Improved constraints on the Hubble parameter from the spectroscopic evolution of cosmic chronometers

measurements and cosmological implications

Michele Moresco

<u>In collaboration with</u>: Cimatti A., Jimenez R., Pozzetti L., Zamorani G., Bolzonella M., Dunlop J., Lamareille F., Mignoli M., Pearce H. , Rosati P. , Stern D. , Verde L. , Zucca E. + zCOSMOS, "cosmic chronometers project" and UDSz collaborators

23 february 2012

Outline

Introduction

- The “cosmic chronometers approach”: basic idea & improved technique
- Why early-type galaxies?
- Sample selection criteria and properties

Outline

Introduction

- The “cosmic chronometers approach”: basic idea & improved technique
- Why early-type galaxies?
- Sample selection criteria and properties

Measurement of the Hubble parameter H(z)

- Estimate of the relevant quantities
- Error budget
- Comparison with previous works

Outline

Introduction

- The "cosmic chronometers approach": basic idea & improved technique
- Why early-type galaxies?
- Sample selection criteria and properties

Measurement of the Hubble parameter H(z)

- Estimate of the relevant quantities
- Error budget
- Comparison with previous works

Cosmology with the Observational Hubble parameter Data

- Direct consequences of the OHD measured on cosmological models
- Constraints to cosmological parameters with OHD
- Constraining the dark energy potential with OHD

Part 1 (Introduction through "Direct consequences of the OHD measured on cosmological models")

Part 2 (Constraints to cosmological parameters with OHD)

Part 3 (Constraining the dark energy potential with OHD)

Measurements of the Hubble parameter

Theoretical background 1/3

The determination of the rate at which the Universe expands is one of the most crucial measurements for cosmologist, since the rate at which it decelerates/accelerates directly depend on the energy components of the Universe

$$H(z) = f(z, \Omega_m, \Omega_{DE}, \Omega_k, H_0, w_0, w_a)$$

BUT... accurate constraints only in the local Universe, i.e. H_0 at 3%
Riess et al. (2010,2011)

To constrain the effect of the expansion of the Universe, and disentangle it from intrinsic evolution effects, ***standards*** are needed:

- standard(-izable) candles → Sne
- standard rulers → BAO

An innovative and challenging method is based on the use of "***cosmic chronometers***" (standardizable clocks)

$$H(z) = -\frac{1}{1+z}\frac{dz}{dt}$$

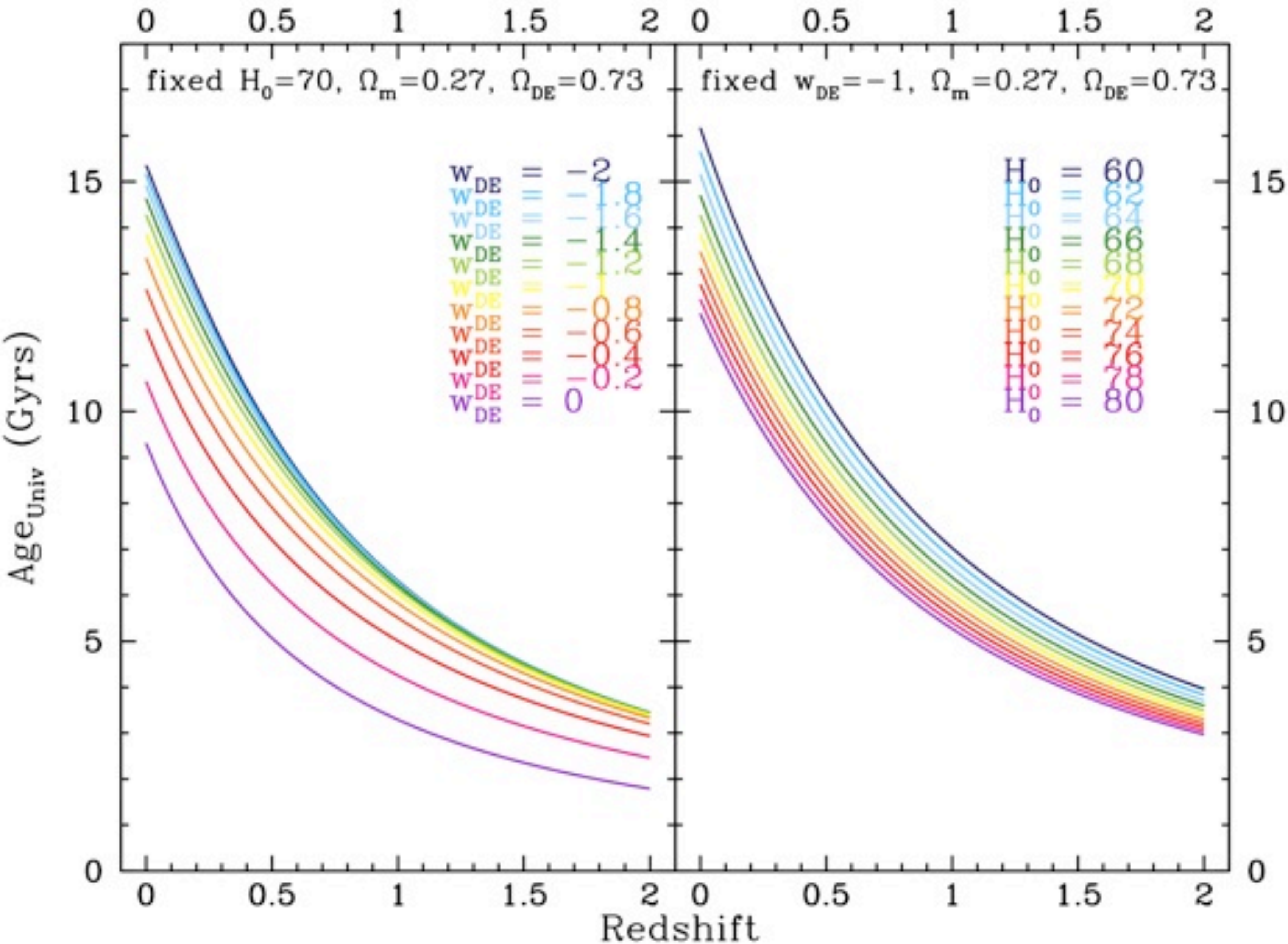
Theoretical background 2/3

Basic idea constrain the cosmological expansion history studying the differential age evolution of the Universe

Jimenez & Loeb (2002)

$$H(z) = -\frac{1}{1+z}\frac{dz}{dt}$$

The age-redshift relation

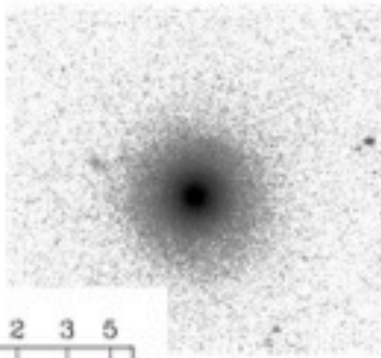


Theoretical background 2/3

Basic idea constrain the cosmological expansion history studying the differential age evolution of the Universe

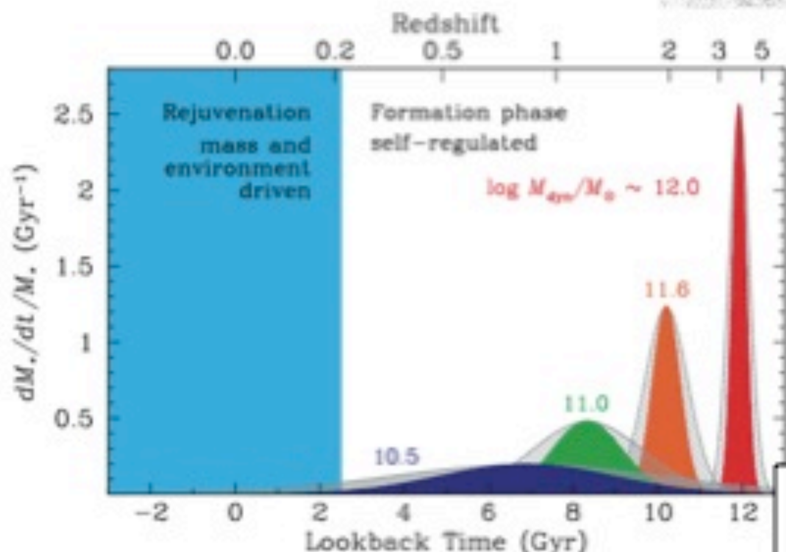
Jimenez & Loeb (2002)

$$H(z) = -\frac{1}{1+z}\frac{dz}{dt}$$



Tracers Early-type galaxies as "***cosmic chronometers***"

- ✓ homogeneous population (colors, morphology, stellar population content)
- ✓ passive evolution
- ✓ oldest population (mass-downsizing)
- ✓ most massive systems
  → more synchronized formation
- ✓ negligible major merger events
- ✓ no significant increase of mass
  → minimal contamination



Thomas et al. 2010

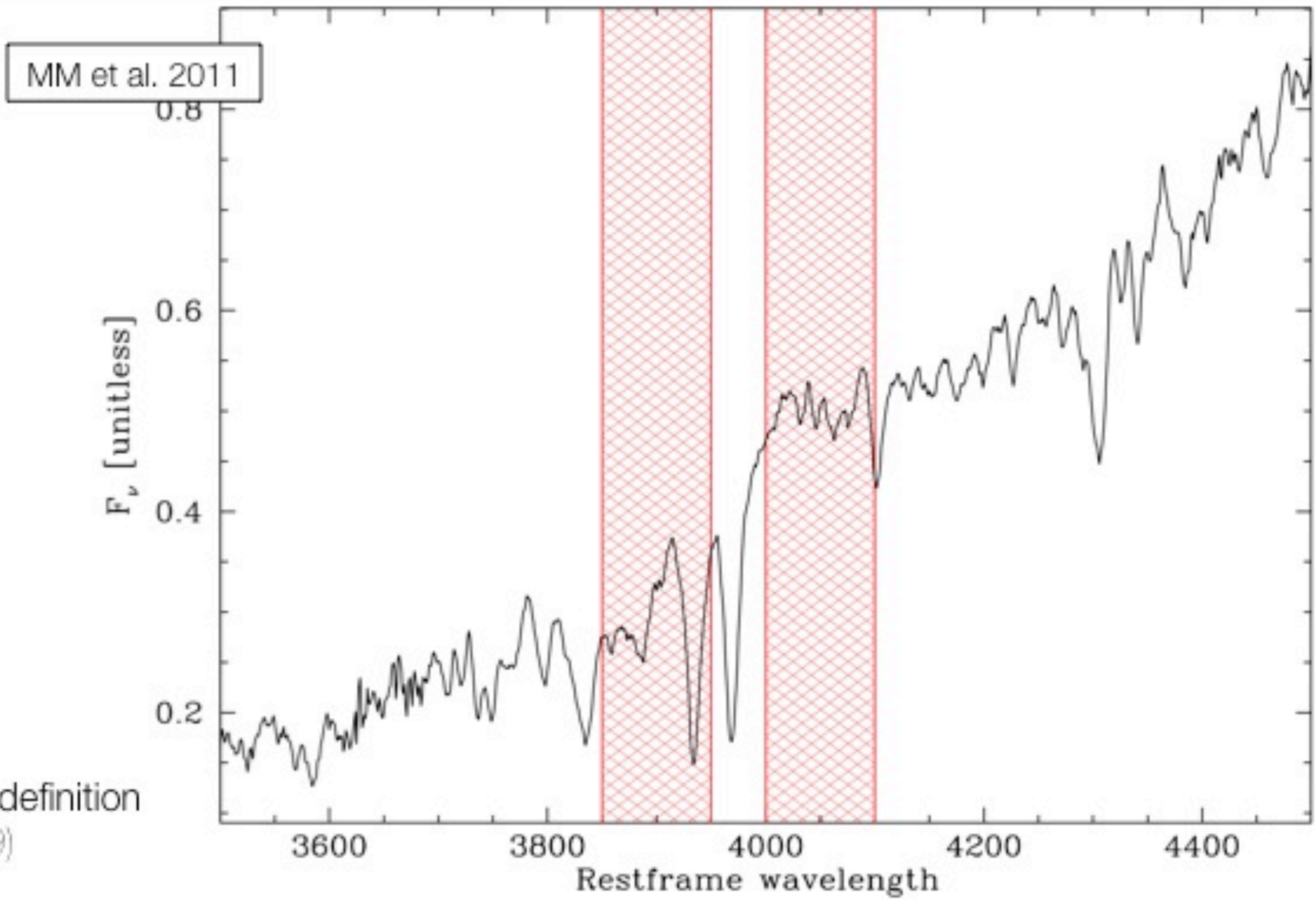
PROs:
- differential approach
- independent technique
- direct measure of H(z)
- high statistic

