheth & Tormen 1999; Basilakos & Plionis 2001; 2003; Basilakos et al. 2008; Tinker et al. 2010; Ma et al. 2011) is a parameter related to the model of AGN clustering evolution (e.g. 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:

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

(26)

The CDM power spectrum is given by: \( P(k) = P_0 k^n T^2(\Omega_m, k) \), with \( T(\Omega_m, k) \) the CDM transfer function (Bardeen et al. 1986; Sugiyama 1995), \( n \approx 0.967 \) and a baryonic density of \( h_0 = 0.02249 \), following the 7-year WMAP results (Komatsu et al. 2011). The normalization of the power-spectrum, \( P_0 \), can be parametrized by the rms mass fluctuations on \( R_s = 8 h^{-1}\text{Mpc} \) scales (\( \sigma_8 \)), according to:

\[ P_0 = 2\pi^2 \sigma_8^2/\Psi(\Omega_m, R_s), \]  

(27)

with

\[ \Psi(\Omega_m, R_s) = \int_0^\infty k^{n+2} T^2(\Omega_m, k) W^2(kR_s) dk \]  

(28)

and \( W(kR_s) = 3(\sin k R_s - k R_s \cos k R_s)/(k R_s)^3 \).

Evidently, the essential parameters needed to characterize any QDE cosmological model are: \( \Omega_m, \Omega_b, h_0 \). Regarding the Hubble constant we will use the WMAP7 results (Komatsu et al. 2011), which practically coincide with those of the HST key project (Freedman et al. 2001), i.e., \( h = H_0/100 = 0.704 \), while regarding the \( \sigma_8 \) normalization of the CDM power spectrum we will use the extrema of the range provided by the recent analysis of SDSS LRGs for a range of dark energy equations of state (\( \sigma_8 \in [0.78, 0.81]; \) Sánchez et al. 2009). Note that the upper limit of the above range corresponds to the WMAP7 ΛCDM value (Komatsu et al. 2011).

Furthermore, to estimate the predicted QDE model correlation function of the underlying mass, \( \xi_{\text{DM}}(r, z) \), in order to compare it with the observed AGN clustering, it is necessary to deal with the following three issues:

(i) **Clustering Evolution Model:** As discussed earlier (see eq. 25), in order to estimate the expected clustering of any mass tracer it is important to assume a clustering evolution model (e.g. de Zotti et al. 1990), which is encapsulated in the value of the parameter \( \epsilon \). A value \( \epsilon = -1.2 \) corresponds to a constant in comoving coordinates clustering model, while a value \( \epsilon = -3 \) to a constant in physical coordinates. According to Kúndic (1997) and Basilakos & Plionis (2005; 2006) we will use the former value of \( \epsilon \) (although we have also tested the effects of using \( \epsilon = -3 \)).

(ii) **Bias Evolution Model:** We need to calibrate the parameters of the bias evolution model to each cosmological model. Although a large number of bias evolution models have been proposed in the literature (see Papageorgiou, Plionis & Basilakos 2011, in preparation for a comparison of different models), we use here the approach of Basilakos...
& Plionis (2001; 2003) which was extended to QDE cosmological models in BPR08. This model is based on linear perturbation theory and the Friedmann-Lemaitre solutions of the cosmological field equations, and includes also the effects of interactions and merging of the mass tracers. Its analytical form has been derived for the QDE cosmological models, and its generalization to the CPL and alternative gravity cosmological models is under-way (Basilakos, et al. in preparation). Considering that each X-ray AGN is hosted by a dark matter halo of mass $M_h$, we can analytically predict its bias evolution behaviour within the QDE models. Conversely fitting the model to observations, we can determine the mass of the DM halo within which AGN live (for more details see Basilakos & Plionis 2010).

