Om3

A new null diagnostic of Cosmological Constant customized for BAO data

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Asia Pacific Center for Theoretical Physics

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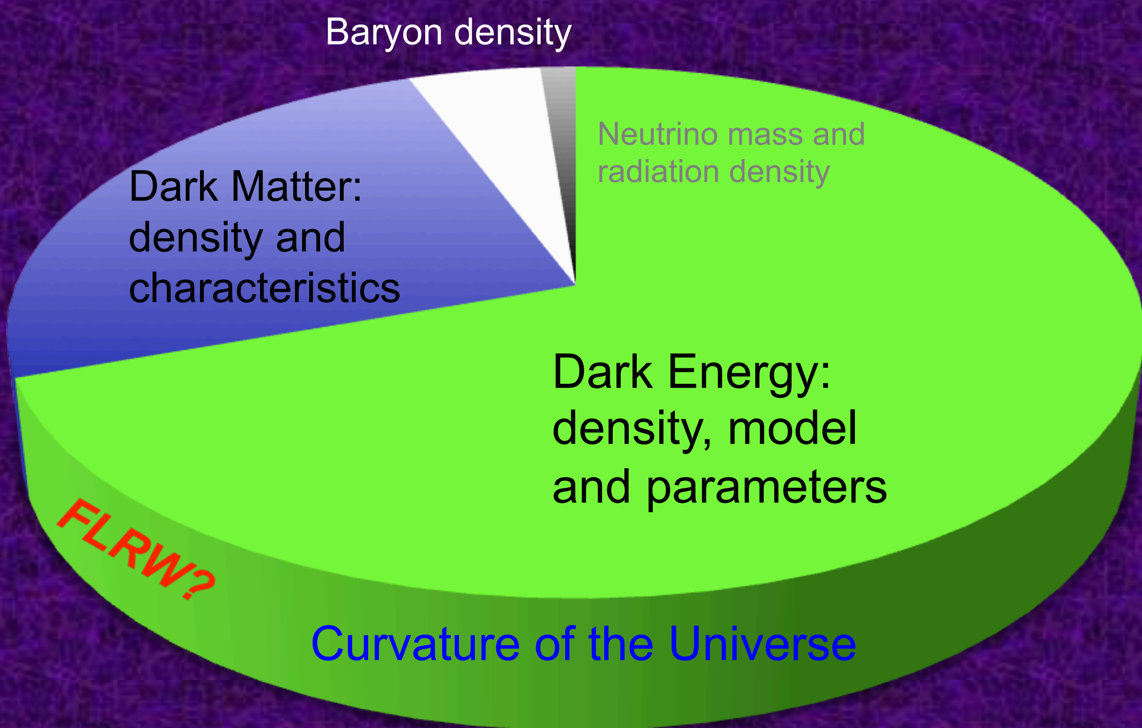
5th KIAS workshop on cosmology and structure formation

Era of Precision Cosmology

Combining theoretical works with new measurements and using statistical techniques to place sharp constraints on cosmological models and their parameters.



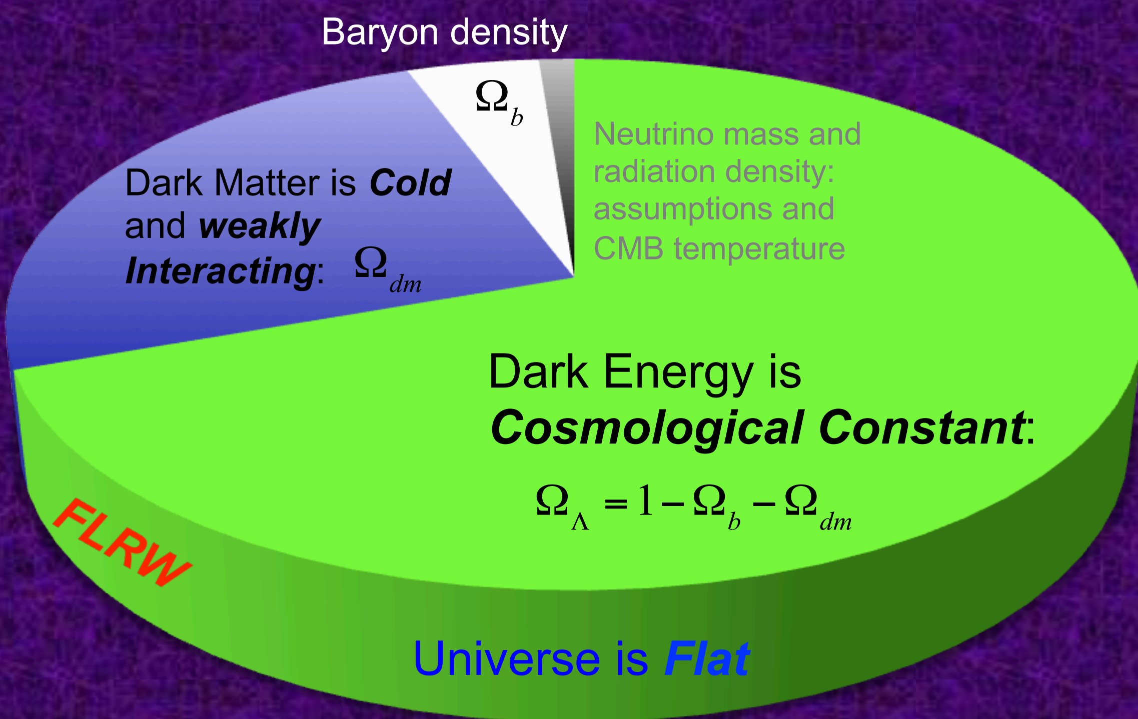
Initial Conditions:
Form of the Primordial Spectrum and Model of Inflation and its Parameters

Epoch of reionization

Hubble Parameter and the Rate of Expansion

Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological models.



Initial Conditions:
Form of the Primordial Spectrum is ***Power-law***

n_s, A_s

Epoch of reionization

τ

Hubble Parameter and the Rate of Expansion

H_0

Beyond the Standard Model of Cosmology

- The universe may be more complicated than its current standard model (Vanilla Model).
- There might be some extensions to the standard model in defining the cosmological quantities.
- Wrong assumptions on any of these cosmological quantities can affect our estimations of the other parameters.