CONs:
- homogeneity of the tracers
- degeneracies
- treatment of systematics

Theoretical background 3/3

Updated technique reduce systematics and model dependencies by studying a direct observable linked to galaxy's age: ***$D4000_n$-z relation***
Moresco et al. (2011)

Theoretical background 3/3



D4000 "narrow" definition

Balogh et al (1999)

$$D4000_n = \frac{\langle F \rangle_{4000-4100AA}}{\langle F \rangle_{3850-3950AA}}$$

Theoretical background 3/3

Updated technique reduce systematics and model dependencies by studying a direct observable linked to galaxy's age: ***$D4000_n$-z relation***
Moresco et al. (2011)

Assumption linear relation between $D4000_n$ and age

$$D4000_n = A(Z,SFH) \cdot age + B(Z,SFH)$$

$$\Delta D4000_n = A(Z,SFH) \cdot \Delta age$$

$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

Data sample

ETGs selection

Different spectroscopic surveys (SDSS MGS+LRGs, zCOSMOS, UDS, GDDS, GOODS-S, K20, …); the general selection criterion includes the following steps:

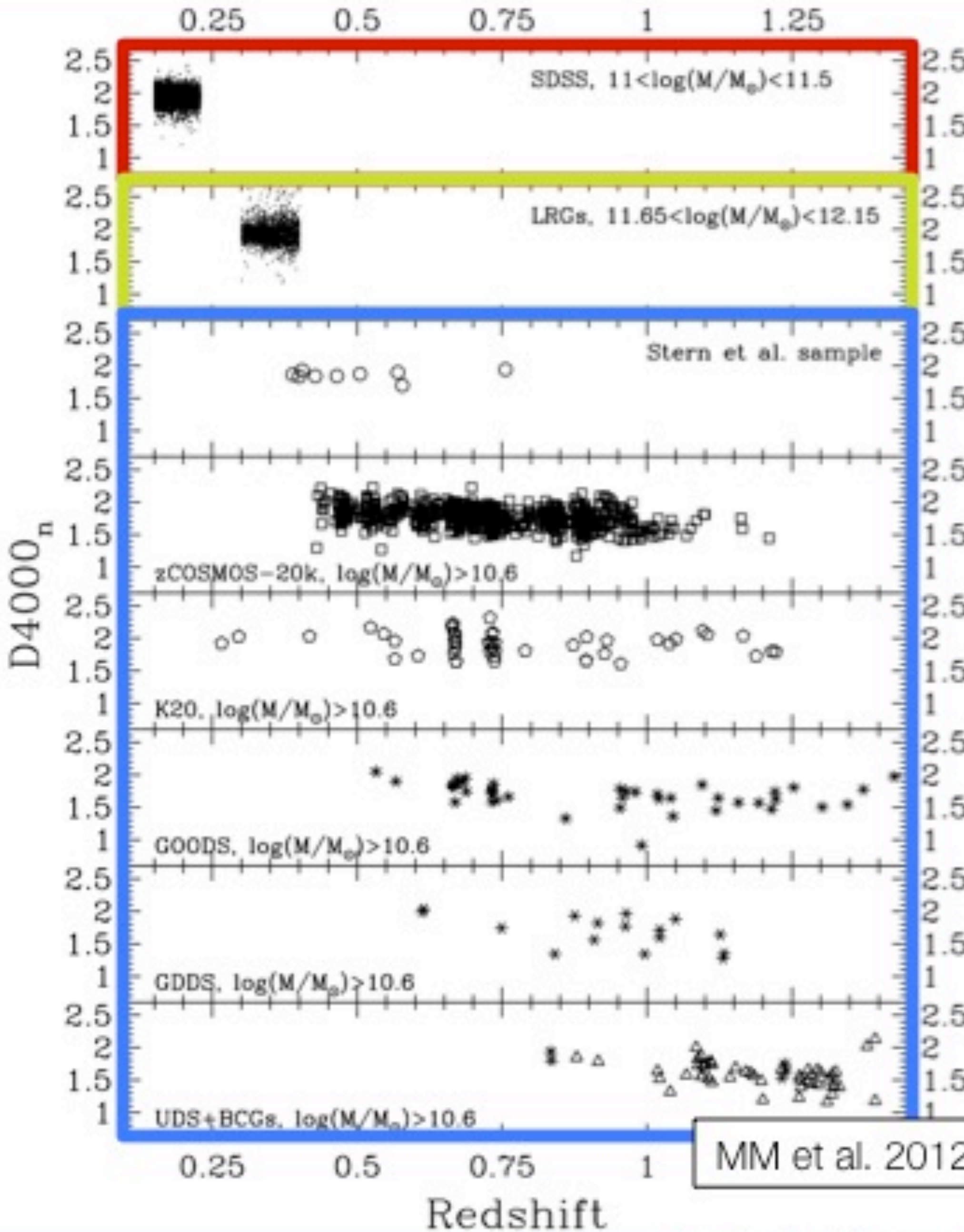
1. extraction of the reddest galaxies with multi-band SEDs compatible with the template of ETGs at z~0 or with old passive stellar populations;
2. high-quality optical spectra with reliable redshifts and suitable to provide D4000n amplitudes up to z~1.5;
3. absence of emission lines (Hα and/or [OII] λ3727 depending on the redshift) in order to exclude ongoing star formation or AGN activity
4. stellar masses (M) estimated from photometric SED fitting to be above $10^{11}M_\odot$ (above $10^{10.6}M_\odot$ at z>0.4);
5. spheroidal morphology typical of elliptical galaxies (when this information was available)

→ 11324 ETGs in the range 0.15<z<1.4

metallicity measurements for SDSS MGS sample
Gallazzi et al. (2005)

Treatment of the data

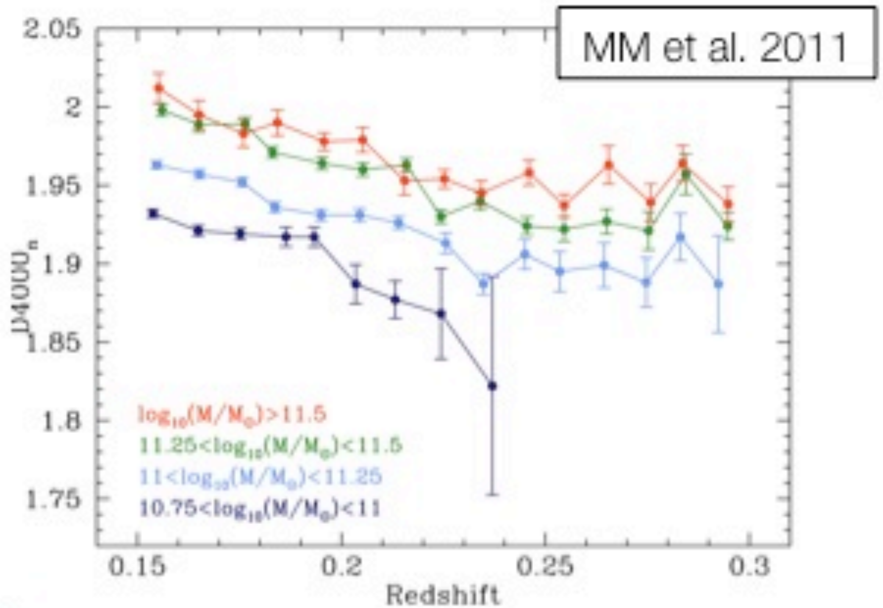
- **SDSS** (0.15<z<0.23), **LRGs** (0.3<z<0.4) and **"z>0.4"** galaxies treated separately, to mitigate the issue of having samples with different selection effects, mass ranges and estimates, and which may suffer of different systematics

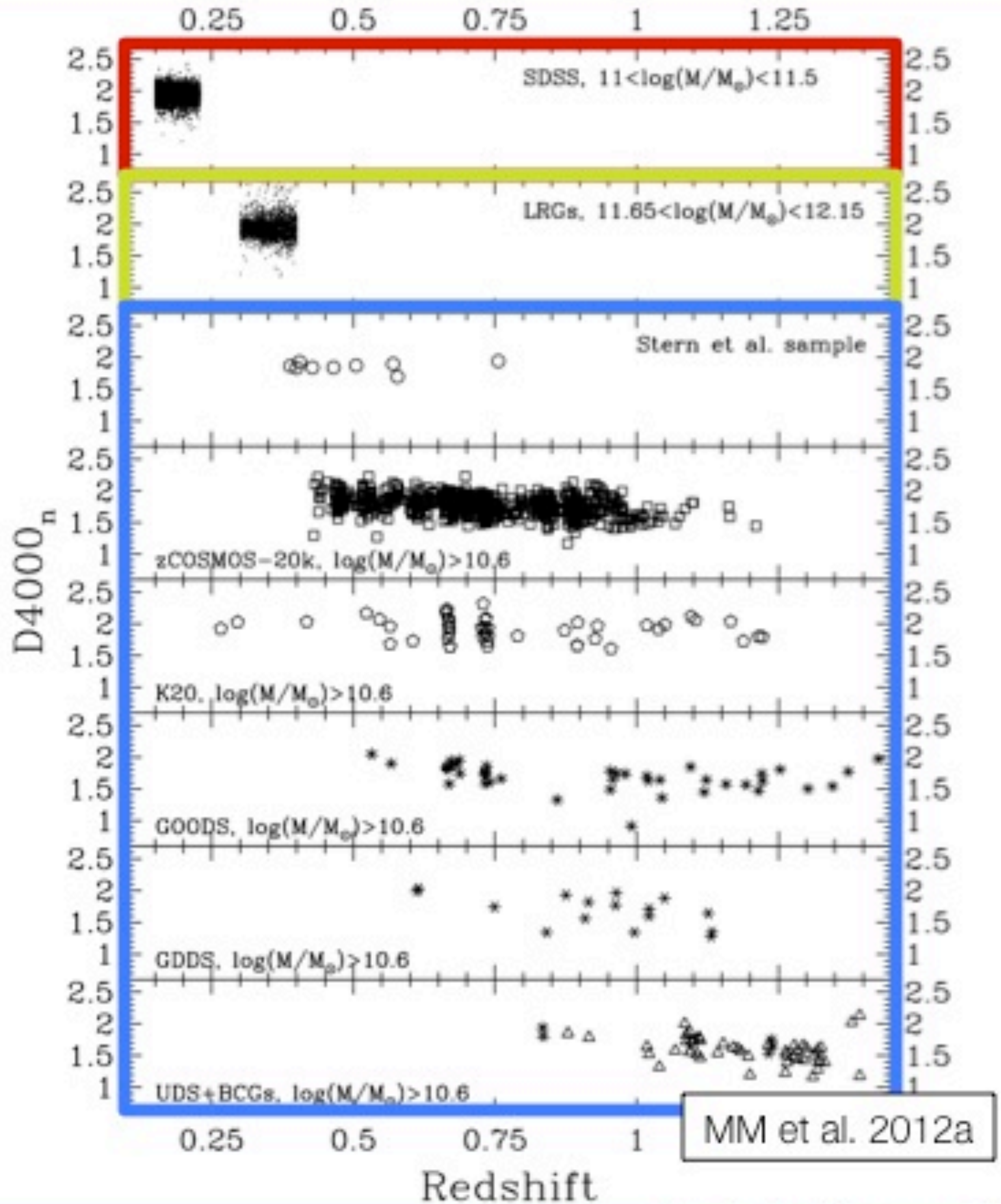


MM et al. 2012a

Treatment of the data

- **SDSS** (0.15<z<0.23), **LRGs** (0.3<z<0.4) and **"z>0.4"** galaxies treated separately, to mitigate the issue of having samples with different selection effects, mass ranges and estimates, and which may suffer of different systematics
- each sample has been divided into 2 different stellar mass subsamples, to take into account the dependence of $D4000_n$ on stellar mass

