The Dark Energy Equation of State using Alternative Cosmic Tracers:
Strategy & Preliminary Results

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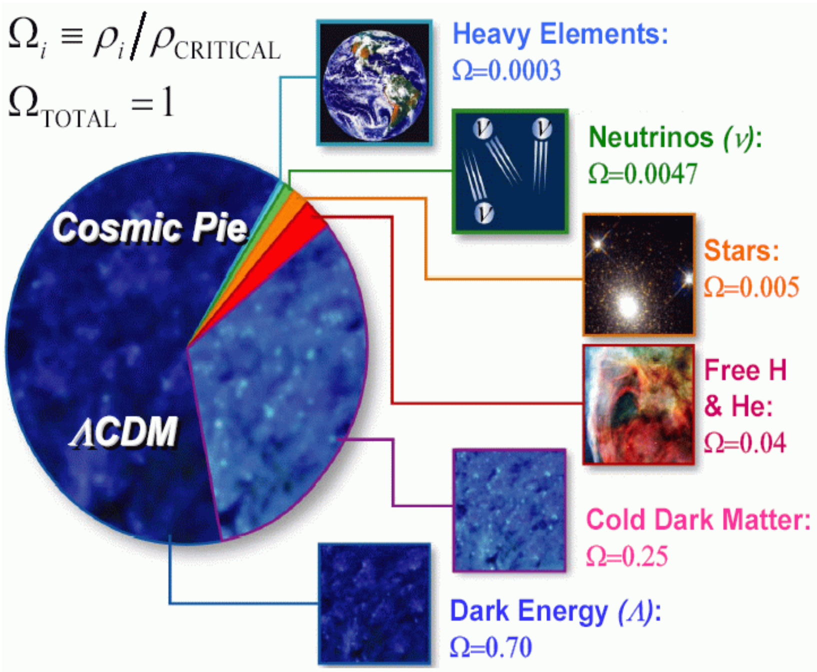
International Efforts to tackle Dark Energy

Is "Dark Energy" the sole interpretation of the observed accelerated expansion of the Universe and if yes then what is its interpretation within a fundamental physical theory.

- ***Is it Einstein's Cosmological Constant, Quintessence, time-varying EoS ?***
- ***Is it related to modified gravity ?***
- ***Is it a manifestation of interacting Dark Matter?***

A large number of **very expensive experiments** (eg., **Dark Energy Survey**, **Euclid**, **Joint Dark Energy Mission**, **XXL** 3Msec XMM survey, **Pan-STARRS**, **Wfirst**, **HETDEX**) are on their way..



"Dark Energy" is considered ***TOP PRIORITY*** for future research: "Report of the Dark Energy Task Force (advising DOE, NASA and NSF), Albrecht et al. (2006), and "Report of the ESA/ESO Working Group on Fundamental Cosmology", Peacock et al. (2006).

Measuring Dark Energy

Dark Energy is manifested in the expansion rate of the Universe, via:

$$H^2(z) = H^2_0 \{\Omega_m(1+z)^3 + \Omega_w \exp \int dz[1+w(z)]/(1+z)\}$$

matter dark energy

Which reduces for w=constant to:

$$H^2(z) = H^2_0[\Omega_m(1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}]$$

matter dark energy

Equation of state parameter w: Λ cosmology: $w = -1$ ($p_{VAC} = -w\rho_{VAC} = -\Lambda/8\pi G$). QDE model where w is variable and is currently constrained to ~20% by WMAP, SDSS, and SN Ia.

However, variable time-dependent equation of states is more generic and necessary to solve the discrepancy between observations and QFT predictions. The CPL model: $w(z)=w_0+w_a [z/(1+z)]$

Measuring H(z) via Standard Candles (e.g., SN Ia) using luminosity distance:

$$d_L = (1+z) \int dz/H(z)$$

observationally we have: $d_L = 10^{(\Delta M-25)/5}$ with $\Delta M = m - M$.

International Collaboration to Constrain the DE EoS using Alternative Cosmic Tracers