Parameter estimation within a cosmological framework

Harisson-Zel'dovich (HZ)

WMAP Cosmological Parameters Model: lcdm+ns=1 Data: wmap	
$10^2\Omega_b h^2$	$2.405^{+0.046}_{-0.047}$
$\Delta^2_{\mathcal{R}}(k=0.002/\mathrm{Mpc})$	$(23.1 \pm 1.2) \times 10^{-10}$
h	0.778 ± 0.032
H_0	77.8 ± 3.2 km/s/Mpc
$\Omega_b h^2$	$0.02405^{+0.00046}_{-0.00047}$
Ω_Λ	0.788 ± 0.031
Ω_m	0.212 ± 0.031
$\Omega_m h^2$	$0.1271^{+0.0086}_{-0.0087}$
σ_8	$0.796^{+0.053}_{-0.054}$
A_{SZ}	$0.92^{+0.63}_{-0.61}$
t_0	13.353 ± 0.096 Gyr
τ	0.141 ± 0.029
θ_A	0.5986 ± 0.0017 °
z_r	14.6 ± 2.0

Power-Law (PL)

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h	$0.732^{+0.031}_{-0.032}$
H_0	$73.2^{+3.1}_{-3.2}$ km/s/Mpc
$\log(10^{10}A_s)$	3.156 ± 0.056
$n_s(0.002)$	0.958 ± 0.016
$\Omega_b h^2$	0.02229 ± 0.00073
$\Omega_c h^2$	$0.1054^{+0.0078}_{-0.0077}$
Ω_Λ	0.759 ± 0.034
Ω_m	0.241 ± 0.034
$\Omega_m h^2$	$0.1277^{+0.0080}_{-0.0079}$
σ_8	$0.761^{+0.049}_{-0.048}$
τ	0.089 ± 0.030
θ_A	0.5952 ± 0.0021 °
z_r	$11.0^{+2.6}_{-2.5}$

PL with Running (RN)

WMAP Cosmological Parameters Model: lcdm+run Data: wmap	
$10^2\Omega_b h^2$	2.10 ± 0.10
$\Delta^2_{\mathcal{R}}(k=0.002/\mathrm{Mpc})$	$(23.9 \pm 1.3) \times 10^{-10}$
$dn_s/d\ln k$	$-0.055^{+0.030}_{-0.031}$
h	$0.681^{+0.042}_{-0.041}$
H_0	$68.1^{+4.2}_{-4.1}$ km/s/Mpc
$n_s(0.002)$	$1.050^{+0.059}_{-0.058}$
$\Omega_b h^2$	0.0210 ± 0.0010
Ω_Λ	$0.703^{+0.056}_{-0.055}$
Ω_m	$0.297^{+0.055}_{-0.056}$
$\Omega_m h^2$	$0.1350^{+0.0099}_{-0.0097}$
σ_8	$0.771^{+0.051}_{-0.050}$
A_{SZ}	$1.06^{+0.62}_{-0.65}$
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Assumptions from the early universe

Tables from NASA - LAMBDA website

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Assumptions from the early universe

Tables from NASA - LAMBDA website

Dark Energy Reconstruction

- Any uncertainties in matter density is bound to affect the reconstructed w(z).

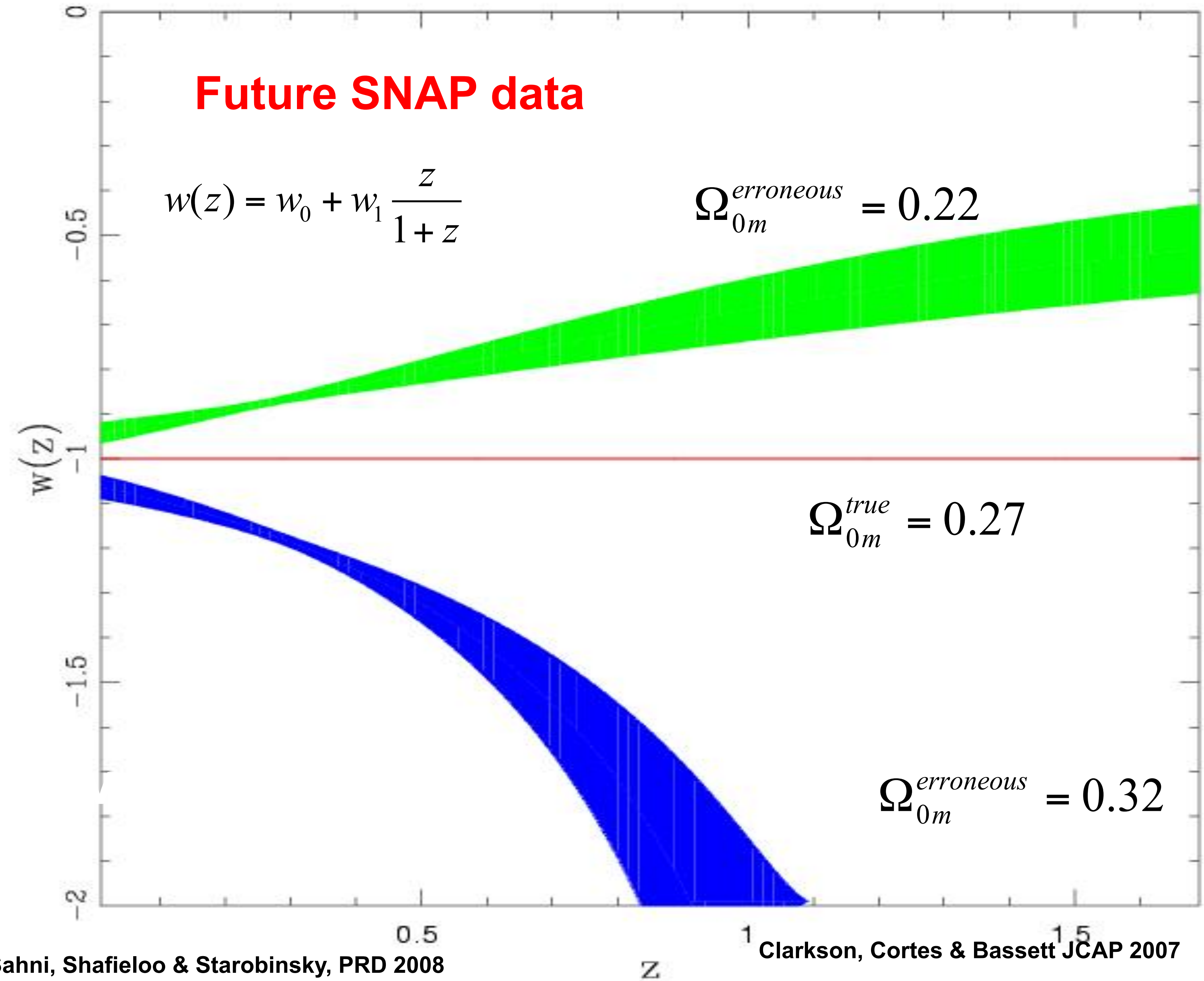
Assumptions from the early universe can affect reconstruction of the late universe.