For the case of a spatially flat cosmological model, our bias evolution model has the following form:

$$b(M_h, z) = C_1(M_h) E(z) + C_2(M_h) E(z) I(z) + y_p(z) + 1,$$  \hspace{0.5cm} (29)

where $y_p(z)$ determines the rate of halo merging. However it is important only for $z > 3$ and therefore we neglect it here (see BPR08). Furthermore, we have

$$I(z) = \int_z^\infty \left( 1 + \frac{1}{x} \right)^3 \frac{dx}{E(x)},$$ \hspace{0.5cm} (30)

while the constants $C_1$ and $C_2$ have been fitted using a QDE simulation with $\Omega_m = 0.3$ and $\sigma_8 = 0.9$ (BPR08), and have been found to follow the form:

$$C_{1,2}(M_h) \simeq \alpha_{1,2} \left( \frac{M_h}{10^{14} h^{-1} M_\odot} \right)^{\beta_{1,2}},$$ \hspace{0.5cm} (31)

with $\beta_1 = 0.34$, $\beta_2 = 0.32$, while $\alpha_1$ and $\alpha_2$ have been found to be cosmological model dependent, with values given by (Papageorgiou, Plionis & Basilakos, 2011 in preparation):

$$\alpha_1 \simeq \kappa_1 \left( \frac{0.9}{\sigma_8} \right) \exp\left[ \kappa_3 (\Omega_m - 0.3) \right]$$ \hspace{0.5cm} (32)

with $\kappa_1 \simeq 3.44$, $\kappa_2 \simeq 2/5$ and $\kappa_3 \simeq 4/5$, and

$$\alpha_2 \simeq -0.36 \left( \frac{\Omega_m}{0.3} \right)^{3/2}.$$ \hspace{0.5cm} (33)

(iii) Non-linear Power Spectrum: Since the correlation function on small angular scales is within the expected non-linear regime, we should include in our model power-spectrum the non-linear contributions. To this end we use the corresponding fitting formula introduced by Peacock & Dodds (1996), for the $\Lambda$CDM model (see also Smith et al. 2003; Widrow et al. 2009). There is only one free parameter in their formulation, which is the slope of the power spectrum at the relevant scales, since the CDM power-spectrum curves slowly and thus it varies as a function of scale: $n_{s,eff} = d\ln P(k)/dk$. On the scales of interest the value is $n_{s,eff} \simeq -2$, but we have decided to actually derive, and then fix, the $n_{s,eff}$ value from the data analysis itself. Using the minimization procedure discussed in section 3.3 we compare the observed 2XMM AGN correlation function with that provided by the WMAP7 $\Lambda$CDM model (i.e., fixing $\Omega_m = 0.272$, $\omega = -1$, and $\sigma_8 = 0.811$) finding the remaining two free parameters (i.e., $M_h$ and $n_{s,eff}$). The corresponding

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig11.png}
\caption{Main Panel: The 1, 2 and 3$\sigma$ likelihood contours for the $\Lambda$CDM (WMAP7) model. Inner Panel: The Ebrero et al. (2009a) 2XMM angular correlation function and the best fit $\Lambda$CDM model (continuous line).}
\end{figure}

solution space can be seen in Fig. 12, while the best fit parameter values are: $M_h \simeq 6.5(\pm 2.1) \times 10^{12} h^{-1} M_\odot$ and $n_{s,eff} \simeq -2.02^{+0.05}_{-0.04}$. In the inset of Fig.11 we also plot the 2XMM angular correlation function together with the best fit $\Lambda$CDM model (continuous line).

As a consistency check we have verified that when fixing the non-linear slope of $P(k)$ to the above fitted value and leave as free parameters $M_h$ and $\sigma_8$, we recover the WMAP7 $\sigma_8$ value and exactly the same $M_h$ value, as above. The derived value of $M_h$ is slightly larger than that provided by Ebrero et al. (2009a) using the Sheth et al. (2001) bias evolution model (i.e., $\sim 5 \times 10^{12} h^{-1} M_\odot$). We have tested also the case of a clustering evolution model with $\epsilon = -3$, in which case the derived value of the halo mass is $\simeq 2 \times 10^{10} h^{-1} M_\odot$, a value significantly below any reasonable value that has been proposed or derived in the literature. We will therefore use $\epsilon = -1.2$ throughout the rest of the paper.