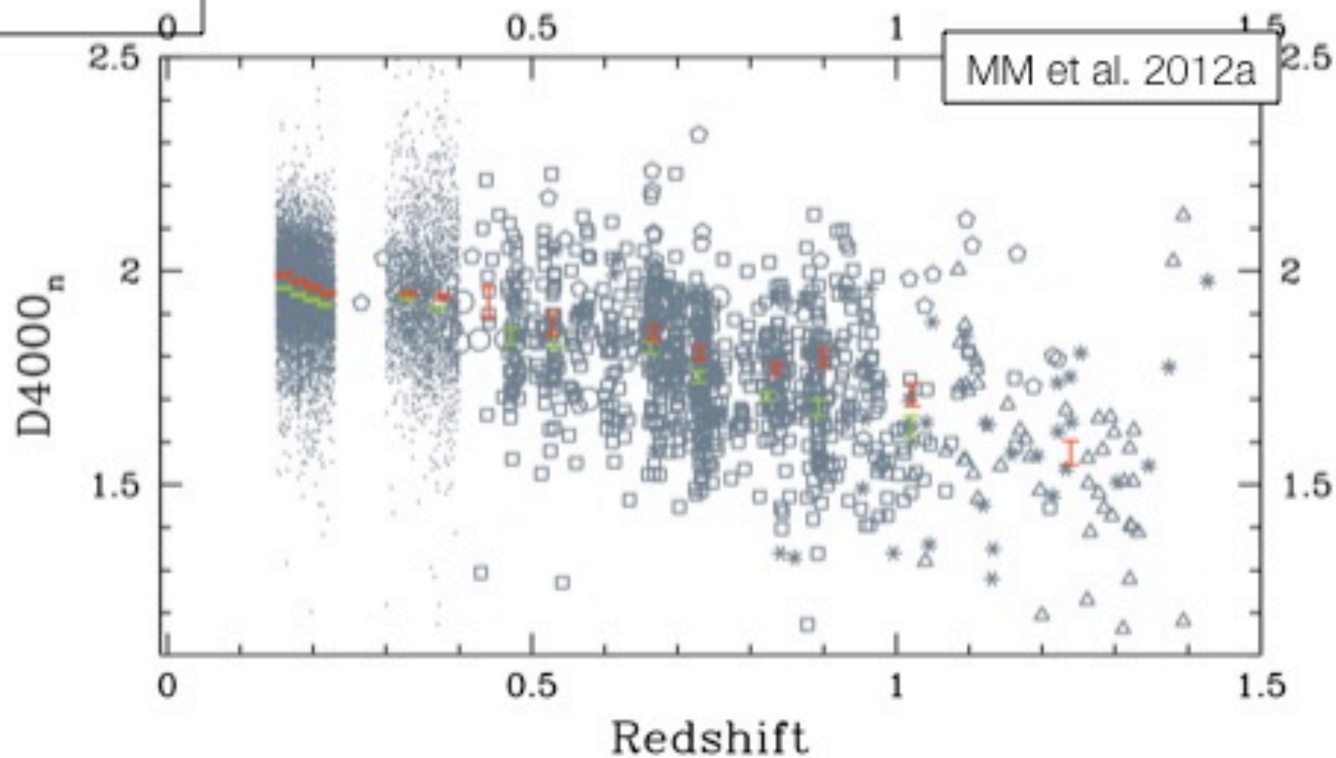




Relevant quantities

$$H(z) = -\frac{1}{1+z} A(Z, SFH) \frac{dz}{dD4000_n}$$

1. Estimated the median $D4000_n$-z relation for each mass subsamples of SDSS, LRGs and "z>0.4" samples



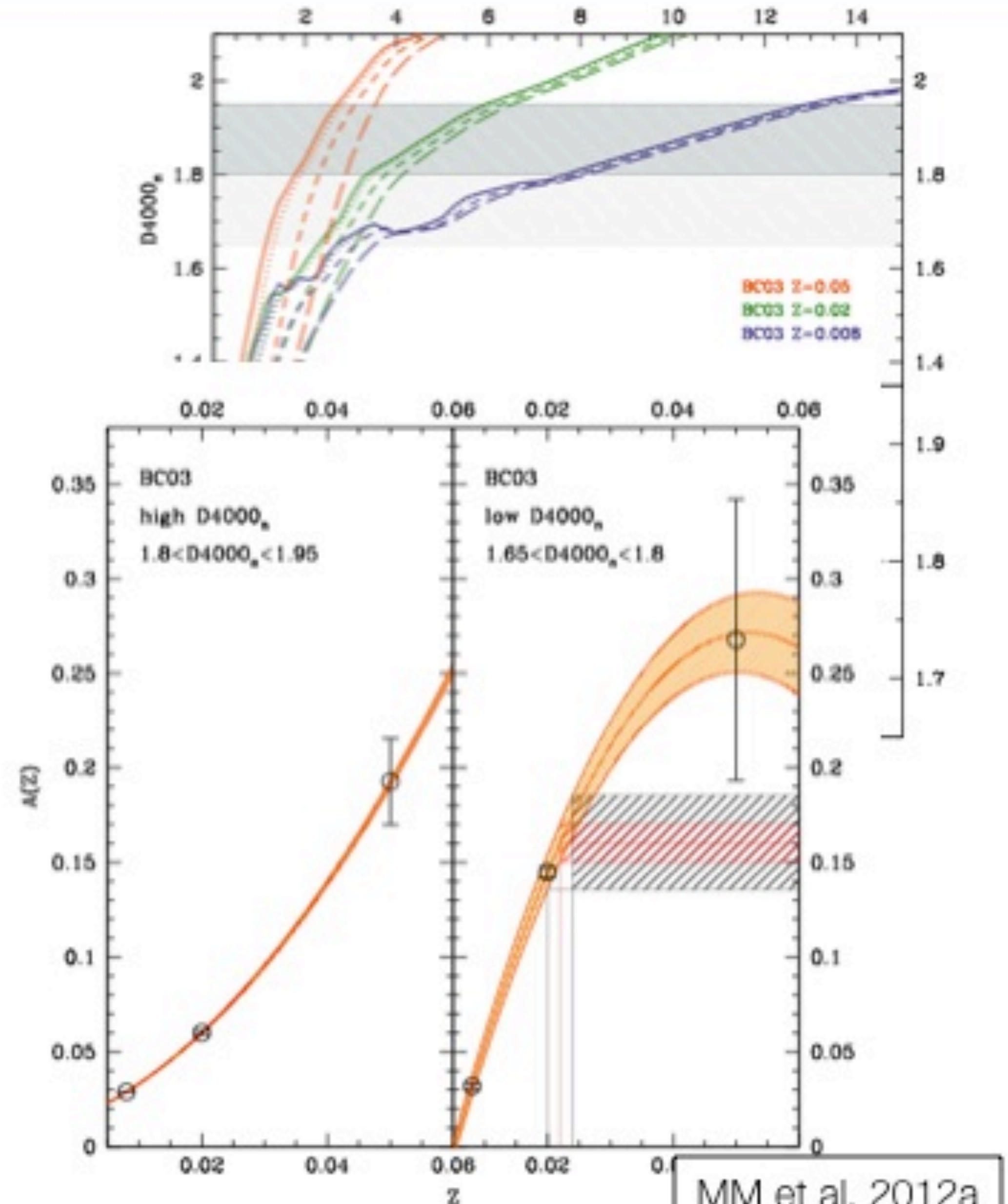
Relevant quantities

$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

1. Estimated the median $D4000_n$-z relation for each mass subsamples of SDSS, LRGs and "z>0.4" samples

2. Estimated from stellar population synthesis models (BC03 and MaStro)

   - grid of SFHs representative of a passive population
   - considering the measured metallicity for SDSS and assuming a range of metallicities for the other samples



MM et al. 2012a

Error budget

Statistical error σ_{stat} standard error propagation

Systematic error σ_{syst} enters in the definition of A(Z,SFH):

SFH contribution ΔD4000$_n$-Δage relations estimated for different SFHs (characteristic of a passive population), and then the slope is averaged, to obtain a mean **A(Z)± σ_A(SFH)**

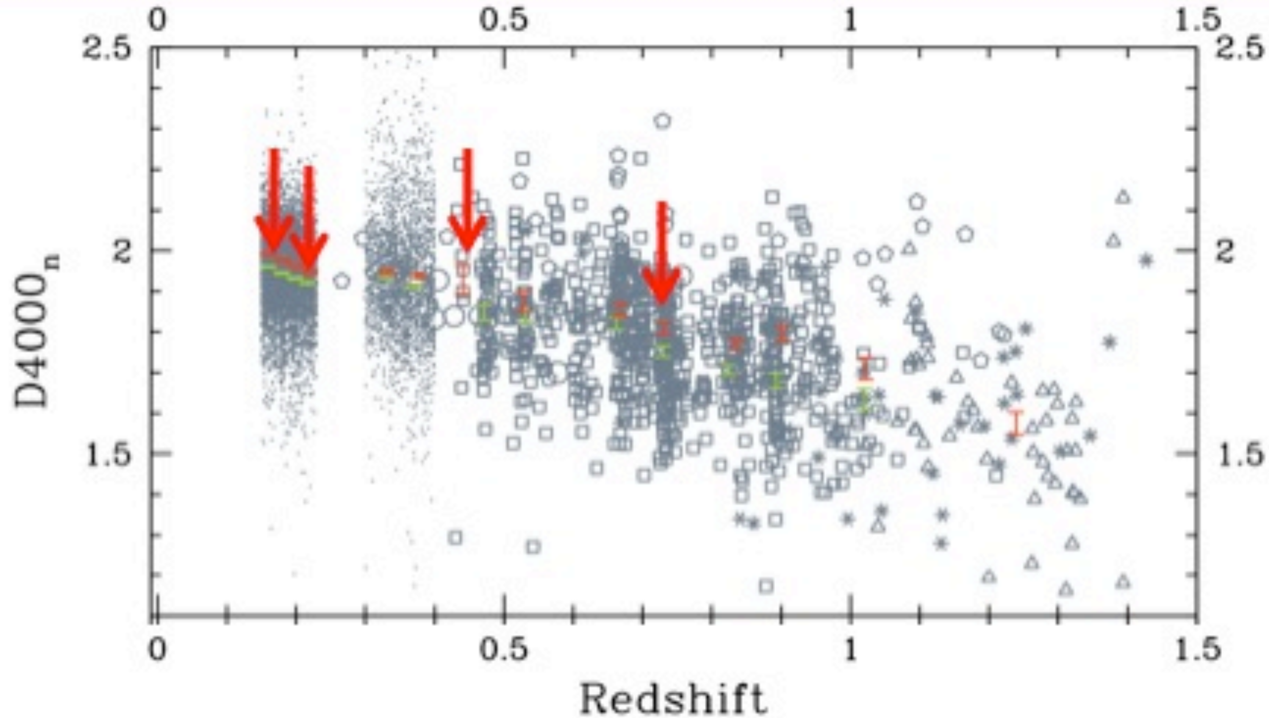
metallicity contribution the factor A(Z) is estimated for a minimum Z_{min} and a maximum Z_{max} value of metallicity (measured in the SDSS, prior for z>0.3)

H(z) is evaluated for A(Z_{min}), A(Z_{med}), A(Z_{max}), and the dispersion between the measurements gives an estimate of the total systematic error

$$\sigma_{tot}^2 = \sigma_{stat}^2 + \sigma_{syst}^2$$

H(z) estimate

- the differential $D4000_n$ has been evaluated between couple of median D4000n points, separately for each mass subsample of the SDSS, LRGs and "z>0.4" sample
- D4000n points have been considered as close as possible to maximize the number of H(z) estimates but not too close to avoid being dominated by the statistical scatter of the data
- estimates obtained with 2 different SPS models