$$H(z) = \left[\frac{d}{dz} \left(\frac{d_L(z)}{1+z} \right) \right]^{-1}$$

$$\omega_{DE} = \frac{\left(\frac{2(1+z)}{3}\frac{H'}{H}\right) - 1}{1 - \left(\frac{H_0}{H}\right)^2 \boxed{\Omega_{0M}} (1+z)^3}$$

Shafieloo et al, MNRAS 2006 ; Shafieloo MNRAS 2007

Quite tricky to work with

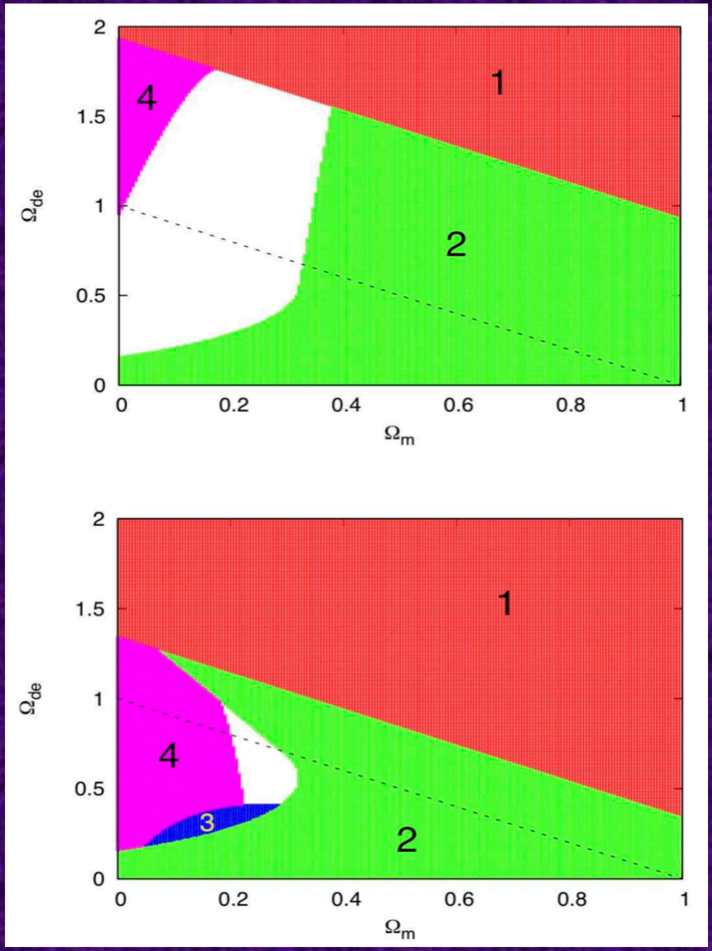


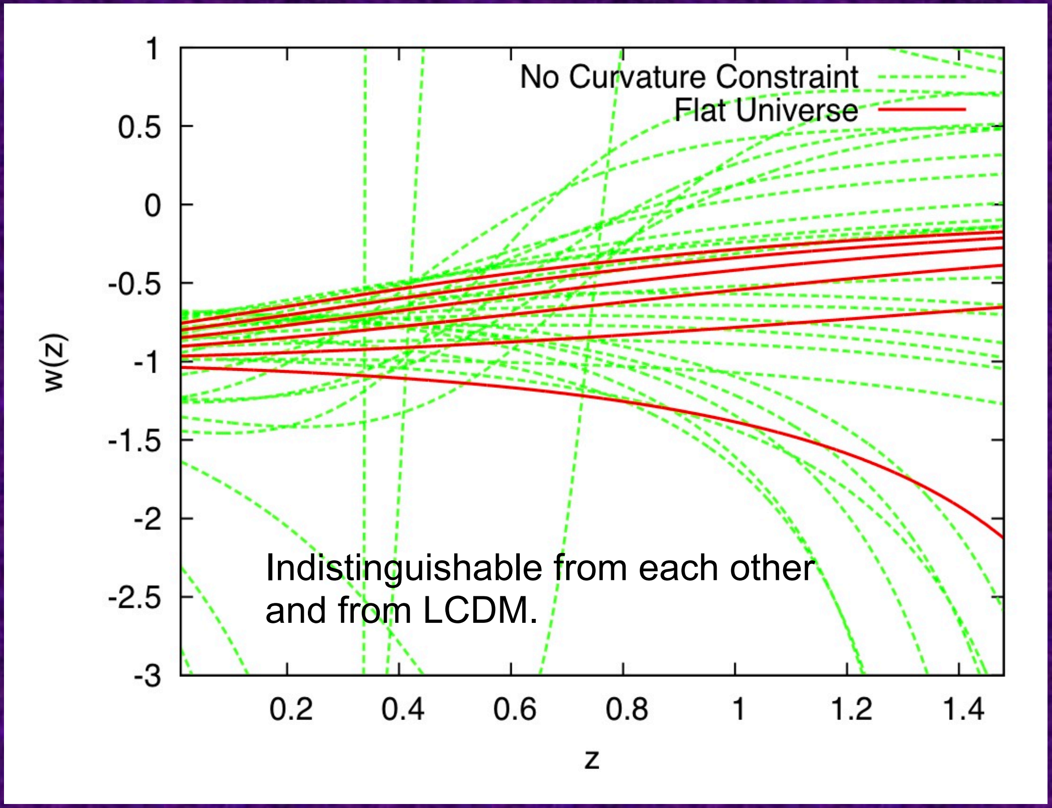
Sahni, Shafieloo & Starobinsky, PRD 2008

Clarkson, Cortes & Bassett JCAP 2007

Shafieloo & Clarkson PRD 2010

- ***Cosmographic Degeneracies*** would make it so hard to pin down the actual model of dark energy even in the near future.