NOA-Greece, INAOE-Mexico, Academy of Athens, IfA-Hawaii, ESO-Chile

Plionis et al. (2011), MNRAS

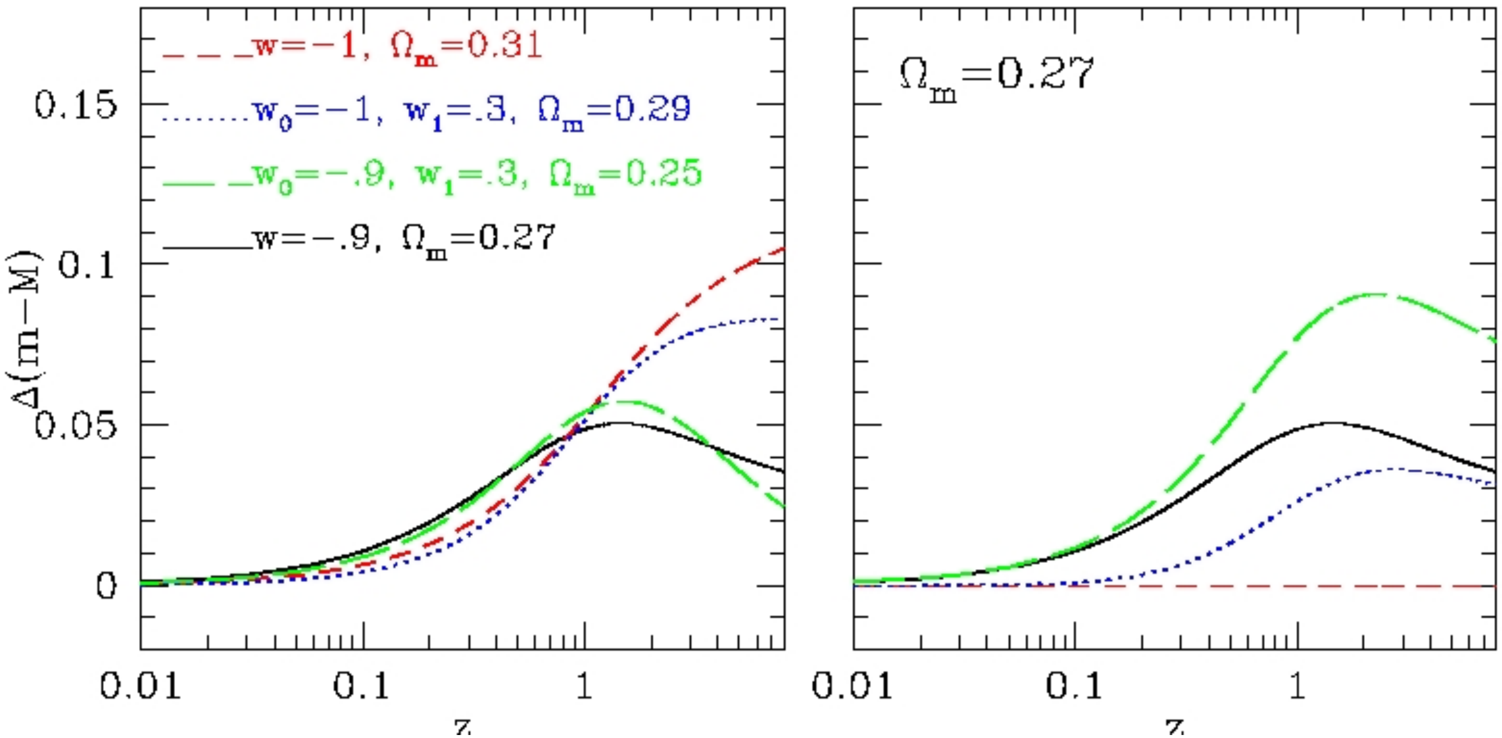
- **The current project is** about constraining the *DE* equation of state using 2 cosmological probes: ***Hubble relation*** **and** ***Clustering*** **of extragalactic mass tracers**. The novelty of our proposal is that for both probes we will utilize ***alternative cosmic tracers***:
  - ***(a) HII galaxies*** and
  - ***(b) X-ray selected AGN***.
- Therefore, our proposed analysis will also provide an ***independent check*** of the forthcoming experiments that are based on more traditional tracers (SN Ia's and galaxies or clusters of galaxies).

Probe 1: Manifestations of different Dark Energy models

What are the expected Distance Modulus variations of different models ?

Assuming a nominal model ($w=-1$, $\Omega_m=0.27$) we plot below the relative distance modulus, $\Delta(m-M)$, between different models. Evidently we have:

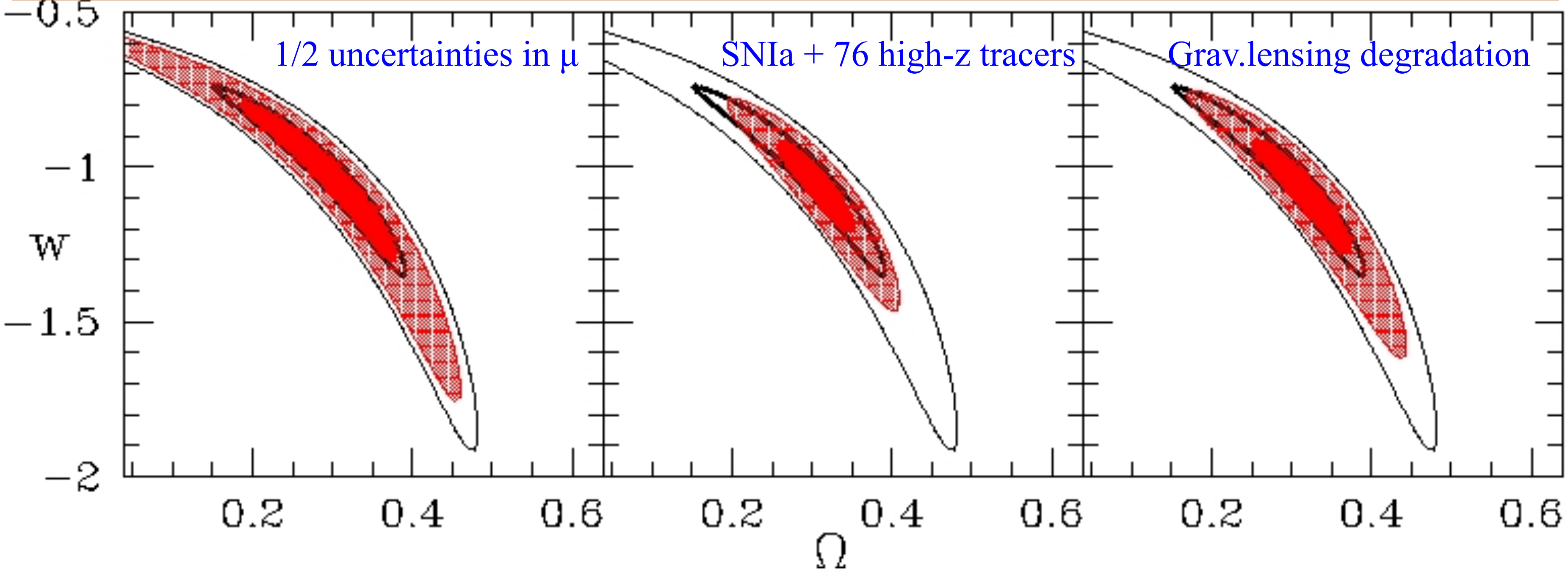
1. **Maximum variation occurs at $z>1.5-2$ (out of current SN Ia reach) !**
2. **There is the known degeneracy between w and Ω_m**
3. **For $z<0.2$ differences are insignificant**