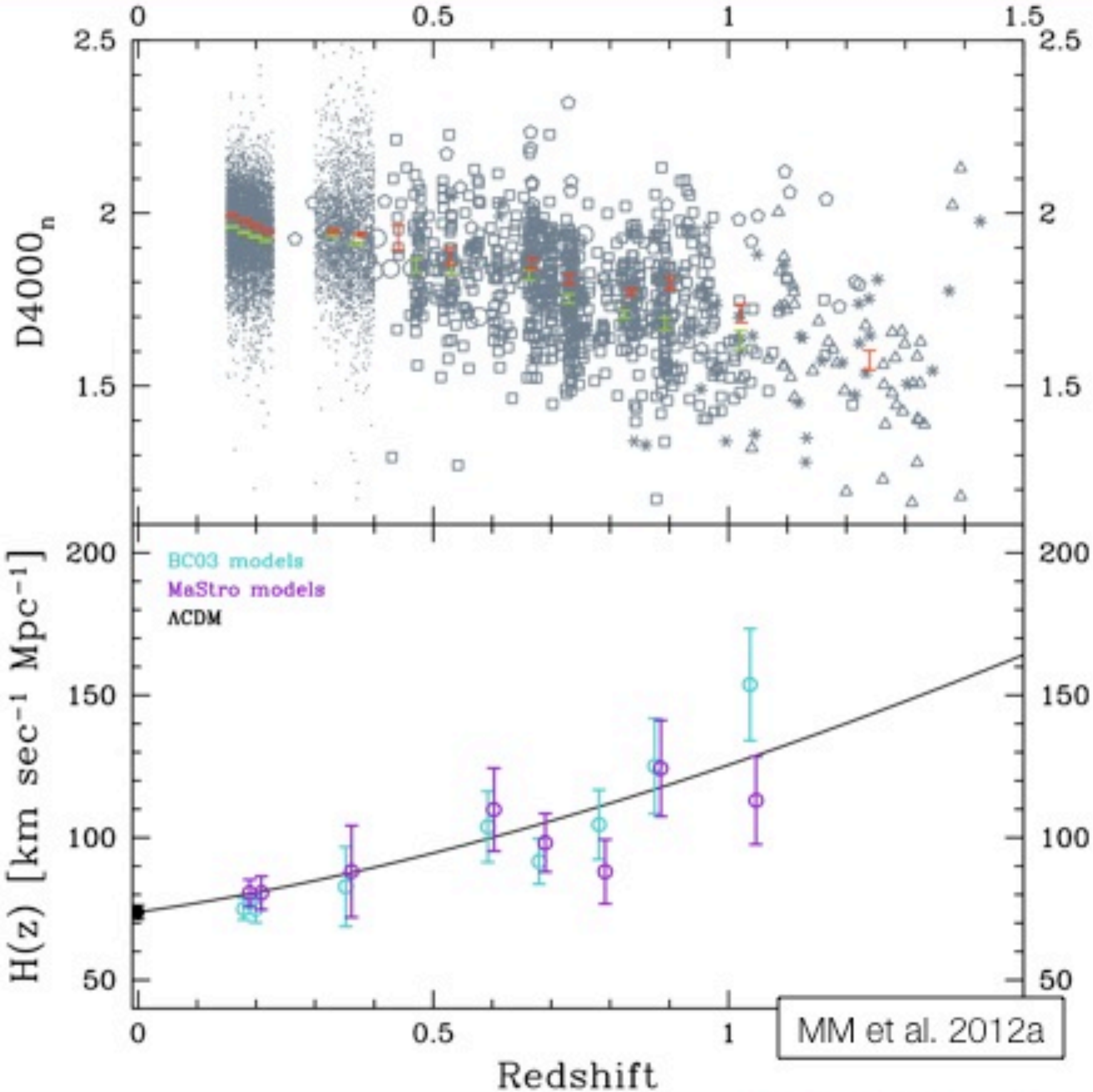


MM et al. 2012a

H(z) estimate

- the differential $D4000_n$ has been evaluated between couple of median D4000n points, separately for each mass subsample of the SDSS, LRGs and “z>0.4” sample
- D4000n points have been considered as close as possible to maximize the number of H(z) estimates but not too close to avoid being dominated by the statistical scatter of the data
- estimates obtained with 2 different SPS models

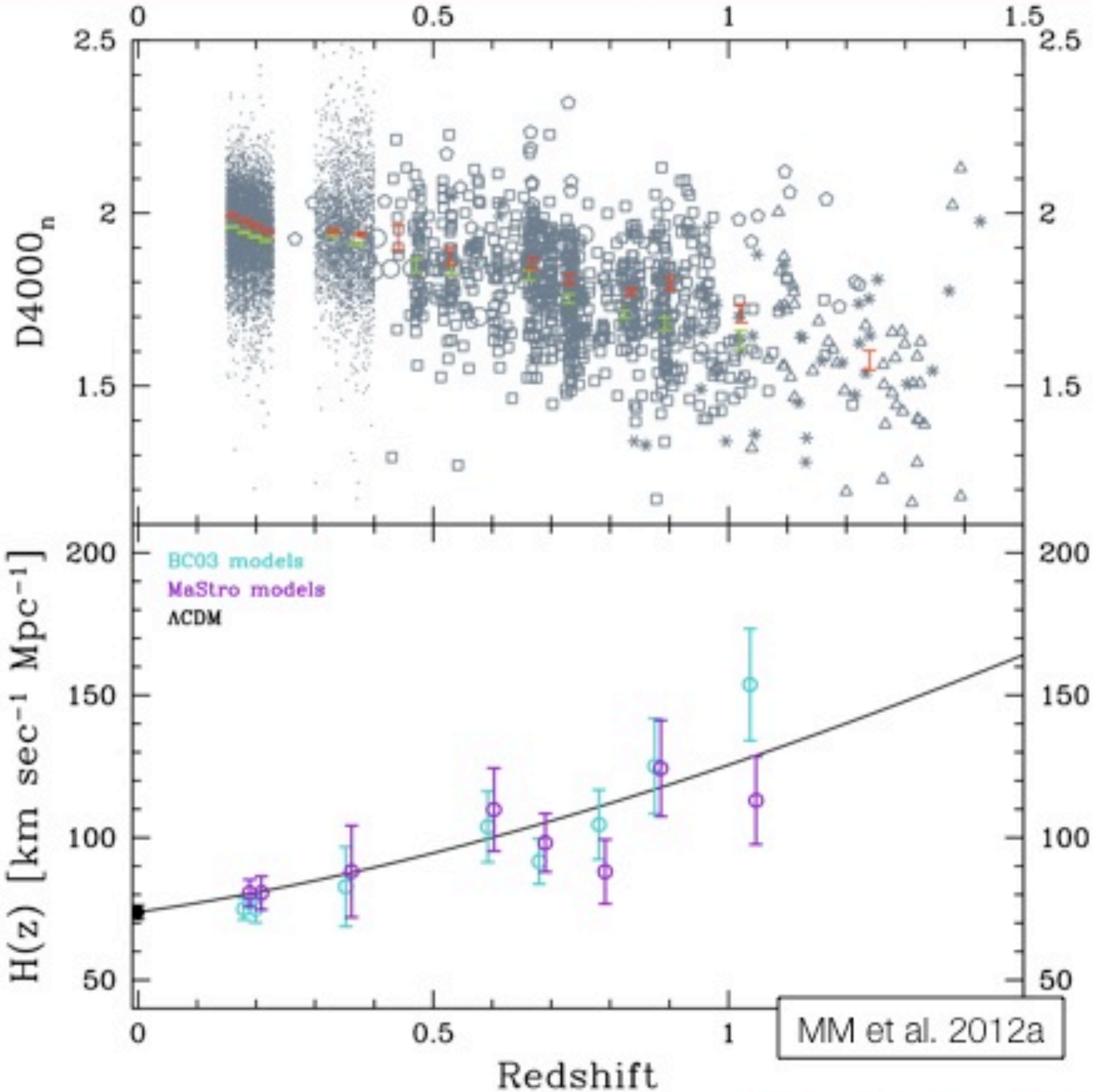
- **precision of ~5% at z~0.2**, comparable with recent estimates of the Hubble constant
- **precision of ~12% across the entire redshift range**



MM et al. 2012a

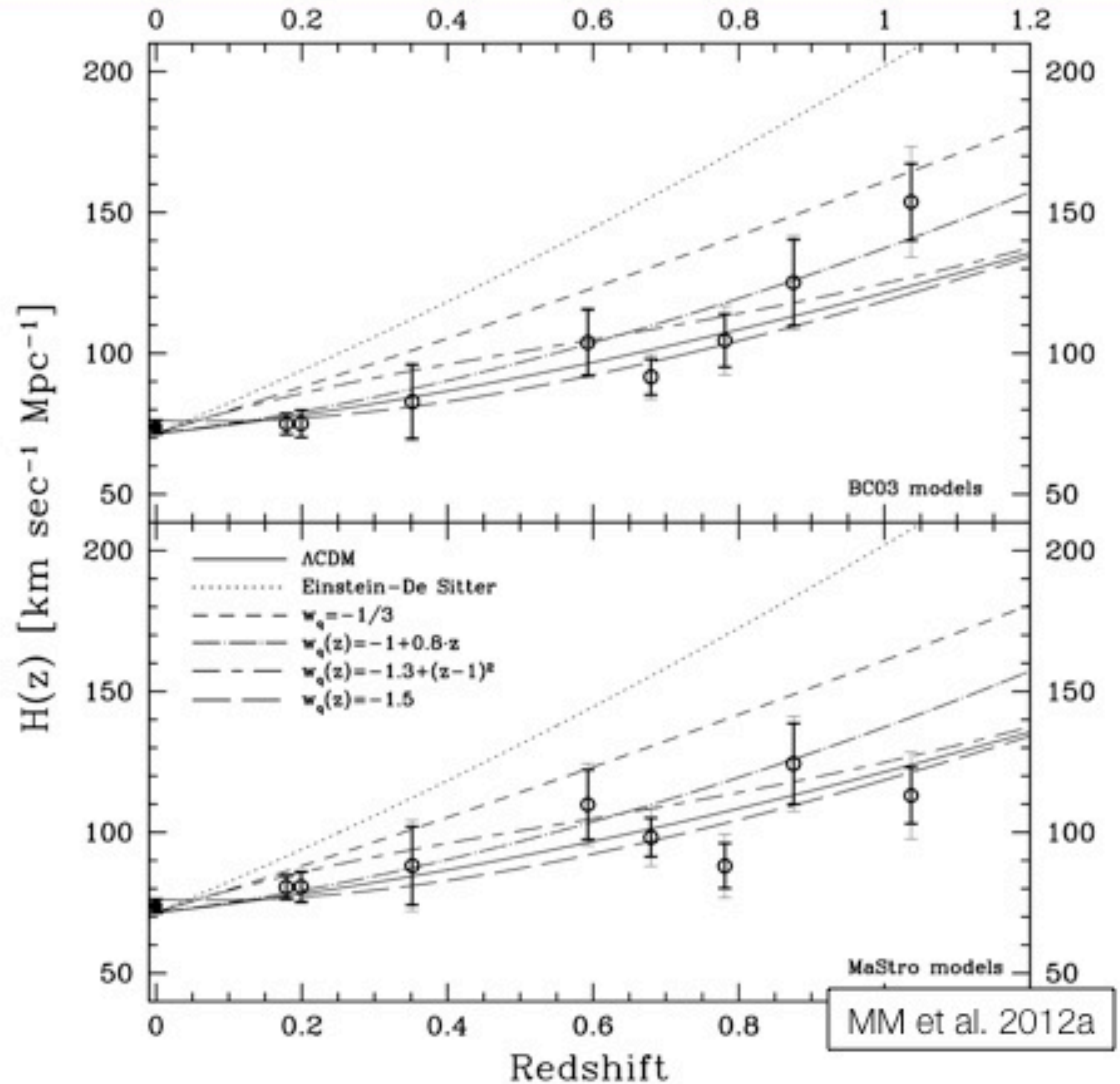
Improvements with respect to previous works

- use of different samples which give consistent results
- analysis performed with two different stellar models, which provide compatible results
- the use of the $D4000_n$ feature, which is less model dependent and more robust
- control of the mass dependence systematics
- homogeneous coverage of the full redshift interval, and particularly in the range 0.15<z<1, which is the crucial cosmic time to disentangle many different models
- higher accuracy across the entire redshift range (5–12% including systematic errors)



Comparison with different cosmological models

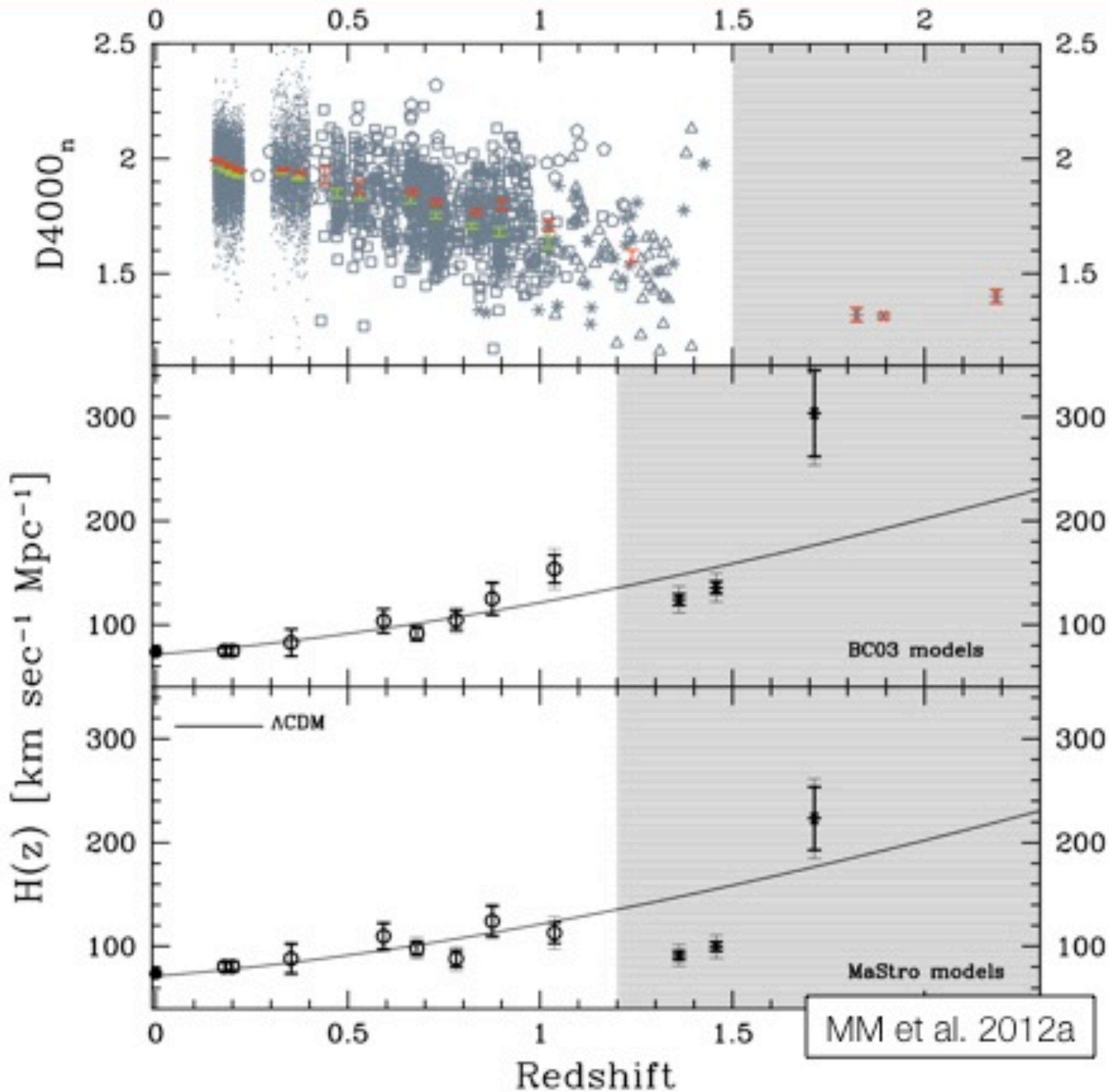
- EdS discarded at >7 sigma
- direct and independent evidence of the accelerated expansion of the Universe, at >6 sigma
- new path to constrain alternative cosmologies (with higher-z data and/or higher statistic at z>0.4)