3.3 Fitting Models to the 2XMM Clustering Data

In order to constrain the cosmological parameters we use again the standard $\chi^2$ likelihood procedure and compare the measured XMM soft-band source angular correlation function (Ebrero et al. 2009a) with the predictions of different spatially flat cosmological models. The corresponding likelihood estimator is defined as: $\mathcal{L}_{\Lambda\text{CDM}}(\mathbf{p}) \propto \exp[-\chi^2_{\text{AGN}}(\mathbf{p})/2]$ with:

$$\chi^2_{\text{AGN}}(\mathbf{p}) = \sum_{i=1}^n \frac{[w_{\text{obs}}(\theta_i, \mathbf{p}) - w_{\text{obs}}(\theta_i)]^2}{\sigma_i^2 + \sigma_{\text{obs}}^2},$$ \hspace{0.5cm} (34)

where $\mathbf{p} \equiv (\Omega_m, \omega, M_h)$, $\sigma_i$ is the uncertainty of the observed angular correlation function and $\sigma_{\text{obs}}$ corresponds to the width of the angular separation bins.

We sample the various parameters as follows: the matter density $\Omega_m \in [0.1, 0.4]$ in steps of 0.002; the equation of state
parameter \( w \in [-1.4, -0.6] \) in steps of 0.005 and the parent dark matter halo \( M_h/10^{13} h^{-1} M_\odot \in [0.1, 3] \) in steps of 0.01. In this likelihood analysis we use as priors a flat universe, and the previously mentioned values of \( h \), \( \sigma_8 \) and \( \Omega_b \).

The results of the minimization procedure for the case of \( \sigma_8 = 0.81 \) are: \( \Omega_m = 0.301 \pm 0.008 \), \( w = -0.990 \pm 0.058 \) and \( M_h = 3.1 (\pm 1.1) \times 10^{12} h^{-1} M_\odot \), with a \( \chi^2 \) of 39.41 for 10 degrees of freedom. The large value of \( \chi^2/dof \) is due to the sinusoidal modulation of the 2XMM \( w(\theta) \), which could be due to systematic effects possibly related to the size of the XMM fields (see discussion in BP09). If we use the 2\( \sigma \) \( w(\theta) \) uncertainty in the denominator of the \( \chi^2 \) function of eq. (34), then the \( \chi^2 \) drops to \( \approx 9.86 \) (and the uncertainties of the fitted parameters increase to roughly twice the values indicated previously).

These results slightly differ with respect to the similar analysis of BP09, due to a number of improvements that we have currently included, apart from the fact that we have also used the WMAP7 cosmological parameters (ie., \( \Omega_b \), \( n \) and \( h \)). The two main improvements have to do with (a) the bias evolution model, in which we have now taken into account the dependence of the parameter \( a_1 \) (see eq.32) on \( \Omega_m \) and \( \sigma_8 \) (which has mostly affected the derived value of \( M_h \), reducing it significantly), and (b) the non-linear power spectrum corrections, for which we have used the Peacock 

Nevertheless our current procedure can and will be improved in the future in a number of ways:

- We will eventually use the clustering of X-ray selected AGN from a large contiguous X-ray survey, a fact which will solve, we believe, the quasi-sinusoidal small amplitude modulation of the 2XMM \( w(\theta) \) (see discussion in BP09). Such a future survey will be the XMM-Newton Very Large Programme (XXL), which was recently granted time to map two extragalactic regions of 25 deg\(^2\), at a depth of \( \sim 5 \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) (Pierre et al. 2011).
- We will investigate more accurate non-linear power-spectrum corrections of \( w(\theta) \) (eg., Widrow et al. 2009), and
- We will ultimately test a large range of Dark Energy equations of state, to include CPL and alternative gravity \( [f(R)] \) models. To this end we will use the recent generalization of the BPR08 bias evolution model of Basilakos, Plionis & Pouri (2011).