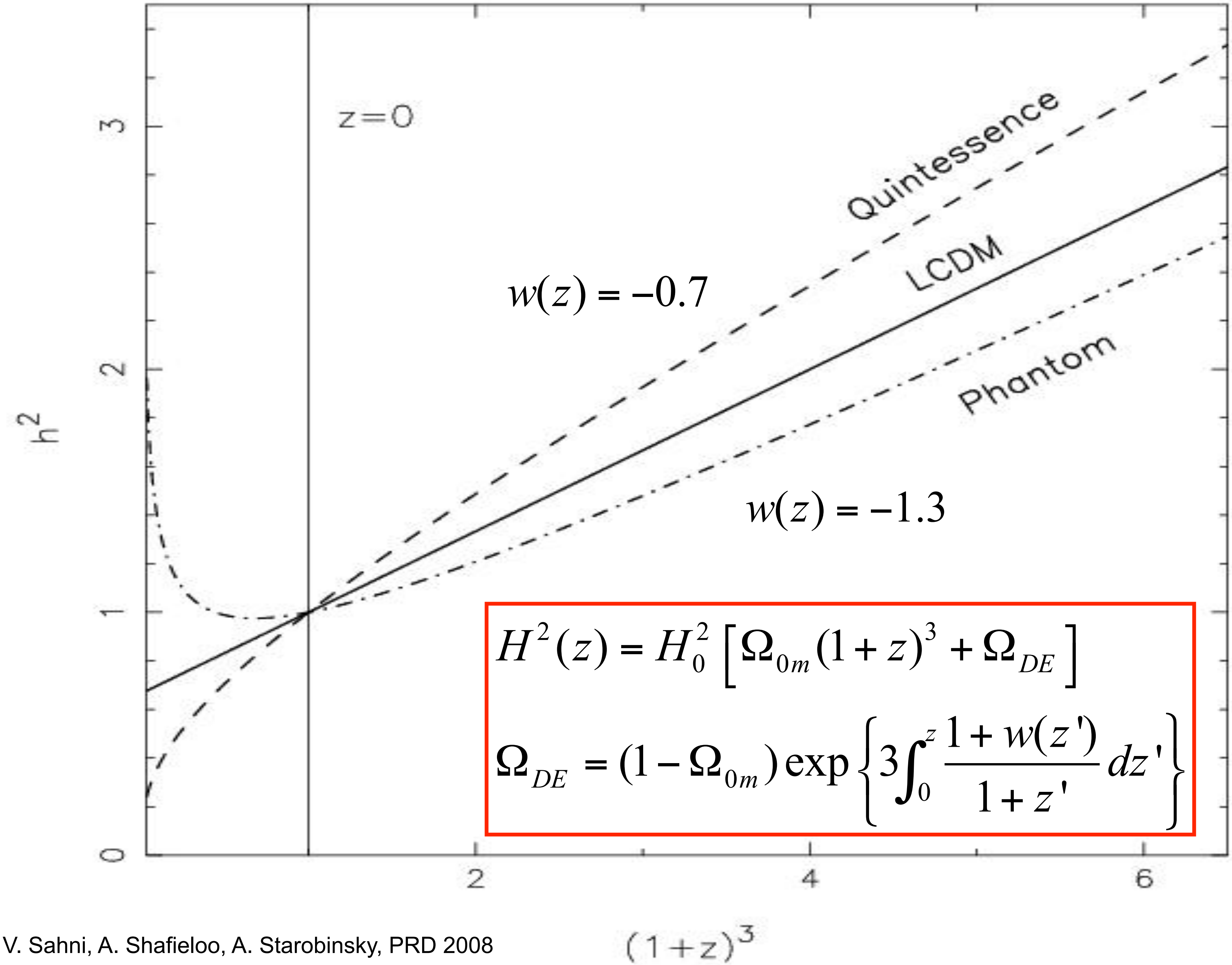
A. Shafieloo & E. Linder, PRD 2011

Changing the strategy:

- Instead of looking for w(z) and exact properties of dark energy at the current status of data, we can concentrate on a more reasonable problem:

Λ OR NOT Λ

Yes-No to a hypothesis is easier than characterizing a phenomena



$$H^2(z) = H_0^2\left[\Omega_{0m}(1+z)^3 + \Omega_{DE}\right]$$

$$\Omega_{DE} = (1-\Omega_{0m})\exp\left\{3\int_0^z \frac{1+w(z')}{1+z'}dz'\right\}$$

V. Sahni, A. Shafieloo, A. Starobinsky, PRD 2008

Om diagnostic

$$Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1}$$

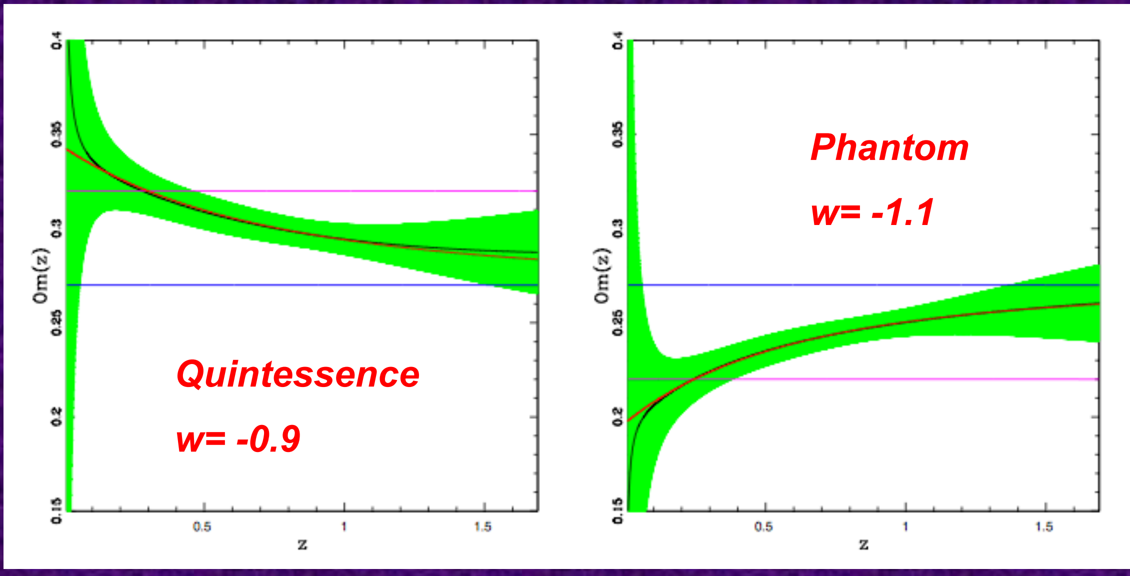
We Only Need h(z)

$$h(z) = H(z)/H_0$$

Om(z) is constant only for FLAT LCDM model

V. Sahni, A. Shafieloo, A. Starobinsky, PRD 2008

$$w = -1 \rightarrow Om(z) = \Omega_{0m}$$
$$w < -1 \rightarrow Om(z) < \Omega_{0m}$$
$$w > -1 \rightarrow Om(z) > \Omega_{om}$$