MM et al. 2012a

Comparison with different cosmological models

- EdS discarded at >7 sigma
- direct and independent evidence of the accelerated expansion of the Universe, at >6 sigma
- new path to constrain alternative cosmologies (with higher-z data and/or higher statistic at z>0.4)
- preliminary study with high-z ETGs (z>1.8)
  Kriek et al. 2009, Onodera et al. 2010, Ferreras et al. 2012



MM et al. 2012a

The importance of the differential approach

$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

Problem	**Solution**
Progenitor bias	Evolution estimated not between z~0 and z~1, but with Δz~0.04 at z<0.4 and Δz~0.3 at z>0.4, i.e. Δage~500 Myr and Δage~1.5 Gyr

The importance of the differential approach

$$H(z) = -\frac{1}{1+z} A(Z, SFH) \frac{dz}{dD4000_n}$$

Problem	Solution
Progenitor bias	Evolution estimated not between z~0 and z~1, but with Δz~0.04 at z<0.4 and Δz~0.3 at z>0.4, i.e. Δage~500 Myr and Δage~1.5 Gyr
Mass evolution	Minor mass evolution for massive ETGs Estimate of $D4000_n$-z for 2 different mass bins

The importance of the differential approach

$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

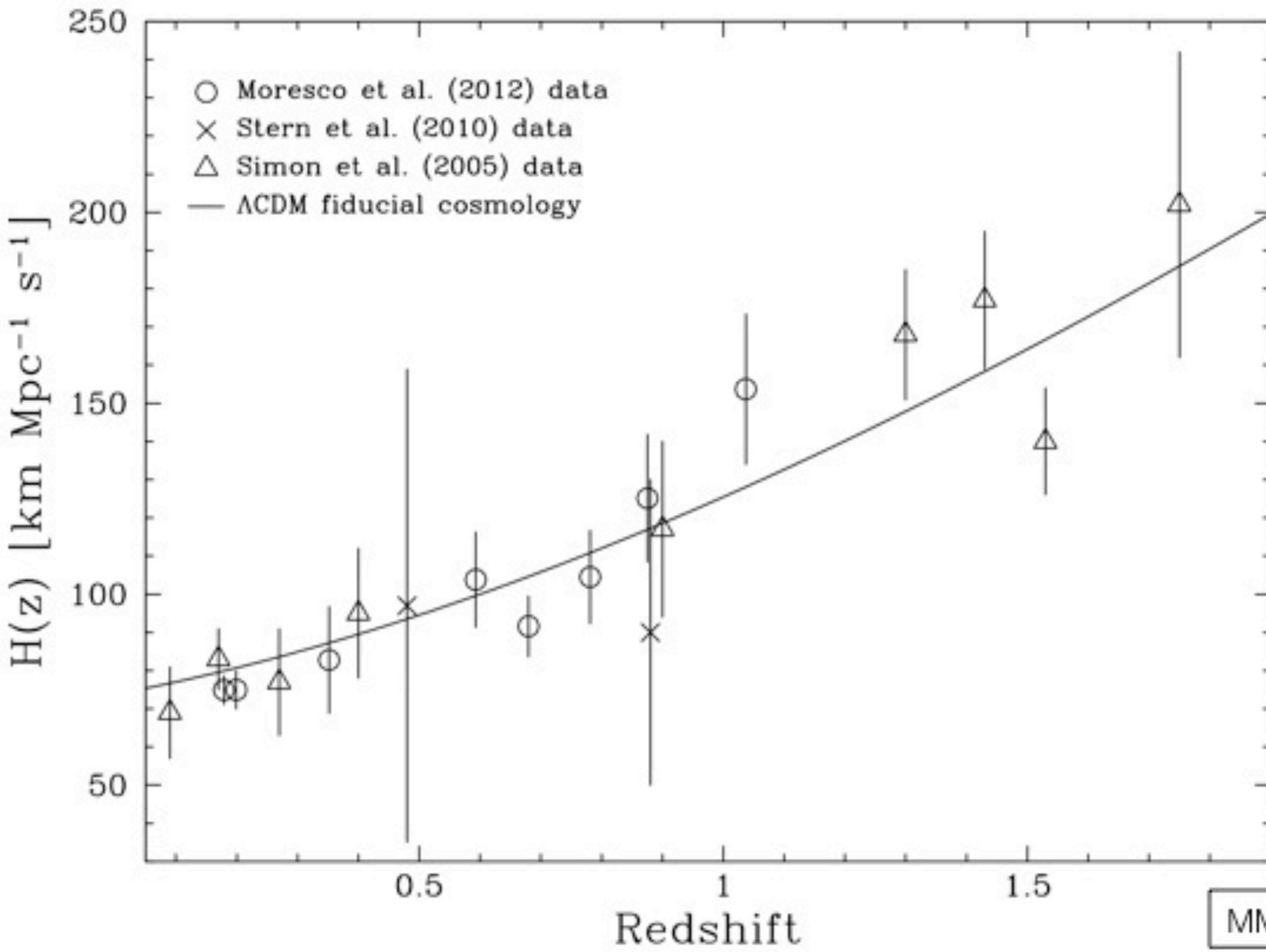
Problem	Solution
Progenitor bias	Evolution estimated not between z~0 and z~1, but with Δz~0.04 at z<0.4 and Δz~0.3 at z>0.4, i.e. Δage~500 Myr and Δage~1.5 Gyr
Mass evolution	Minor mass evolution for massive ETGs Estimate of $D4000_n$-z for 2 different mass bins
Non-homogeneity of the samples	Separate treatment of SDSS, LRG and "z>0.4" samples

Moreover…

1. No dependence on the overall normalization (relative instead of absolute ages)
2. Synchronicity is required only where the differences are taken
3. Minimization of the impact of non-homogeneous samples
4. Standard(-izable) clocks = chronometers

Constraints to cosmological parameters
with the Observational Hubble parameter Data

Observational Hubble parameter Data (OHD)

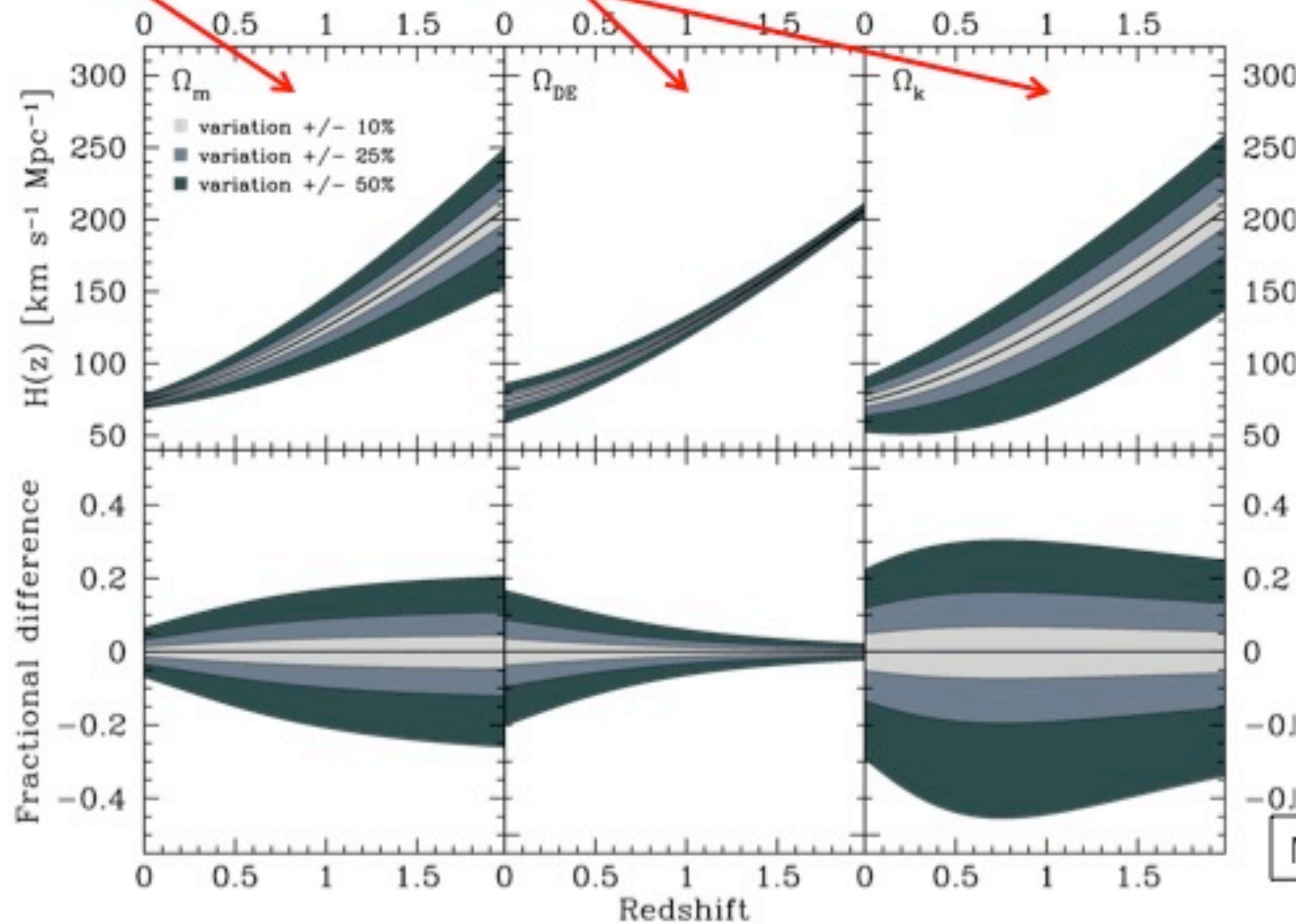


MM et al. 2012b

Constraining cosmological parameters with OHD 1/2

$$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w_0+w_a)} e^{-3 w_a \frac{z}{1+z}} \right]^{1/2}$$