4 JOINT HUBBLE-RELATION, AGN CLUSTERING AND BAO ANALYSIS

Here we will perform an example of the joint analysis between the previously discussed results from 2XMM clustering and the Hubble relation, which is the basic aim of our overall project. For the current exercise we will use the Constitution SNIa Hubble relation since we are still working on the development of the HII-galaxy based methodology. For completeness we will also use the recent results of the baryonic acoustic oscillation technique (BAO). We remind the reader that BAOs are produced by pressure (acoustic) waves in the photon-baryon plasma in the early universe generated by dark matter overdensities. At the recombination era (\( z \sim 1100 \)), photons decouple from baryons and free stream while the pressure wave stalls. Its frozen scale, which constitutes a standard ruler, is equal to the sound horizon length, \( r_s \sim 100 h^{-1} \) Mpc (e.g. Eisenstein & Hu 1998). This appears as a small, \( \sim 10\% \) excess in the galaxy, cluster, or AGN power spectrum (and its Fourier transform, the 2-point correlation function) at a scale corresponding to \( r_s \). First evidence of such an excess have been reported in the clustering of the SDSS luminous red galaxies (LRGs) (see Eisenstein et al. 2005, Padmanabhan et al. 2007; Percival et al. 2010). In this work we use the latest measurement of Percival et al. (2010):

\[
r_s(z_d)/D_V(z_s) = 0.1390 \pm 0.0037 ,
\]

(see also Kazin et al. 2010a, 2010b). Note that \( r_s(z_d) \) is the comoving sound horizon size at the baryon drag epoch \( z_d \), which is given by the fitting formula of Eisenstein & Hu (1998), \( D_V(z_s) \) is the effective distance measure and \( z_s = 0.275 \). Of course, the quantities \( r_s \), \( D_V \) can be defined analytically, and are given by:

\[
r_s(z_d) = \frac{c}{\sqrt{3}} \int_0^{z_d} \frac{da}{a^2 H(a) \sqrt{1 + (3\Omega_b/4\Omega_m)a}}
\]

(35)

where \( a_d = (1 + z_d)^{-1} \) and \( \Omega_m h^2 \sim 2.47 \times 10^{-5} \) the energy density of photons. In this context, the effective distance is (Eisenstein et al. 2005):

\[
D_V(z) \equiv \left[ (1+z)^2 D_A(z) \frac{cz}{H(z)} \right]^{1/3}
\]

(36)

where \( D_A(z) \) is the angular diameter distance. Therefore, the corresponding \( \chi^2_{BAO} \) function is simply written as:

\[
\chi^2_{BAO}(p) = \frac{[r_s(z_d)/D_V(z_s)](p) - 0.1390]^2}{0.0037^2}
\]

(37)

where \( p \) is the vector containing the cosmological parameters that we want to fit for. In this case \( p = (\Omega_m, w) \).

We therefore perform a joint likelihood analysis, assuming that any two pairs of cosmological data sets are independent (which indeed they are) and thus the joint likelihood can be written as the product of the two individual ones. The results based on the joint analysis of the different pairs of cosmological data are shown in Fig.12 and quantified in Table 3. It is evident that the addition of the XMM clustering analysis provides significantly more stringent constraints than, for example, the joint SNIa and BAO results. The reduction parameter, ie., the ratio of the Figure of Merit of the joint XMM-SNIa analysis to that of the Constitution SNIa analysis (see definition in section 2.3.4) shows that the 2\( \sigma \) range of the \( (\Omega_m, w) \) solution space is reduced by a factor of \( \sim 5/2 \) with respect to that of the BAO-SNIa analysis (see lower right panel of Fig.12).

The necessity, however, to impose constraints on a more general, time-evolving, dark-energy equation of state (eq. 2), implies that there is ample space for improving the current analysis and indeed our aim is to develop further this project by (a) using a new Hubble relation analysis, based on high \( z \) HI galaxies, as detailed in this paper, and (b) by generalizing the BPR08 bias evolution model for any DE equation of state (CPL and alternative gravity models).