Once Ω_m is fixed there are significant $\Delta(m-M)$, differences due to w variations

Probe 1: Necessary to reduce the current SNIa Cosmological Parameter Solution space & their degeneracy

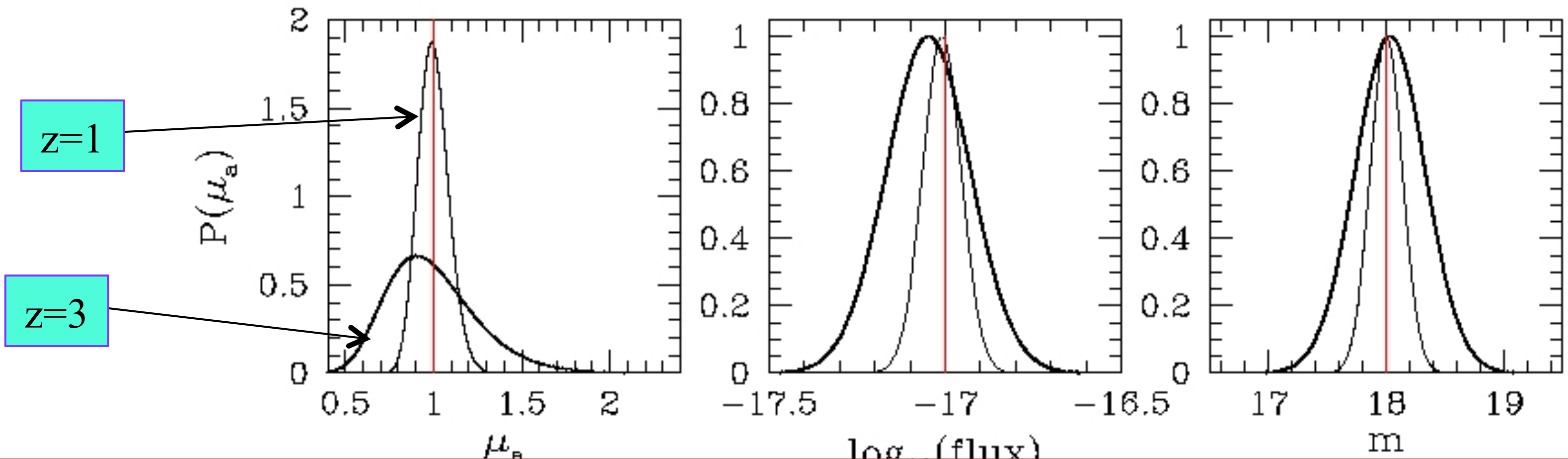
Using extended Monte-Carlo simulations we have verified that it is more efficient to include a few tens of high-z tracers of the Hubble expansion rather than decrease even dramatically the uncertainties of the low-z (SNIa range) tracers or increase their numbers.



However, there is a sort of *catch-22* effect in the sense that higher-z sources are to be preferred, but the higher you go the more you are hampered by the systematic effect of gravitational lensing.