$$w(z) = w_0 + w_a \left(\frac{z}{1+z}\right)$$

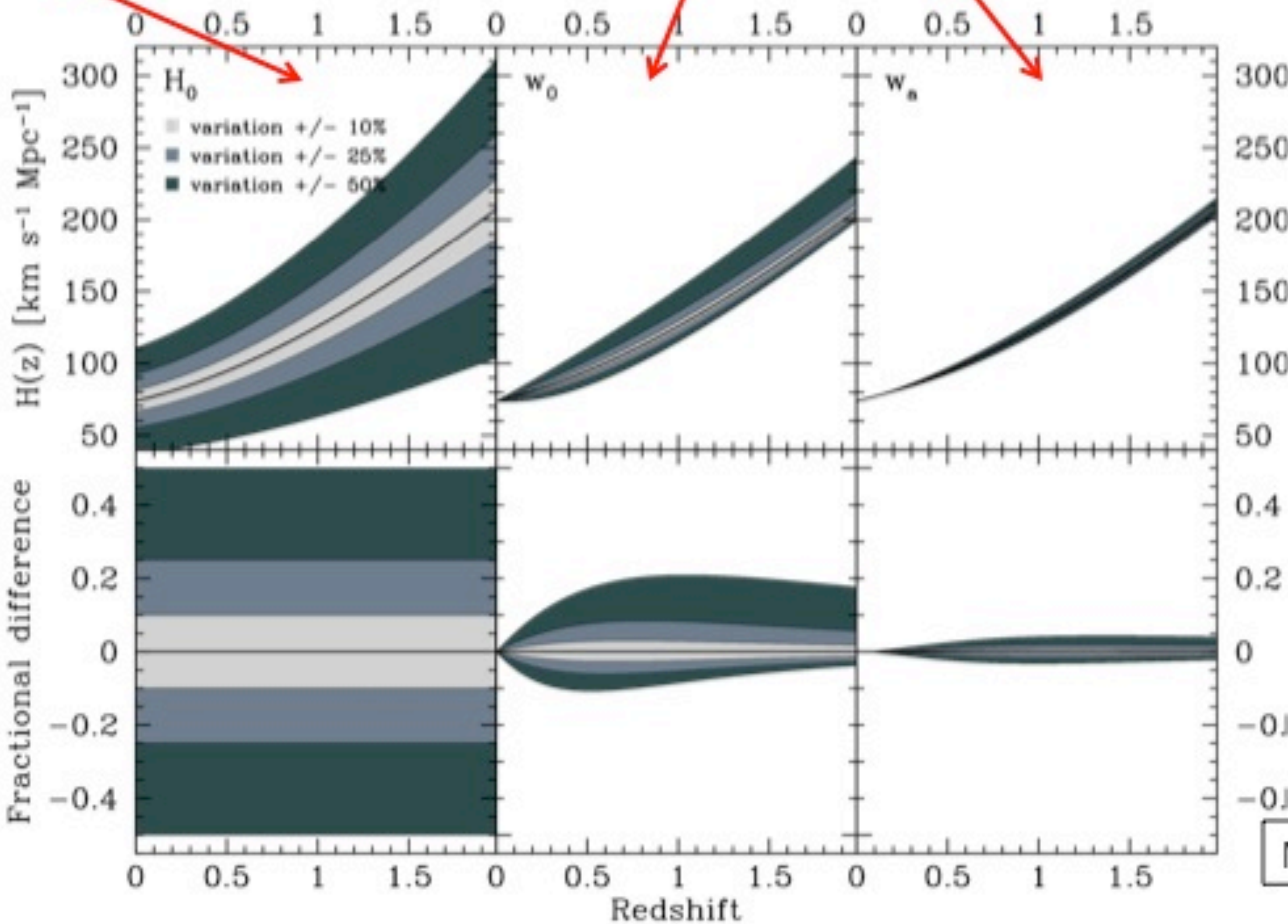


MM et al. 2012b

Constraining cosmological parameters with OHD 2/2

$$H(z) = H_0\left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{DE}(1+z)^{3(1+w_0+w_a)}e^{-3w_a\frac{z}{1+z}}\right]^{1/2}$$

$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right)$$



MM et al. 2012b

Explored cases

OHD measurements used to break CMB parameters degeneracies for models beyond the "minimal" ΛCDM model

Dataset

OHD Simon et al. (2005) + Stern et al. (2010) + Moresco et al. (2012)
CMB 7-years data Larson et al. (2011)
H_0 Riess et al. (2011)

Science Cases

1. Constraints on deviations from ΛCDM that affect directly the expansion history

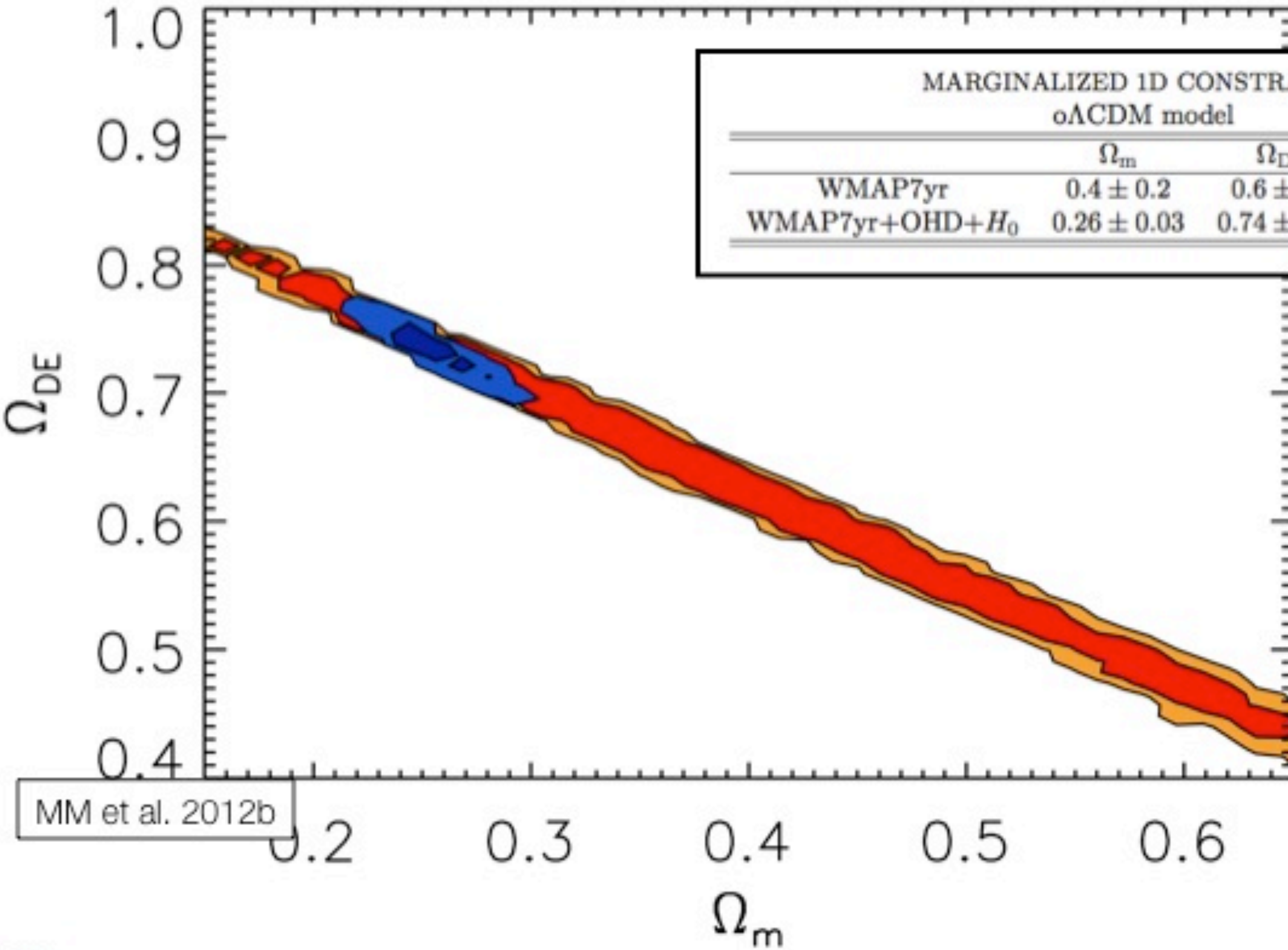
oΛCDM → owCDM → ow(z)CDM

2. Constraints on deviations from ΛCDM that affect the expansion history only through parameter degeneracies

Σm_ν (ΛCDM)

N_{rel} (ΛCDM, using also SPT or ACT data)

Direct constraints: oΛCDM



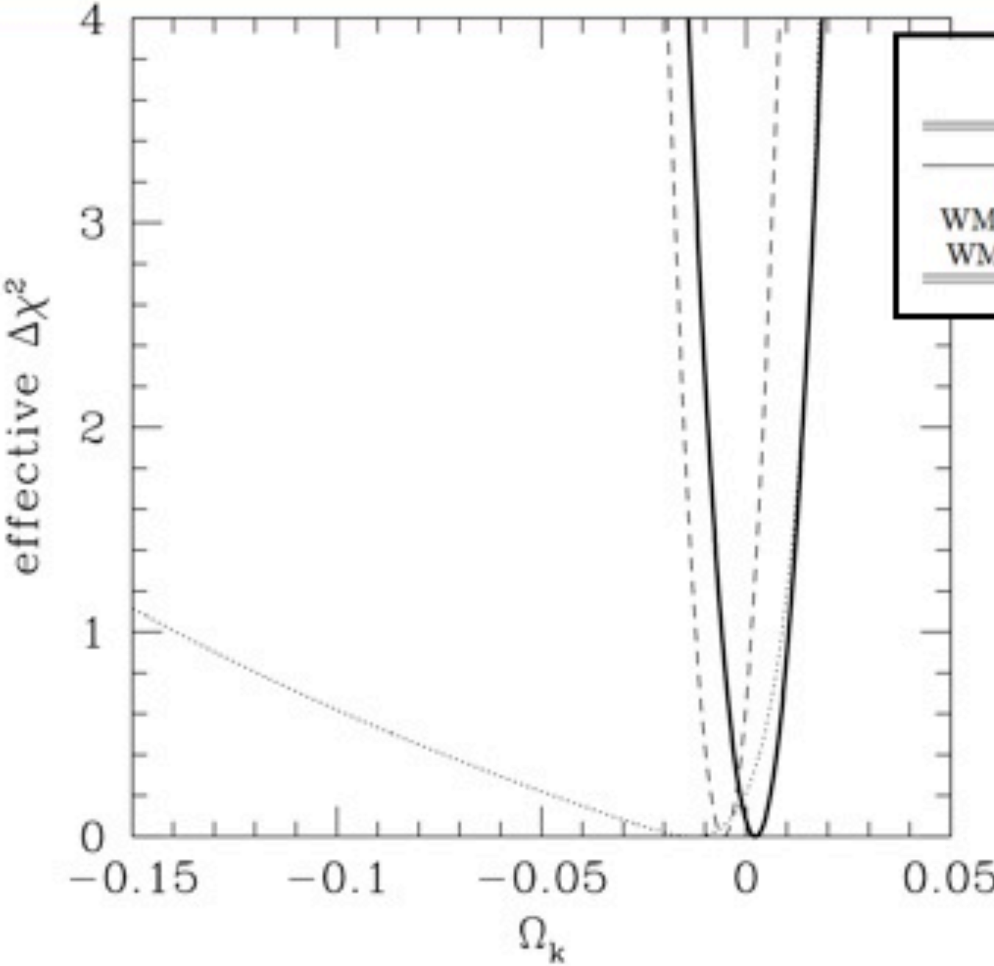
MARGINALIZED 1D CONSTRAINTS
oΛCDM model

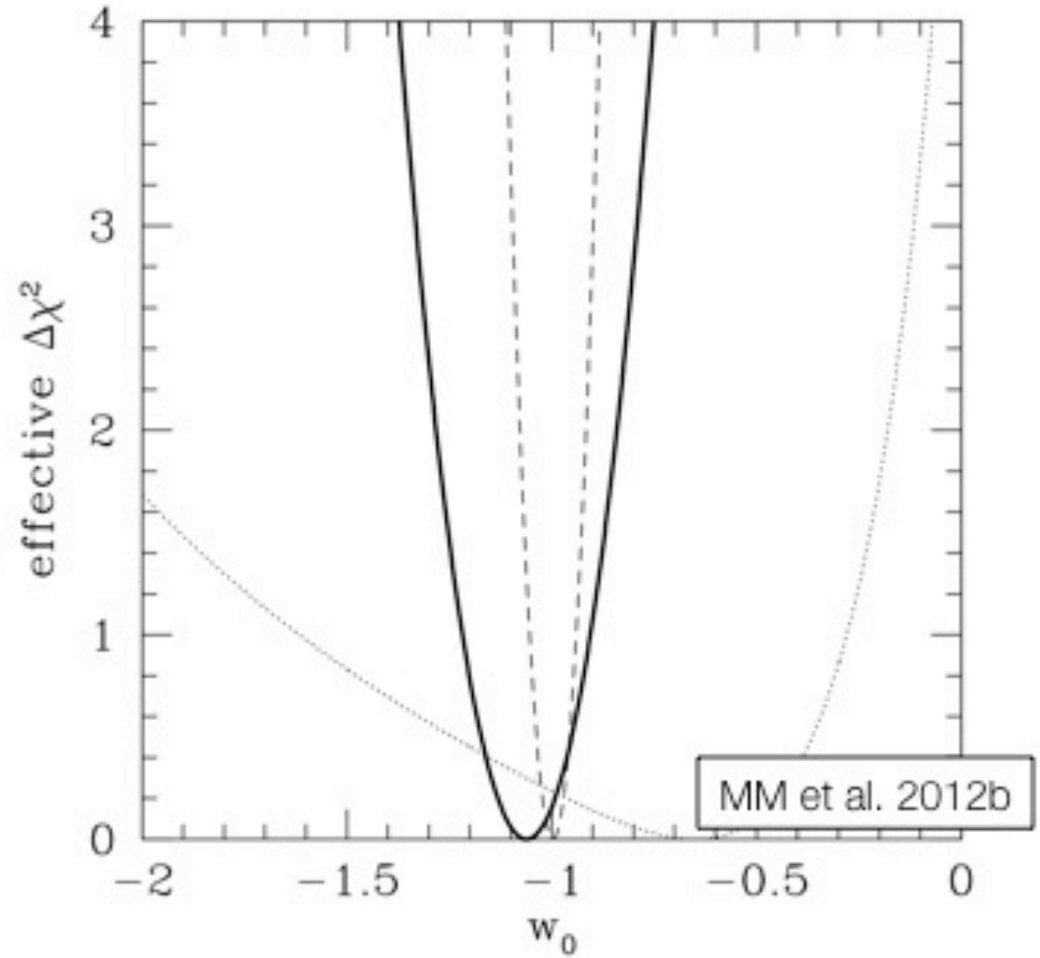
	Ω_m	Ω_{DE}	Ω_k
WMAP7yr	0.4 ± 0.2	0.6 ± 0.2	-0.001 ± 0.1
WMAP7yr+OHD+H_0	0.26 ± 0.03	0.74 ± 0.02	0.001 ± 0.007