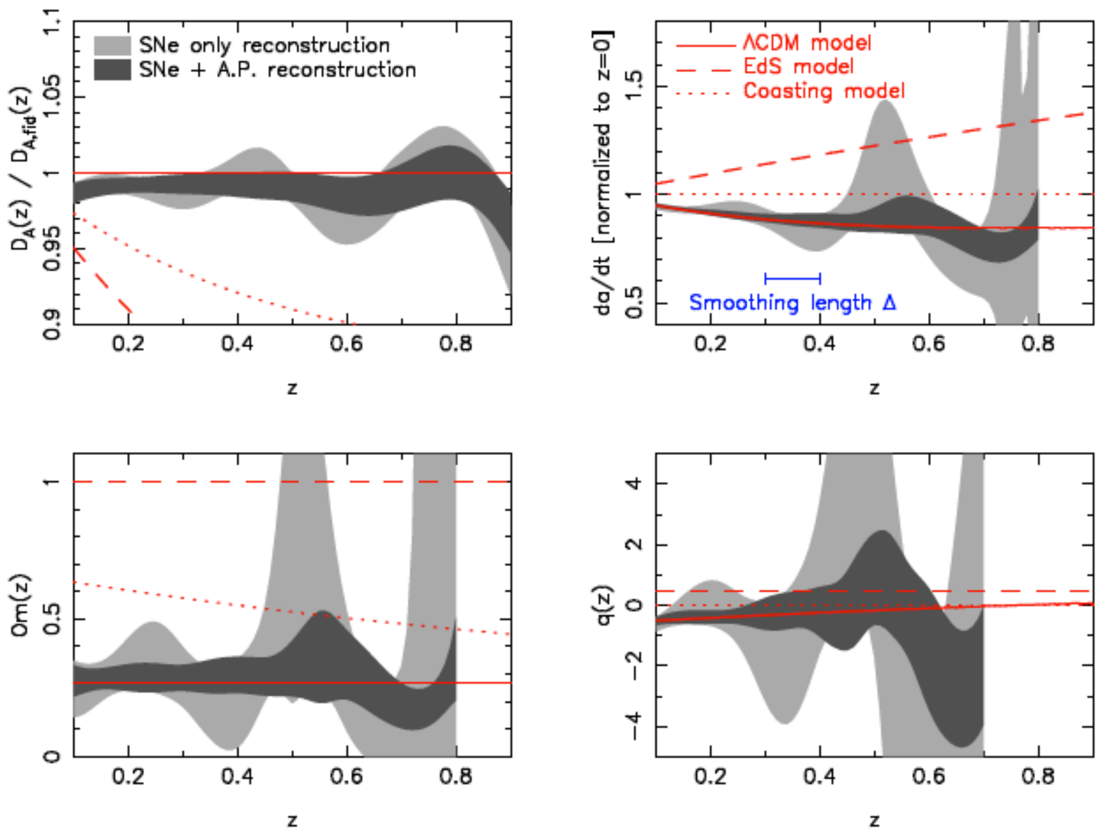


Figure 6. This Figure shows our non-parametric reconstruction of the cosmic expansion history using Alcock-Paczynski and supernovae data. The four panels of this figure display our reconstructions of the distance-redshift relation $D_A(z)$, the expansion rate $\dot{a}/H_0$, the $\mathrm{Om}(z)$ statistic and the deceleration parameter $q(z)$ using our adaptation of the iterative method of Shafieloo et al. (2006) and Shafieloo & Clarkson (2010). The distance-redshift relation in the upper left-hand panel is divided by a fiducial model for clarity, where the model corresponds to a flat ΛCDM cosmology with $\Omega_m = 0.27$. This fiducial model is shown as the solid line in all panels; Einstein de-Sitter and coasting models are also shown defined as in Figure 5. The shaded regions illustrate the 68% confidence range of the reconstructions of each quantity obtained using bootstrap resamples of the data. The dark-grey regions utilize a combination of the Alcock-Paczynski and supernovae data and the light-grey regions are based on the supernovae data alone. The redshift smoothing scale $\Delta = 0.1$ is also illustrated. The reconstructions in each case are terminated when the SNe-only results become very noisy; this maximum redshift reduces with each subsequent derivative of the distance-redshift relation [i.e. is lowest for $q(z)$].