Probe 1: High-z Hubble relation hampered by grav. lensing effects

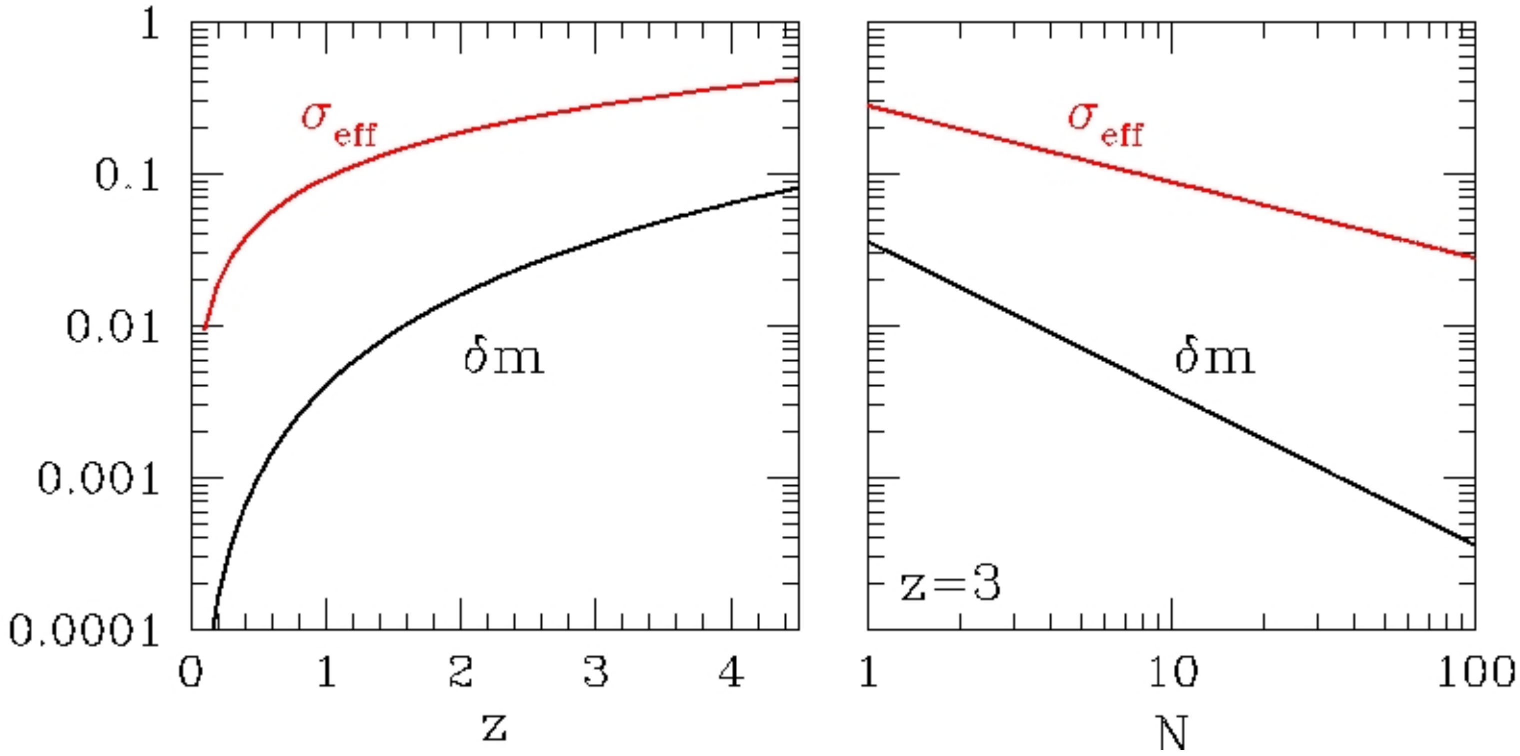
The LSS affects the propagation of light from high-z sources (eg., Holz & Wald 1998; Holz & Linder 2005; Brouzakis & Tetradis 2008). Assuming a Robertson-Walker background superimposing a locally inhomogeneous universe and taking into account both strong and weak lensing effects, results in a *magnification distribution of a single source over different paths which is non-Gaussian*. Monte-Carlo and ray-tracing techniques indicate that the magnification probability density function $P(\mu_\alpha)$ resembles *a log-normal distribution* with $\mu=0$ (mean flux over all possible different paths is conserved since photon numbers are unaffected by lensing), with the mode shifted towards the de-magnified regime with a long tail to high magnification.



Thus most sources will be de-magnified, inducing an apparently enhanced accelerated expansion, while a few will be highly magnified. The effect is obviously stronger for higher z sources since the lower the redshift the less the optical depth of lensing. The shape of $P(\mu_\alpha)$ dependents only weakly on underlying cosmology, density profile and evolutionary phase of the intervening cosmic structures (eg., Wang et al. 2002).

Probe 1: High-z Hubble relation hampered by grav. lensing effects

Gravitational lensing effects as a function of Redshift & Number of sources per redshift

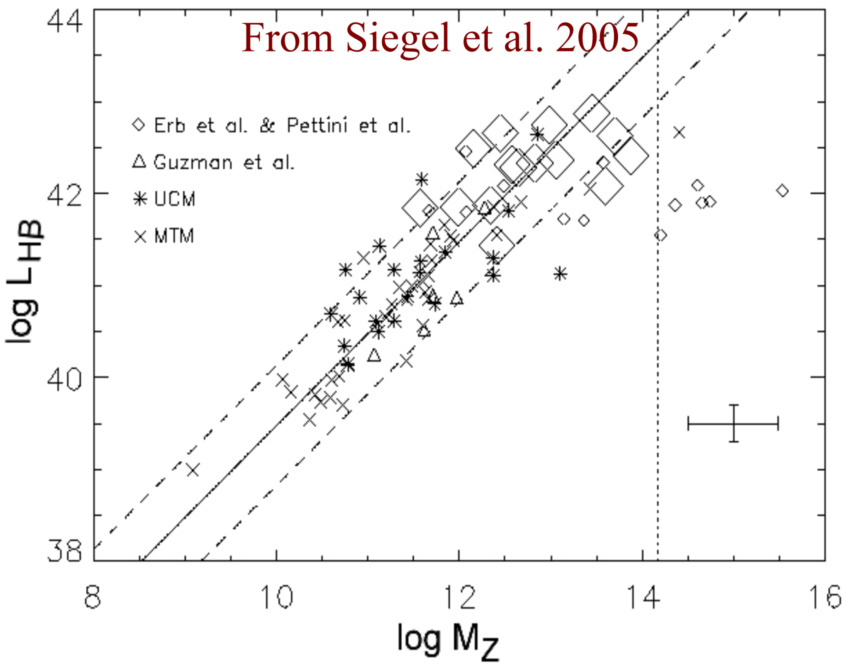


For the 1st time the distance moduli of observed standard candles (SNIa, GRBs, HII-galaxies, etc) can be corrected statistically by subtracting an offset δm(z) from their raw distance moduli, within redshift bins of ~0.1z width and using as the total distance modulus uncertainty that given by $\sigma^2_m(z)=\sigma^2_{obs}+(0.093z)^2/N$. **THEREFORE WE ARE ARMED IN ORDER TO USE HIGH-z TRACERS OF THE HUBBLE EXPANSION ! (see Plionis et al. 2011, MNRAS)**

Probe 1: An Alternative high-z Distance Indicator: HII galaxies

Correlation between H_β line luminosity and stellar velocity dispersion, measured from the line-widths of local HII regions (eg., Terlevich & Melnick 1981, Melnick, Terlevich & Moles 1988).