Direct constraints: owCDM

MARGINALIZED 1D CONSTRAINTS
owCDM model

	Ω_m	Ω_{DE}	Ω_k	w_0
WMAP7yr	0.6 ± 0.3	> 0.5	$-0.01^{+0.04}_{-0.1}$	-0.7 ± 0.6
WMAP7yr+BAO+SNe	0.29 ± 0.02	0.72 ± 0.02	-0.006 ± 0.006	-1 ± 0.06
WMAP7yr+OHD+H_0	0.25 ± 0.02	0.75 ± 0.02	0.002 ± 0.008	-1.1 ± 0.2



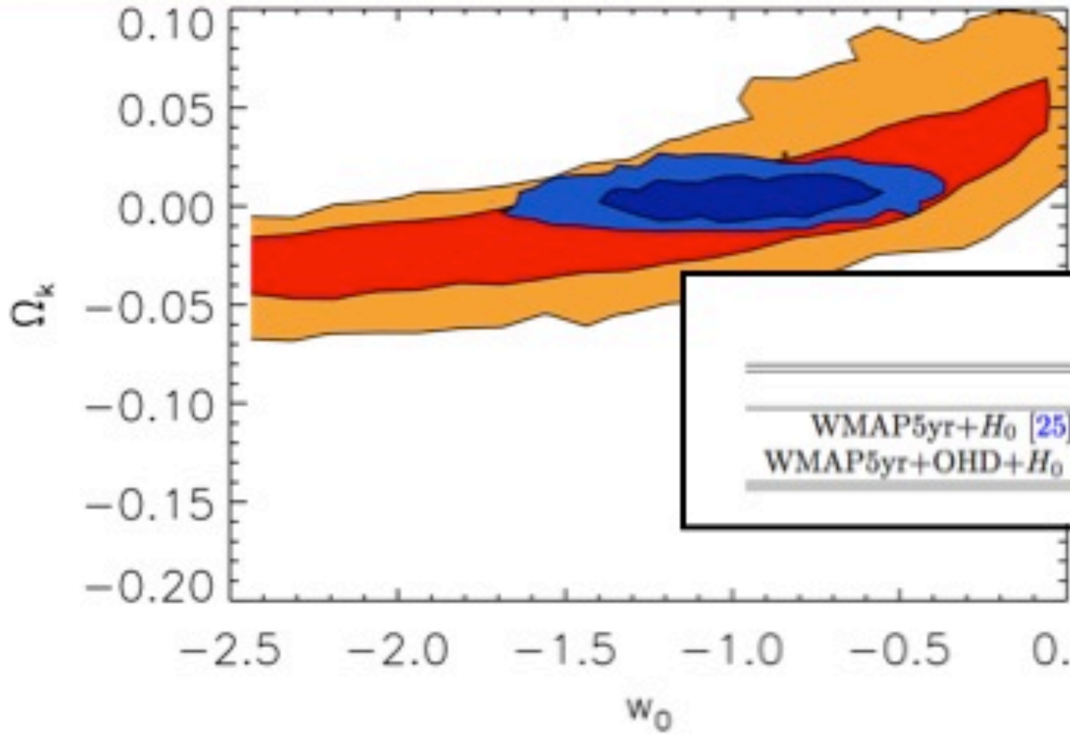


WMAP7yr dotted lines

WMAP7yr+BAO+SNe dashed lines

WMAP7yr+OHD+H_0 thick lines

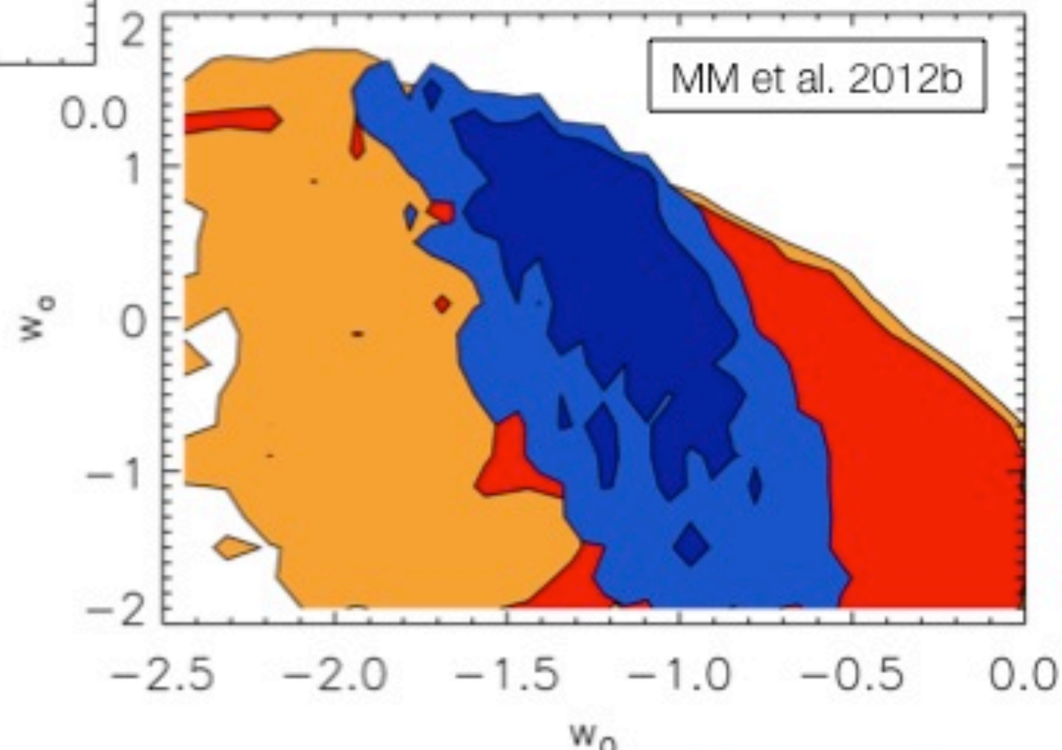
Direct constraints: ow(z)CDM



$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right)$$

MARGINALIZED 1D CONSTRAINTS
$ow(z)$CDM model

	Ω_m	Ω_{DE}	Ω_k	w_0	w_a
WMAP5yr+H_0 [25]	0.29 ± 0.06	0.71 ± 0.06	-0.01 ± 0.4	-0.7 ± 0.7	< -0.2
WMAP5yr+OHD+H_0 [16]	0.27 ± 0.02	0.73 ± 0.03	0.004 ± 0.009	-1.2 ± 0.3	$0.6^{+0.9}_{-1}$