WiggleZ collaboration

C. Blake et al, arXiv:1108.2637 (Alcock-Paczynski measurement)

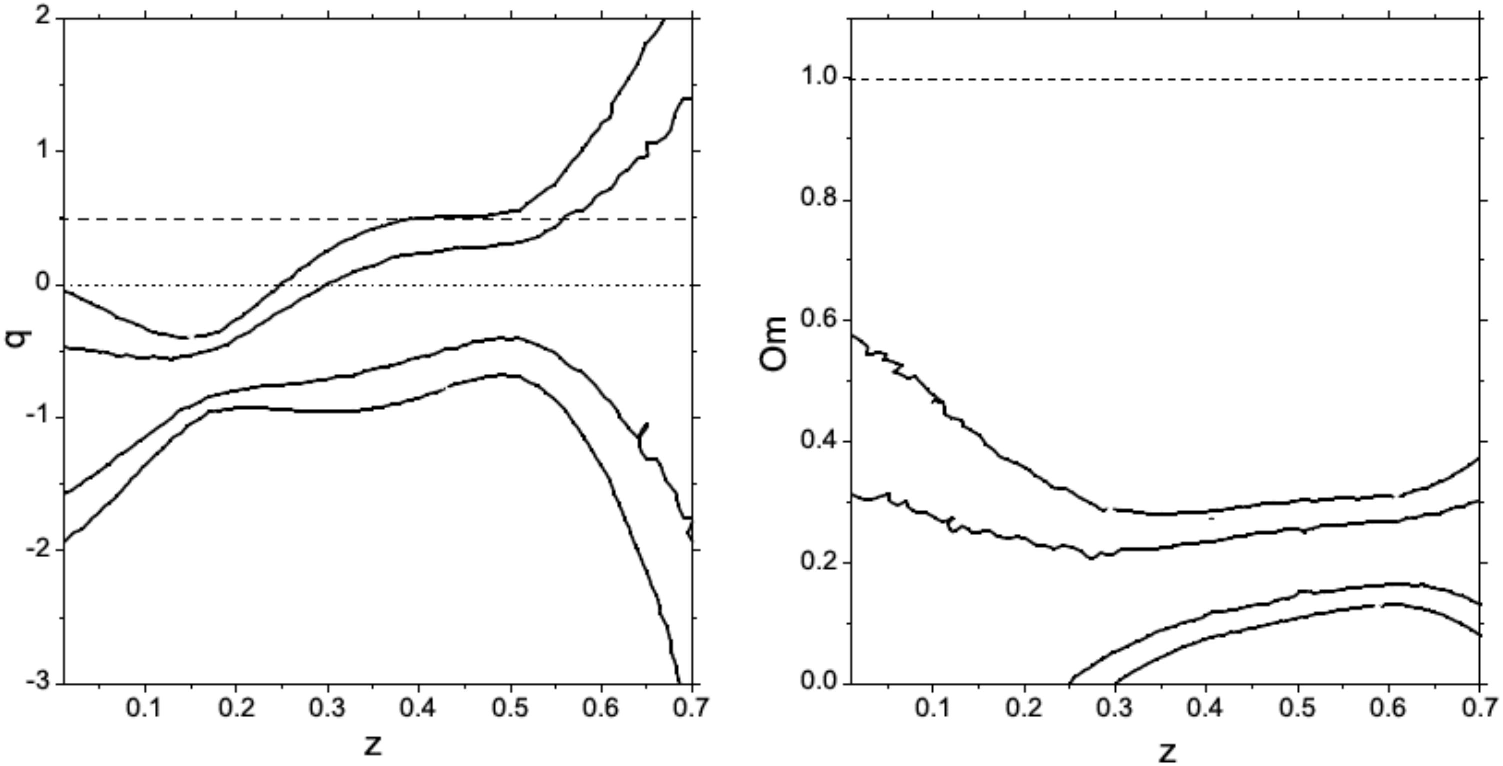


Figure 12. Confidence levels (1σ and 2σ) for the deceleration parameter as a function of redshift and Om(z) reconstructed from the compilation of geometric measurements in tables 2 and 3. H_0 is marginalised over with an HST prior. The dotted line in the left panel demarcates accelerating expansion (below the line) from decelerated expansion (above the line). The dashed line in both panels shows the expectation for an EdS model.

SDSS III / BOSS collaboration
L. Samushia et al, arXiv:1206.5309

Model Independent Reconstruction of ***h(z)***

$$H(z) = \left[\frac{d}{dz} \left(\frac{d_L(z)}{1+z} \right) \right]^{-1}$$

Smoothing SN Ia data

Gaussian Processes on SN Ia data

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

Real time cosmology, redshift drift

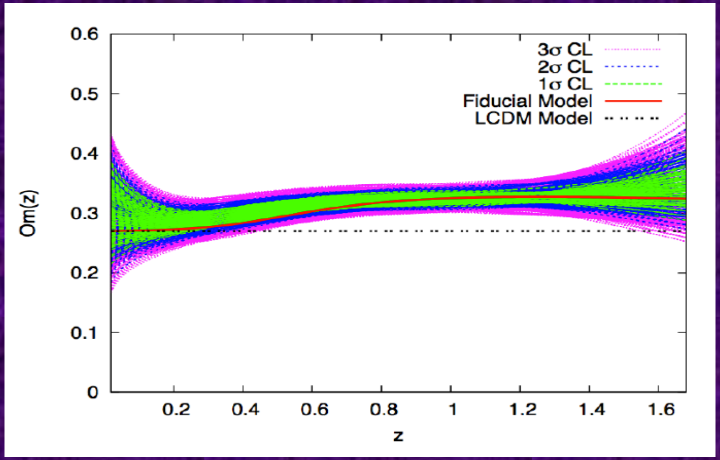
Age of passively evolving galaxies

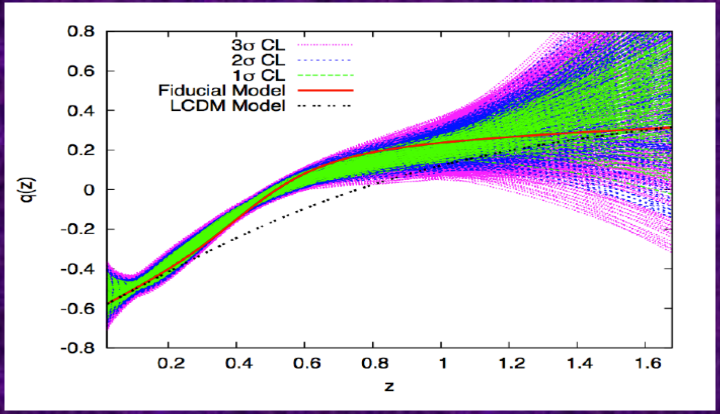
$$D_V(z)^3 = \left(\frac{c}{H_0} \right)^3 \frac{z d_L(z)^2}{(1+z)^2 h(z)}$$

Volume distance from baryon acoustic oscillation measurements

Model independent reconstruction of h(z) from SN Ia data

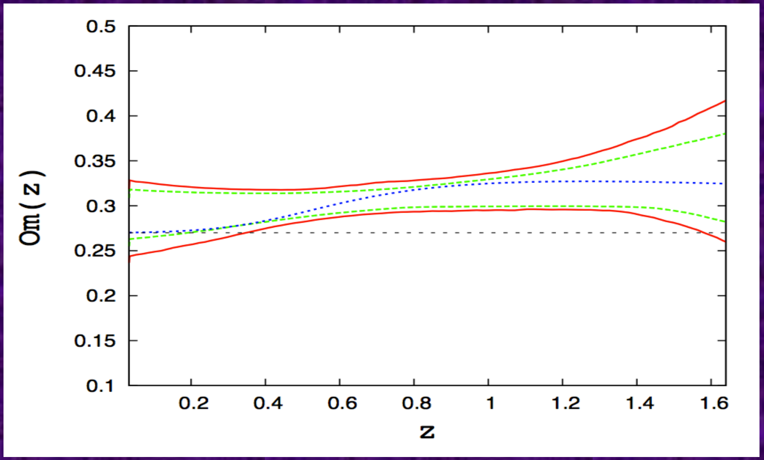
Crossing Statistic + Smoothing

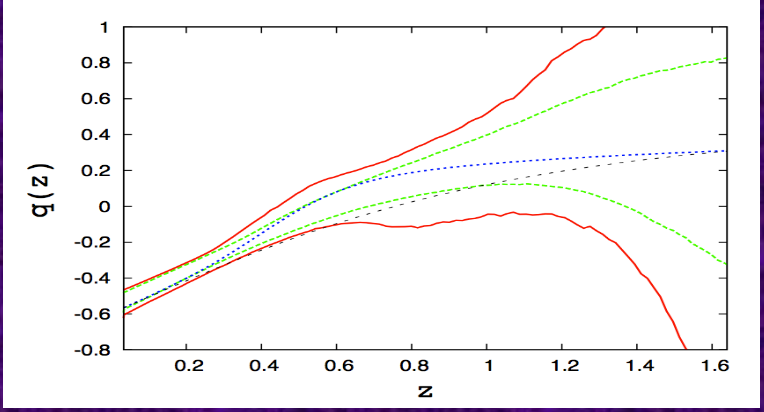




A. Shafieloo, JCAP (b) 2012

Gaussian Processes





A. Shafieloo, A. Kim & E. Linder, PRD 2012

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Volume distance from baryon acoustic oscillation measurements