$L(H_\beta)$-σ correlation holds at large z's (eg. Siegel et al. 2005; Melnick, Terlevich & Terlevich 2000)



It is the presence of O and B-type stars in HII regions that causes the strong Balmer line emission, in both Hα and Hβ. **Furthermore, the fact that the bolometric luminosities of HII galaxies are dominated by the starburst component** they can be observed at very large redshifts, and this fact makes them cosmologically very interesting objects.

Melnick et al (1987) used giant HII regions in nearby late-type galaxies and derived the following empirical relation (using H_0=71 km/sec/Mpc):

$$\log L(H_\beta) = \log M_z + 29.60, \quad M_z=\sigma^5/(O/H)$$

where O/H is the metallicity.The distance modulus of HII galaxies can be derived from (Melnick, Terlevich & Terlevich 2000):

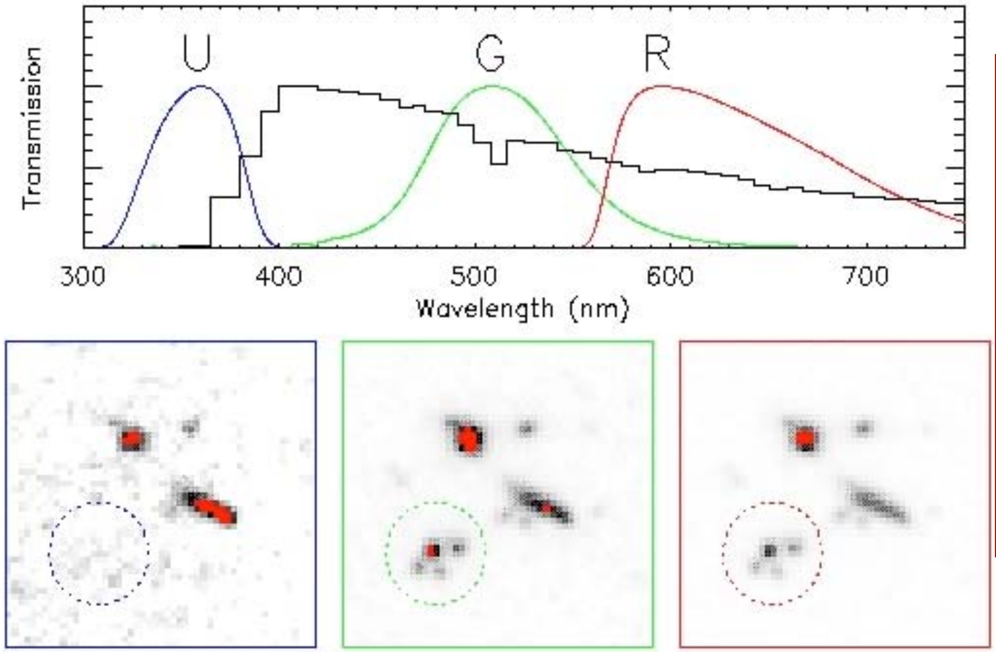
$$m-M=2.5 \log(\sigma^5/F_{H\beta})-2.5 \log(O/H)- A_{H\beta} -26.44$$

with $F_{H\beta}$ and $A_{H\beta}$ is the flux and extinction in H_β. The rms dispersion is **$\sigma[\Delta(m-M)]$=0.52 mag**, out of which **~0.35 mags** are due to observationally related uncertainties.

Probe 1: An Alternative high-z Distance Indicator: HII galaxies

Candidate high-z HII galaxies are the **Lyman-Break Galaxies:** detected by deep imaging in U, G, R, since star-forming galaxies at z> 2.5 will be too faint in the U (bluer than Lyman-limit in gals rest frame), since too few stars are hot enough to produce energetic photons and photons from bluer side of Ly-limit can ionize neutral H are being absorbed as well as by Neutral H along line-of-sight.

Also, **Narrow band filters at SUBARU and deep slit-less surveys using WFC3 on HST** have revealed many HII galaxies with strong emission lines and weak continua at intermediate and high z's. **Sample has more than 400 HII galaxies covering 0.5<z<3.7** (Xia et al. 2011; Nestor et al. 2011; Straughn et al., 2011)