WMAP7yr
red contours

WMAP7yr
+OHD+H_0
blue contours

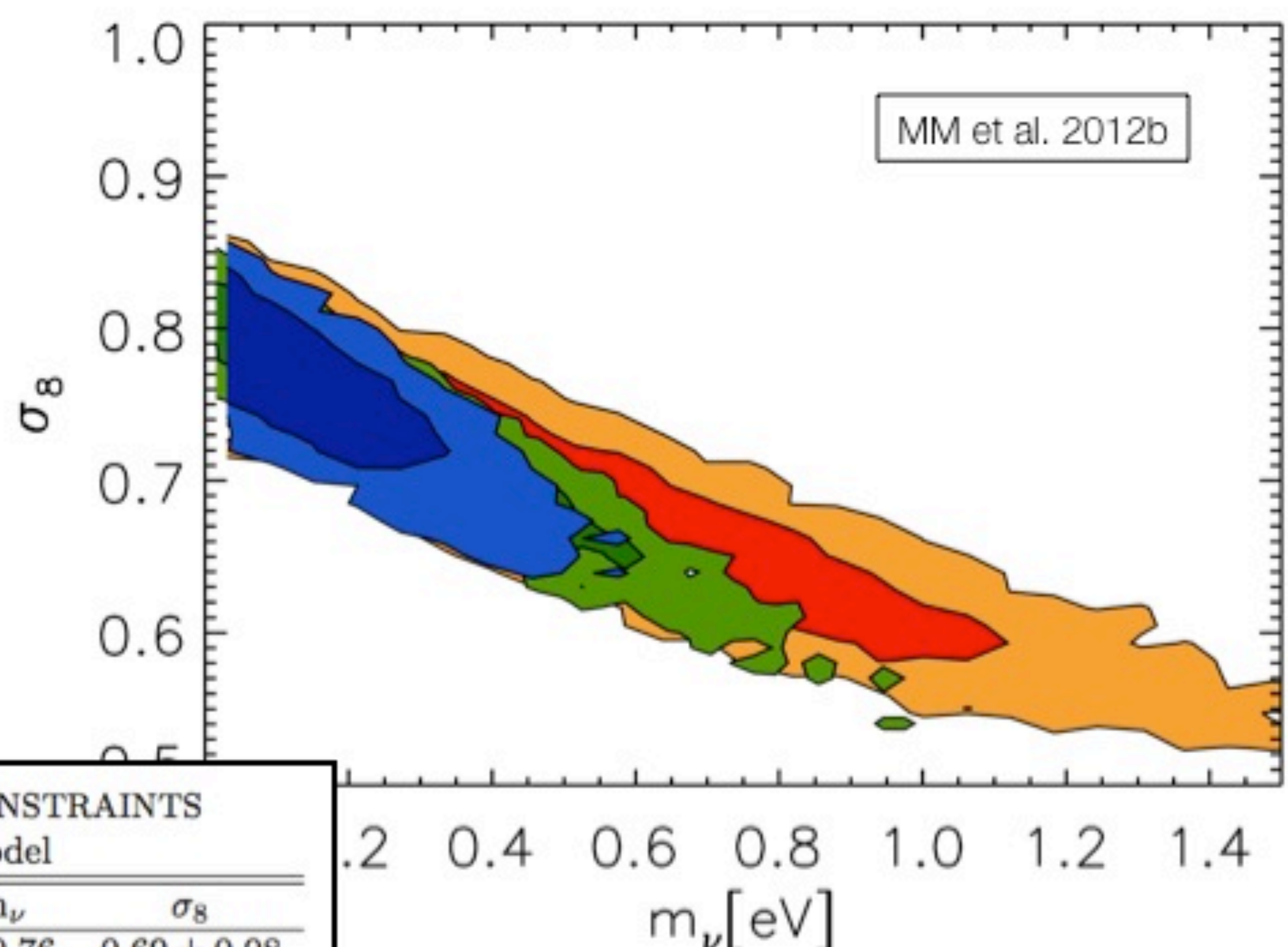
Michele Moresco

Indirect constraints: Σmν and ΛCDM

WMAP7yr
red contours

WMAP7yr
+BAO+SNe
green contours

WMAP7yr
+OHD+H_0
blue contours



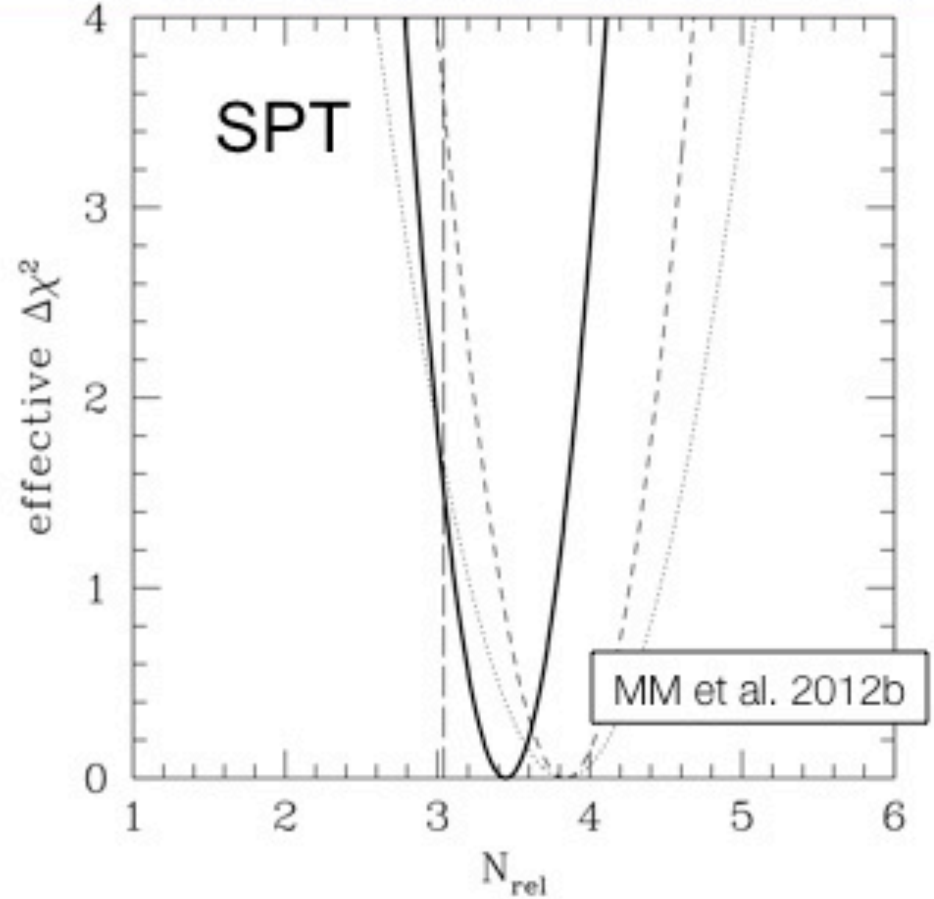
MARGINALIZED 1D CONSTRAINTS
ΛCDM+m_ν model

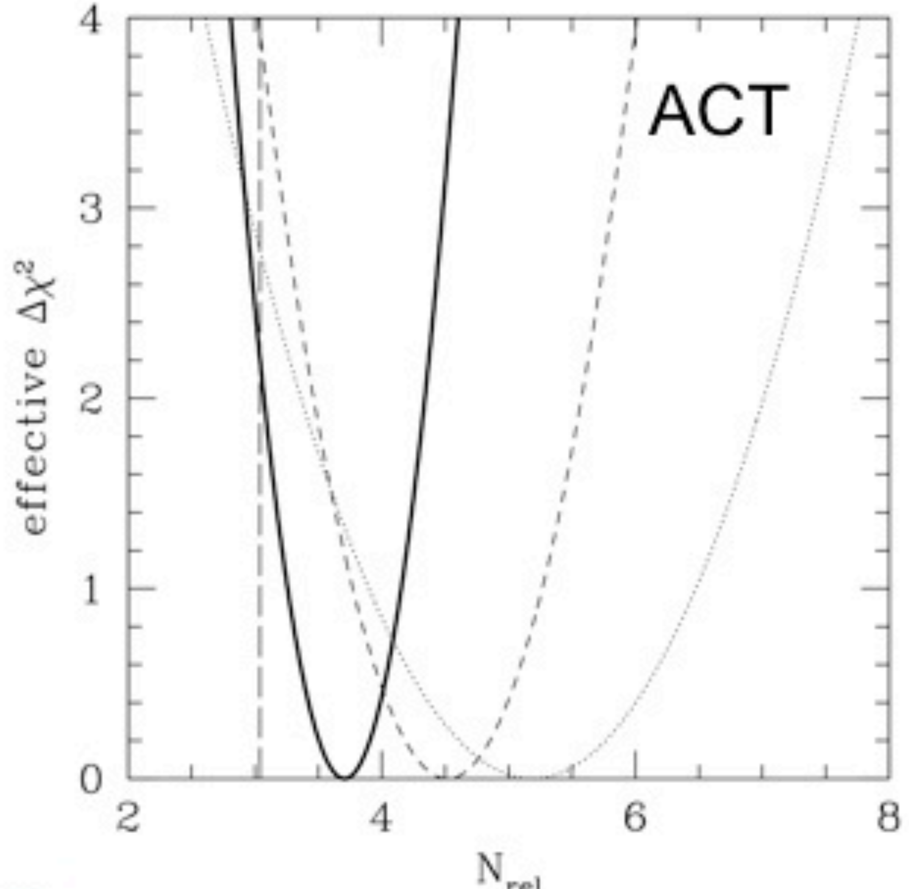
	m_ν	σ_8
WMAP7yr	< 0.76	0.69 ± 0.08
WMAP7yr+BAO+SNe	< 0.42	0.73 ± 0.06
WMAP7yr+OHD+H_0	< 0.24	0.76 ± 0.05

Indirect constraints: Nrel and ΛCDM

MARGINALIZED 1D CONSTRAINTS
ΛCDM+N_{rel} model

	N_{rel} using SPT data	N_{rel} using ACT data
WMAP7yr+SPT(/ACT)	3.8 ± 0.6	5.2 ± 1.3
WMAP7yr+SPT(/ACT)+BAO+H_0	3.8 ± 0.4	4.5 ± 0.7
WMAP7yr+SPT(/ACT)+OHD+H_0	3.5 ± 0.3	3.7 ± 0.4





WMAP7yr+SPT(/ACT) dotted lines

WMAP7yr+SPT(/ACT)+BAO+H_0 dashed lines

WMAP7yr+SPT(/ACT)+OHD+H_0 thick lines

Part 3

Constraints to dark energy potential
with the Observational Hubble parameter Data

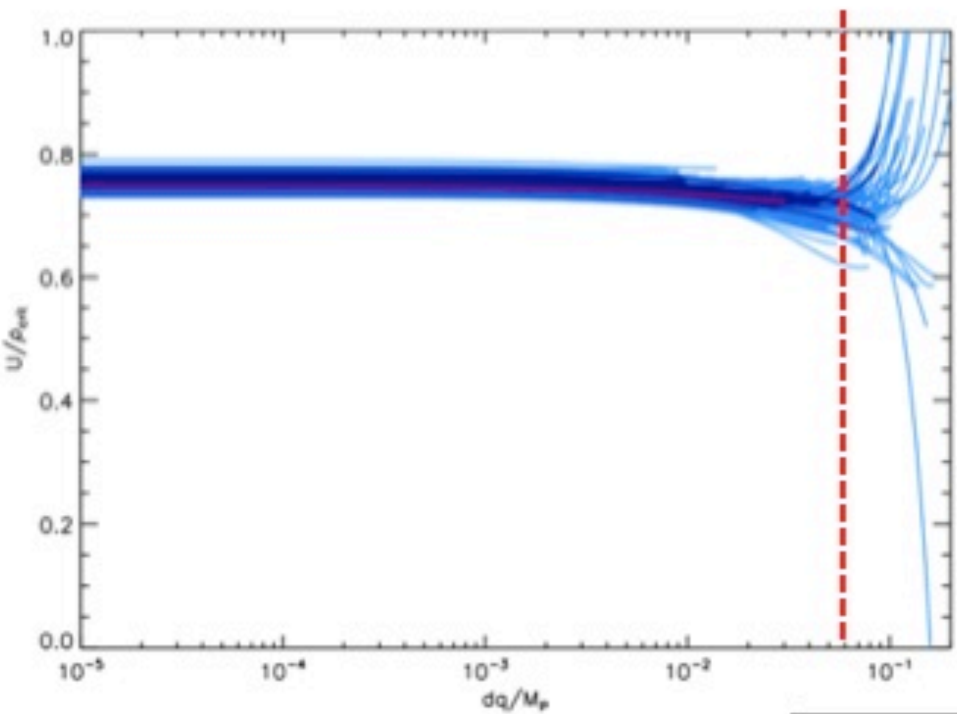
The effective Lagrangian of dark energy

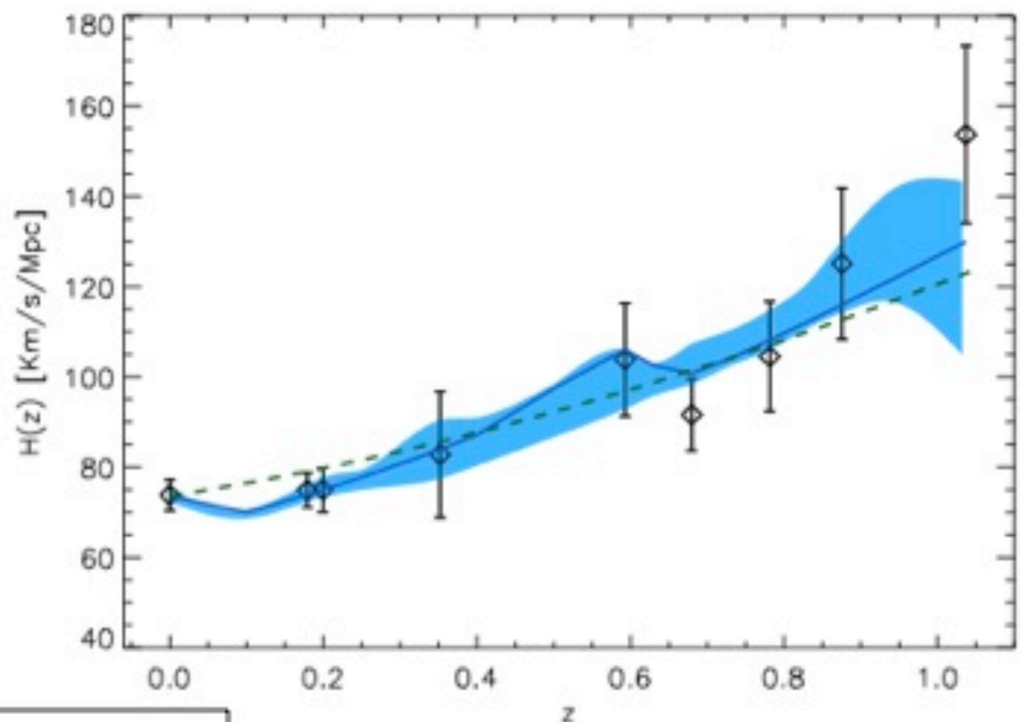
$$S = \int d^4x \sqrt{-g}\left(\frac{m_p^2}{2}R + f_9 C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} - \frac{1}{2}g^{\mu\nu}\partial_\mu q \partial_\nu q - U(q)\right)$$

with

$$U(q) = \lambda_0 + \lambda_1 q + \lambda_2 q^2 + \lambda_3 q^3 + \lambda_4 q^4 + \ldots$$

Effective potential consistent with being flat, i.e. cosmological constant





Jimenez et al. 2012

Conclusions

- ☐ We presented a large and reliable sample of ETGs in the range 0.15<z<1.4, extracted from different surveys to be the most massive and passively evolving
- ☐ The "cosmic chronometers" approach has been applied to this sample, to estimate the Hubble parameter H(z) from the differential evolution of the D4000n as a function of redshift
- ☐ Different SPS models have been analyzed to verify the assumption of a linear relation between D4000n and the age of a galaxy (in the D4000n range relevant for our data), and studied to estimate the conversion parameter as a function of the SFH and metallicity, i.e. A(SFH,Z)
- ☐ Median D4000n-z relations have been obtained for two mass bins, separately for SDSS, LRG and "z>0.4" sample to minimized the impact of the different selection effect in the different surveys; the Hubble parameter H(z) has been estimated for the two mass bins
- ☐ Statistical and systematic errors have been evaluated (taking into account the effect of both SFH and metallicity), and included in the total error budget
- ☐ We provided 8 new measurements of H(z) in the redshift range 0.15<z<1.1, with a precision of 5-12%, improving significantly both the error bars and the redshift coverage w.r.t. previous work
- ☐ OHD has been used to constrain the cosmological parameters, obtaining in many case for the combination of WMAP7yr+OHD+H_0 a precision competitive to WMAP7yr+BAO+SNe
- ☐ The number of relativistic species has been constrained to be compatible with 3 in a LCDM scenario, and the total mass of neutrinos <0.24 eV (68% C.L.)
- ☐ The effective potential of dark energy has been constrained from observations consistent to being flat, i.e. a cosmological constant

Thank you