Deriving h(z) from BAO

$$d(z) = \frac{r_s(z_{\rm CMB})}{D_V(z)}$$

Observable BAO

$$D_V(z)^3 = \left(\frac{c}{H_0}\right)^3 \frac{z D(z)^2}{h(z)},$$

Effective dilation distance

$$D = (1+z)d_A/(c/H_0)$$

Comoving sound horizon at baryon drag epoch

$$r_s(z_d) = \frac{c}{\sqrt{3}} \int_0^{1/(1+z_d)} \frac{da}{a^2 H(a)\sqrt{1+(3\Omega_b/4\Omega_\gamma)a}}.$$

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Deriving h(z) from BAO

$$d(z) = \frac{r_s(z_{CMB})}{D_V(z)}$$

$$\frac{r_s(z_{CMB})}{D_V(z=0.20)} = 0.1905 \pm 0.0061 \qquad \frac{r_s(z_{CMB})}{D_V(z=0.35)} = 0.1097 \pm 0.0036$$

Percival et. al. 2010

$$\sigma_{D_V(z)}{}^2 = \left[\frac{\partial D_V(z)}{\partial r_s(z_{CMB})}\right]^2 \sigma_{r_s(z_{CMB})}{}^2 + \left[\frac{\partial D_V(z)}{\partial\, d(z)}\right]^2 \sigma_{d(z)}{}^2$$

$$r_s(z_{CMB}) = 153.2 \pm 1.7$$

LAMBDA website

$$h(z) = \left(\frac{c}{H_0}\right)^3 \frac{z d_L^{\rm rec}(z)^2}{(1+z)^2 D_V(z)^3}.$$

$$H_0 = 73.8 \pm 2.4$$

Riess et. al. 2011

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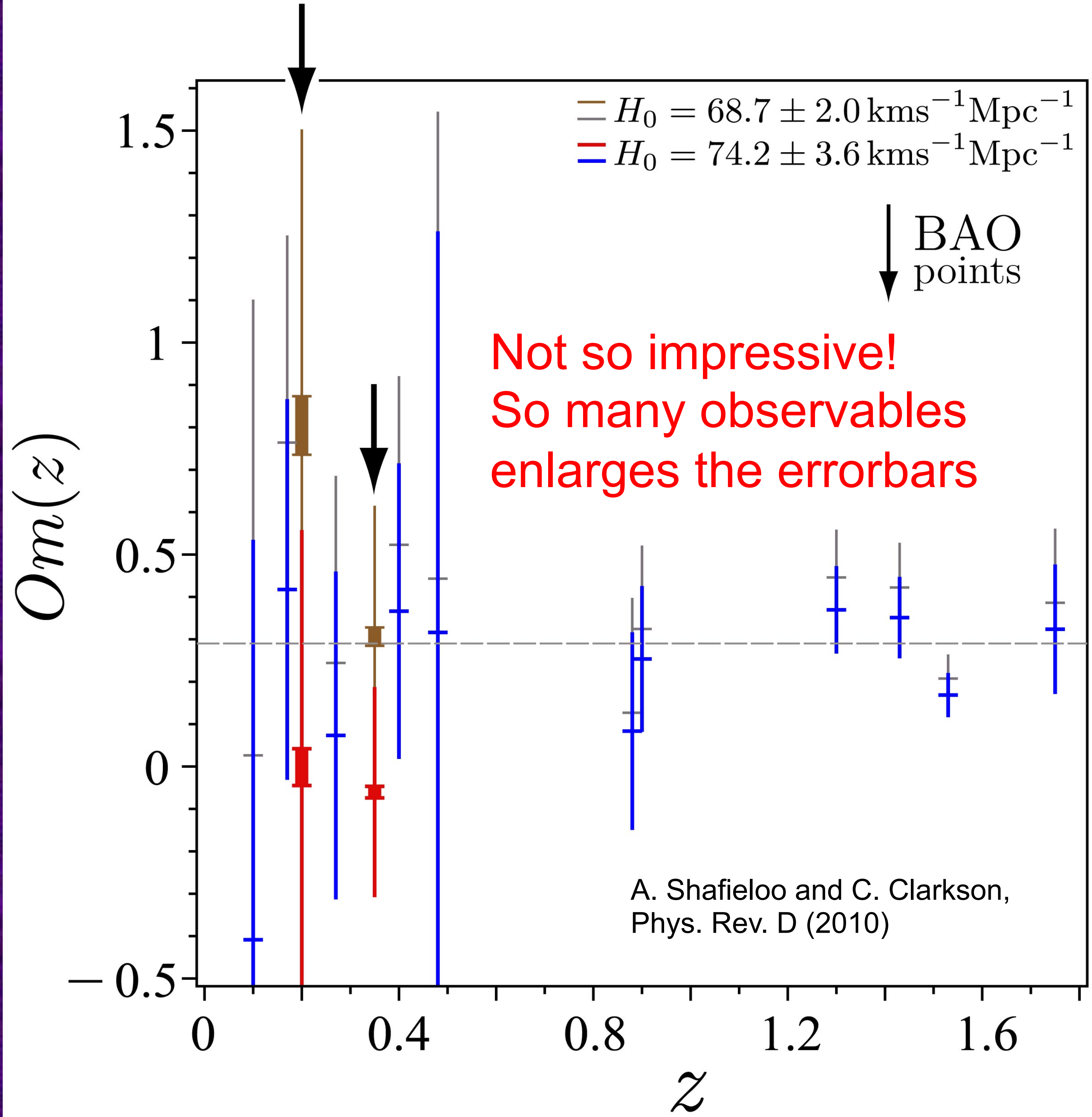
$$Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1}$$

Om diagnostic

$${\sigma_{Om(z)}}^2 = \left[\frac{2h(z)}{(1+z)^3 - 1}\right]^2 \sigma_{h(z)}^2.$$