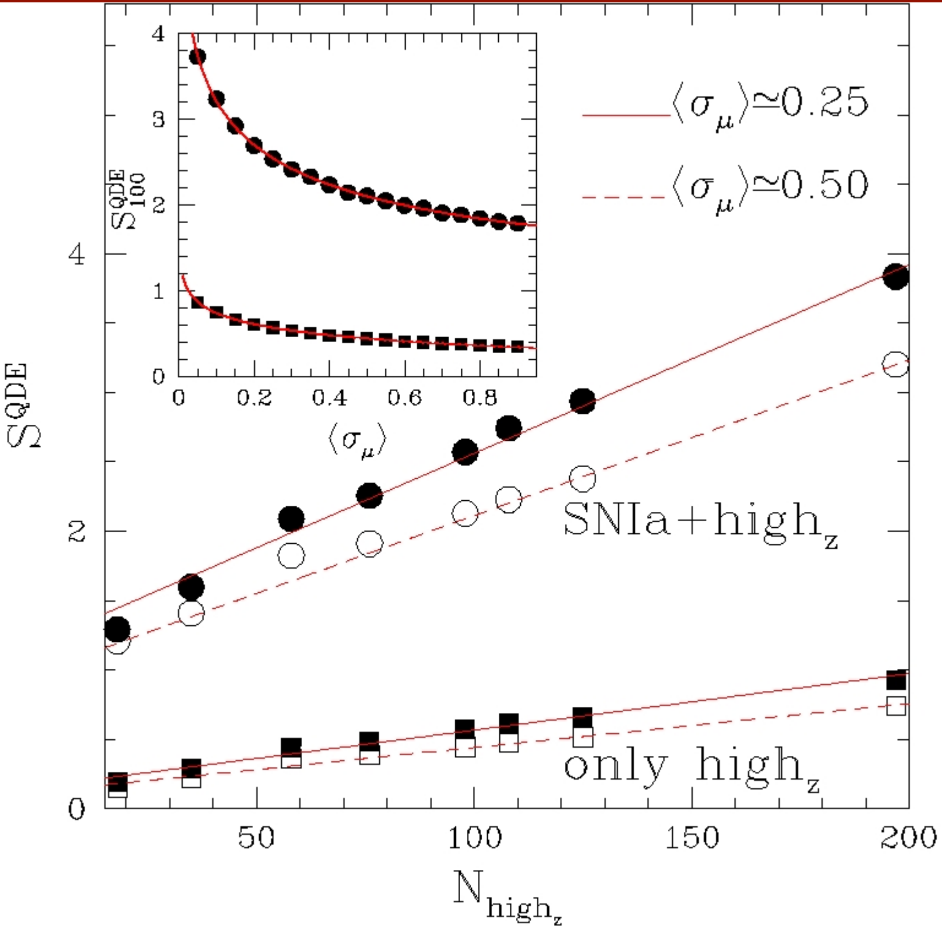


1000's of LBGs are detected (eg. Steidel et al. 1998) but it is **necessary** to obtain **NIR spectroscopy** since Hβ moves to H-band at z~2 and in K-band at z~3. **8m-class telescopes** are necessary to obtain spectra at a reasonable time (~1h integration per object). See Pettini et al. (2001), Erb et al. (2003).

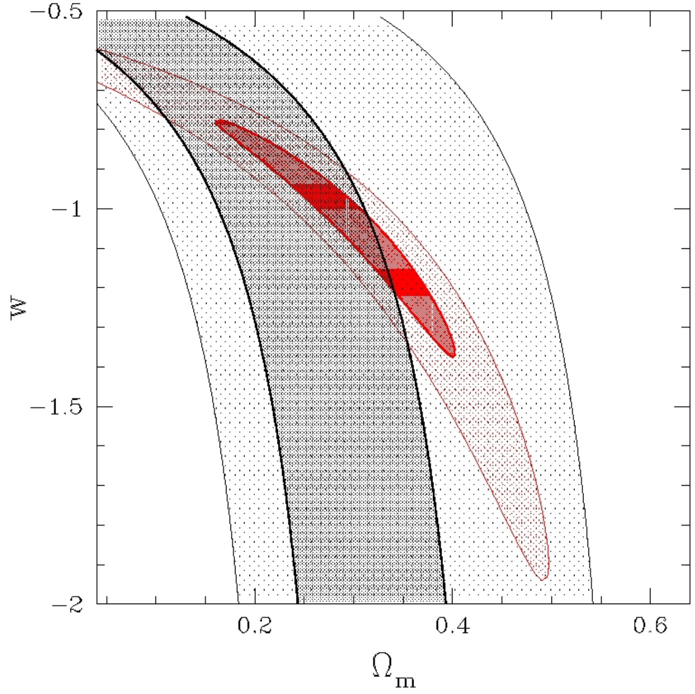
Probe 1: An Alternative high-z Distance Indicator: HII galaxies

DEFINE BEST STRATEGY: Using extensive ***Monte Carlo simulations*** and ***Figure of Merit analysis*** we have found that it is better to increase the number of high-z HII galaxies, rather than decrease significantly their random distance modulus uncertainty. Also our analysis provides the necessary numbers of tracers needed to decrease the Figure of Merit by a given amount with respect to current SNIa constraints.

FoM(HII galaxies)/ FoM(SNIa)



Preliminary results of only 15 high-z HII galaxies (Siegel et al. 2005) ➔ $\Omega_m \approx 0.23 \pm 0.05$ **(for w=-1)**, and a QDE solution space consistent with that of SNIa.



Probe 2: Cosmological Inference from X-ray AGN Clustering

- X-ray selected AGNs can be detected at very high z´s and thus can provide important clues on $\delta\rho/\rho$ at such z´s. Furthermore their clustering properties can provide important constraints both on structure formation theories, on the relation between AGN activity and DM halo hosts, and on Cosmological parameters while when combined with other LS data (SNIa) on the dark-energy equation of state.

- X-rays have the advantage over optical in that (a) high-z´s are probed and (b) that type 2 AGNs, largely missed in optical surveys, are included in X-ray surveys.

- We are in the process of generating the largest todate XMM X-ray source catalogue with more than 100000 and 50000 soft and hard -band sources, respectively, a fact which will enable is to pin-down their $w(\theta)$ with great accuracy.

Probe 2: Cosmological Inference from X-ray AGN Clustering

Model AGN Correlations

$$\xi_{\rm th}(r,z) = b^2(z) D^2(z) \frac{1}{2\pi^2} \int_0^\infty k^2 P(k) \frac{\sin(kr)}{kr} {\rm d}k$$

P(k) is the Cold Dark Matter power spectrum.
• **b(z)** and **D(z)** is the evolution of bias and linear growing fluctuation mode respectively.