5 CONCLUSION

We have investigated the question of which is the most efficient strategy to tighten the cosmological constraints pro-
Figure 12. QDE model parameter constraints (i.e., in the $\Omega_m, w$ plane) provided by the joint likelihood analysis of pairs of cosmological data. The red shaded contours are the joint-likelihood contours of the indicated pairs of data. For clarity we show only contours corresponding to the 1 and 3 $\sigma$ confidence levels. The 2XMM results shown correspond to those based on a power spectrum normalization of $\sigma_8 = 0.81$. Note also that we have followed the conservative approach of using 2$\sigma$ $w(\theta)$ uncertainties in the minimization process, to allow for the small amplitude sinusoidal $w(\theta)$ modulation (see main text and BP09). Upper Left Panel: Constitution SNIa Hubble relation (blue contours) and 2XMM AGN clustering (black contours). Upper Right Panel: Constitution SNIa Hubble relation (blue contours) and LRGs BAO (green contours). Lower Left Panel: 2XMM AGN clustering (black contours) and LRGs BAO (green contours). Lower Right Panel: The joint likelihood contours of the SNIa-2XMM (red contours) and of the SNIa-BAO (blue contours) pairs.
tion space, presently provided by the Constitution set, by a desired factor of our choice and for any level of rms distance modulus uncertainty. This analysis has shown that in order to significantly reduce the cosmological parameter solution space, it is more efficient to increase the number of high-$z$ tracers than to reduce their individual uncertainties. A re-analysis of the cosmological constraints provided by a small sample of high-$z (2.2 \lesssim z \lesssim 3.4)$ HII galaxies, previously analysed by Siegel et al. (2005), but now using a novel determination of the zero-point of the relevant distance scaling relation, provides consistent cosmological results with those of SNIa, although the dark energy EoS parameter remains unconstrained at present.

Finally, using the clustering of X-ray selected AGN we provide the framework that will be used, joining their cosmological likelihood with that of the Hubble relation analysis, to put stringent dark energy equation of state constraints. An example of such a joint analysis, using the 2XMM clustering and the Constitution SNIa Hubble relation, and under the priors of a flat universe, $h = 0.704$ and $\sigma_8 = 0.81$ or 0.78, provide significantly more stringent QDE model constraints, as indicated by the fact that the Figure of Merit increases by a factor $\sim 2$, with respect to that of the joint SNIa-BAO analysis. The QDE cosmological parameters provided by the 2XMM-SNIa joint analysis are: $\Omega_m = 0.31 \pm 0.01$ and $w = -1.06 \pm 0.05$, with the uncertainties being estimated after marginalizing over one parameter.

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### Table 3. The best fit values of the cosmological parameters based on the joint likelihood analysis of the indicated cosmological data.

For the case of the 2XMM clustering analysis we followed the conservative approach of using $2\sigma$ $w(\theta)$ uncertainties. The uncertainty of each fitted cosmological parameter has been estimated after marginalizing over the other parameter (i.e., by fixing one parameter at its best value and allowing the other to vary, providing as its uncertainty the range for which $\Delta \chi^2 < 2.3$). The last column indicates the reduction parameter (related to the Figure of Merit) as defined in section 2.3.4.

| Joint data | $\Omega_m$ | $w$ | $\chi^2$ | dof | $S$ |
|------------|-----------|-----|----------|-----|-----|
| SNIa+BAO   | $0.296 \pm 0.021$ | $-1.027 \pm 0.053$ | 439.711 | 365 | 2.32 |
| XMM$^a$+SNIa | $0.310 \pm 0.012$ | $-1.064 \pm 0.053$ | 449.591 | 374 | 4.49 |
| XMM$^b$+BAO | $0.302 \pm 0.014$ | $-0.995 \pm 0.128$ | 9.860 | 11 | 1.74 |
| XMM$^b$+SNIa | $0.318 \pm 0.013$ | $-1.085 \pm 0.059$ | 449.644 | 374 | 4.35 |
| XMM$^b$+BAO | $0.306 \pm 0.015$ | $-0.973 \pm 0.121$ | 9.861 | 11 | 1.70 |

$^a$ 2XMM results based on a $P(k)$ normalization of $\sigma_8 = 0.811$, $^b$ based on $\sigma_8 = 0.78$. 

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