Limbers Inversion to get w(θ)

With ingredients:

1. Cosmology - DE EoS
2. N(z)

Evolution of Bias Parameter

From Continuity, Euler's, Poisson's equations & L.P.T. we derive the evolution equation of δ:

$$\ddot{\delta} + 2H(t)\dot{\delta} = 4\pi G \rho_m \delta \ , \quad \delta_g = b\delta$$

we seek the time evolution equation for b:

From continuity equation and if gals and DM share the same v-field:

$$\dot{\delta} + \nabla u \approx 0 \ \ , \dot{\delta}_g + \nabla u \approx 0 \Longrightarrow \quad \dot{\delta}_g - \dot{\delta} = 0$$

From $\delta_g = b\delta$ and $y = b - 1 \Longrightarrow$

$$\frac{d}{dt}(y\delta) = 0 \Longrightarrow \frac{d^2}{dt^2}(y\delta) = \ddot{y}\delta + 2\dot{y}\dot{\delta} + y\ddot{\delta} = 0$$

$$y\ddot{\delta} = -2H\dot{\delta}y + 4\pi G \rho_m \delta y$$

and together with $y\dot{\delta} = -\dot{y}\delta \Longrightarrow$

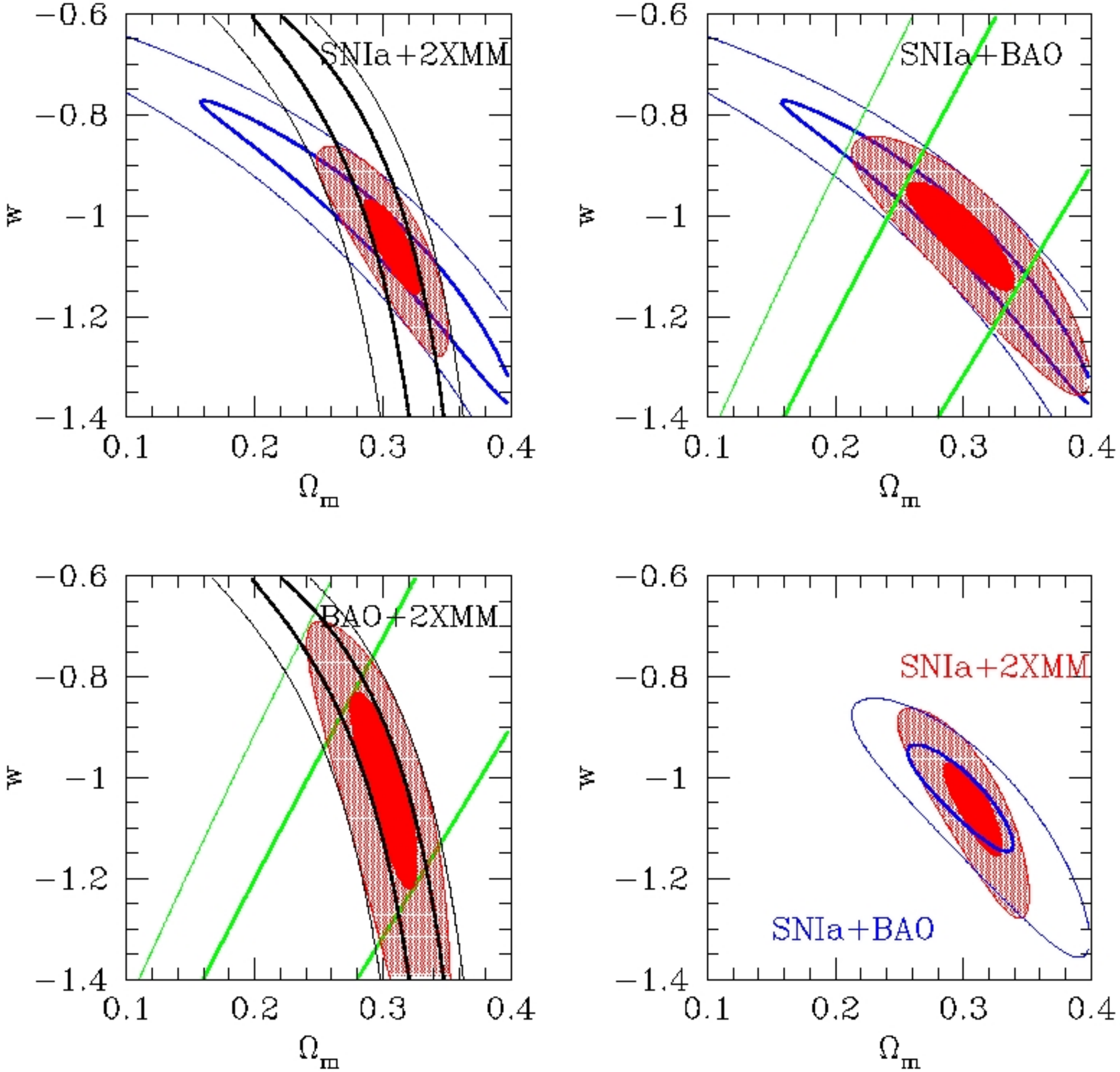
$$\boxed{\ddot{y}\delta + 2(\dot{\delta} + H\delta)\dot{y} + 4\pi G \rho_m \delta y = 0}$$

$$\Longrightarrow b(t) - 1 = At^{-2/3} + Bt^{-1} \quad \text{for} \quad \Omega_o = 1$$

Bias using Linear Perturbation Theory: Basilakos & Plionis ApJ 2001, 2003, 2008

Precision Cosmology using Hubble expansion + X-ray AGN Clustering Probes

(Basilakos & Plionis 2009; Plionis et al. 2011)



Example of our methodology: The joint likelihood analysis, of the 2XMM clustering and the SNIa Hubble relation, and under the priors of a flat universe, h=0.704 and σ_8=0.81 provide significantly more stringent QDE constraints, as indicated by the fact that the ***Figure of Merit increases by a factor ~2***, with respect to that of the joint SNIa-BAO analysis.

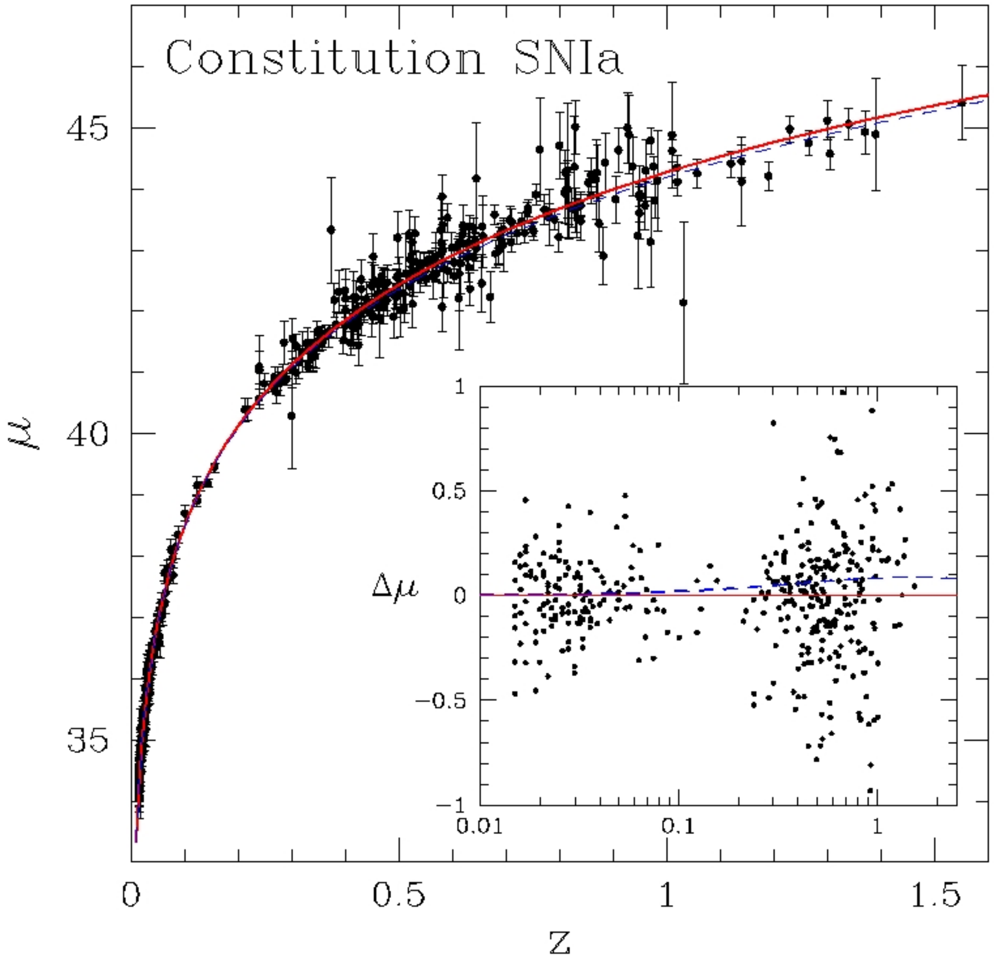
Ω_m=0.31±0.01, w=-1.06±0.05

Conclusions

1. *We are working towards using **Alternative Tracers** of the **Hubble Relation** probe, at significantly larger redshifts than those of current SNIa samples **(using HII galaxies**) and of the **Clustering of cosmic structures probe (using X-ray AGN)** in order to constraint the Dark Energy Equation of State.*
2. *To this end we have developed a statistical correction procedure for the effects of gravitational lensing that affects significantly the high-z Hubble relation cosmological probe and which has not been taken into account by any study todate.*
3. *Important outcome of preliminary work is that the QDE EoS model Figure of Merit of the joint Xray AGN (clustering)-SNIa (Hubble relation) likelihood analysis is reduced by a factor of ~2 with respect to the corresponding BAO-SNIa analysis. Furthermore, the fact that **using the HII-galaxy Hubble relation will provide significantly more stringent cosmological constraints than those provided by current SNIa surveys**, further indicates that our proposed methodology is a powerful alternative to provide stringent constraints of the DE EoS.*

Recent SN Ia based Results *(May 2009)*

397 SN Ia (Constitution Sample)
Largest Homogeneous Sample (Hicken et al. 2009)



$$\mathcal{L}^{\rm SNIa}(\mathbf{c}) \propto \exp[-\chi^2_{\rm SNIa}(\mathbf{c})/2]$$

with:

$$\chi^2_{\rm SNIa}(\mathbf{c}) = \sum_{i=1}^{172}\left[\frac{\log D_{\rm L}^{\rm th}(z_i,\mathbf{c}) - \log D_{\rm L}^{\rm obs}(z_i)}{\sigma_i}\right]^2$$

where $D_{\rm L}(z)$ is the dimensionless luminosity distance

$$D_{\rm L}(z) = H_0 d_{\rm L} = H_0(1+z)x(z)$$