Reconstruction of Om(z)



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Observable CMB

Characteristics of Om

Om is constant only for Flat LCDM model

$$Om(z_2; z_1) = \frac{h^2(z_2) - h^2(z_1)}{(1+z_2)^3 - (1+z_1)^3}, \quad h(z) = H(z)/H_0$$

$$Om(z; 0) \equiv Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1} \,.$$

Om diagnostic

$$Om_{\rm diff}(z_1, z_2) := Om(z_1) - Om(z_2)$$

$$Om_{\rm ratio}(z_1, z_2, z_3, z_4) := \frac{Om(z_2; z_1)}{Om(z_4; z_3)} \,,$$

$$Om_{\rm diff}(z_1, z_2) = 0, \quad Om_{\rm ratio}(z_1, z_2, z_3, z_4) = 1 \,.$$

Characteristics of Om3

Om is constant only for Flat LCDM model
Om3 is equal to one for Flat LCDM model

$$Om_{\mathrm{ratio}}(z_1, z_2, z_3, z_4) := \frac{Om(z_2; z_1)}{Om(z_4; z_3)} ,$$

Departure from 1 serves as smoking gun

$$Om_{\mathrm{ratio}}(z_1, z_2, z_1, z_3) := Om3(z_1, z_2, z_3) = \frac{Om(z_2; z_1)}{Om(z_3; z_1)}$$

Om3! Om3 has some special characteristics

Characteristics of Om3

Om is constant only for Flat LCDM model
Om3 is equal to one for Flat LCDM model

$$Om3(z_1,z_2,z_3)=\frac{Om(z_2,z_1)}{Om(z_3,z_1)}=\frac{\dfrac{h^2(z_2)-h^2(z_1)}{(1+z_2)^3-(1+z_1)^3}}{\dfrac{h^2(z_3)-h^2(z_1)}{(1+z_3)^3-(1+z_1)^3}}=\frac{\dfrac{\frac{h^2(z_2)}{h^2(z_1)}-1}{(1+z_2)^3-(1+z_1)^3}}{\dfrac{\frac{h^2(z_3)}{h^2(z_1)}-1}{(1+z_3)^3-(1+z_1)^3}}=\frac{\dfrac{\frac{H^2(z_2)/H_0^2}{H^2(z_2)/H_0^2}-1}{(1+z_2)^3-(1+z_1)^3}}{\dfrac{\frac{H^2(z_2)/H_0^2}{H^2(z_2)/H_0^2}-1}{(1+z_3)^3-(1+z_1)^3}}=\frac{\dfrac{\frac{H^2(z_2)}{H^2(z_1)}-1}{(1+z_2)^3-(1+z_1)^3}}{\dfrac{\frac{H^2(z_3)}{H^2(z_1)}-1}{(1+z_3)^3-(1+z_1)^3}}$$

$$d(z)=\frac{r_s(z_{\rm CMB})}{D_V(z)}$$

Observables

$$H(z_i;z_j):=\frac{H(z_i)}{H(z_j)}=\frac{z_i}{z_j}\left[\frac{D(z_i)}{D(z_j)}\right]^2\left[\frac{D_V(z_j)}{D_V(z_i)}\right]^3=\frac{z_i}{z_j}\left[\frac{D(z_i)}{D(z_j)}\right]^2\left[\frac{d(z_i)}{d(z_j)}\right]^3,$$

Characteristics of Om3

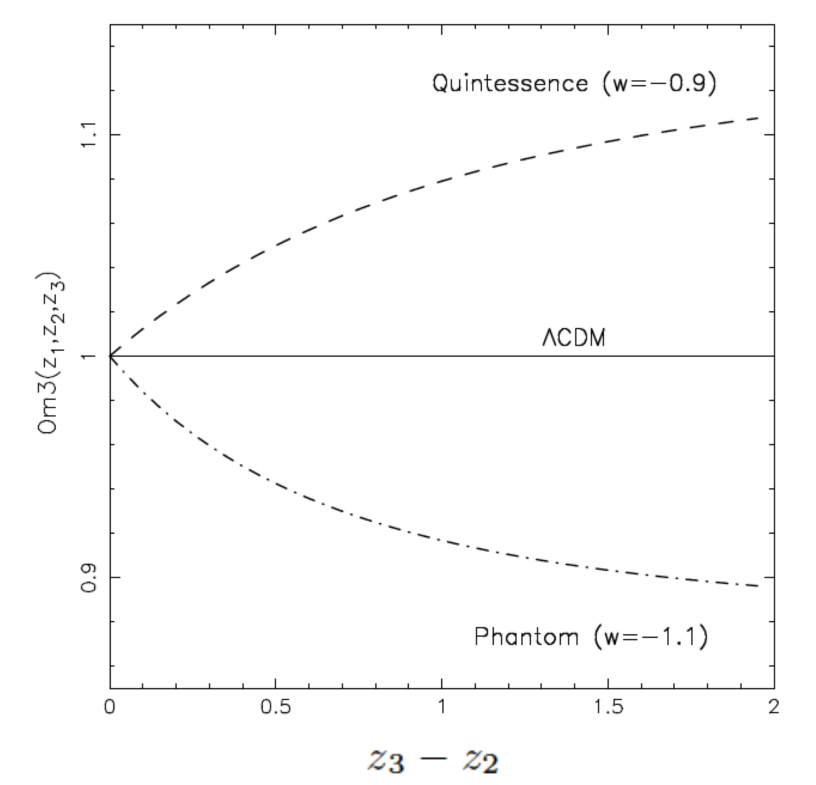
Om is constant only for Flat LCDM model
Om3 is equal to one for Flat LCDM model

$$Om3(z_1;z_2;z_3) = \frac{H(z_2;z_1)^2 - 1}{x_2^3 - x_1^3} \bigg/ \frac{H(z_3;z_1)^2 - 1}{x_3^3 - x_1^3}, \quad \text{where} \quad x = 1 + z,$$

$$H(z_i;z_j) = \left(\frac{z_j}{z_i}\right)^2 \left[\frac{D(z_i)}{D(z_j)}\right]^2 \left[\frac{A(z_j)}{A(z_i)}\right]^3 = \frac{z_i}{z_j} \left[\frac{D(z_i)}{D(z_j)}\right]^2 \left[\frac{d(z_i)}{d(z_j)}\right]^3 ,$$

Om3 is independent of H0 and the distance to the last scattering surface and can be derived directly using BAO observables.

Characteristics of Om3



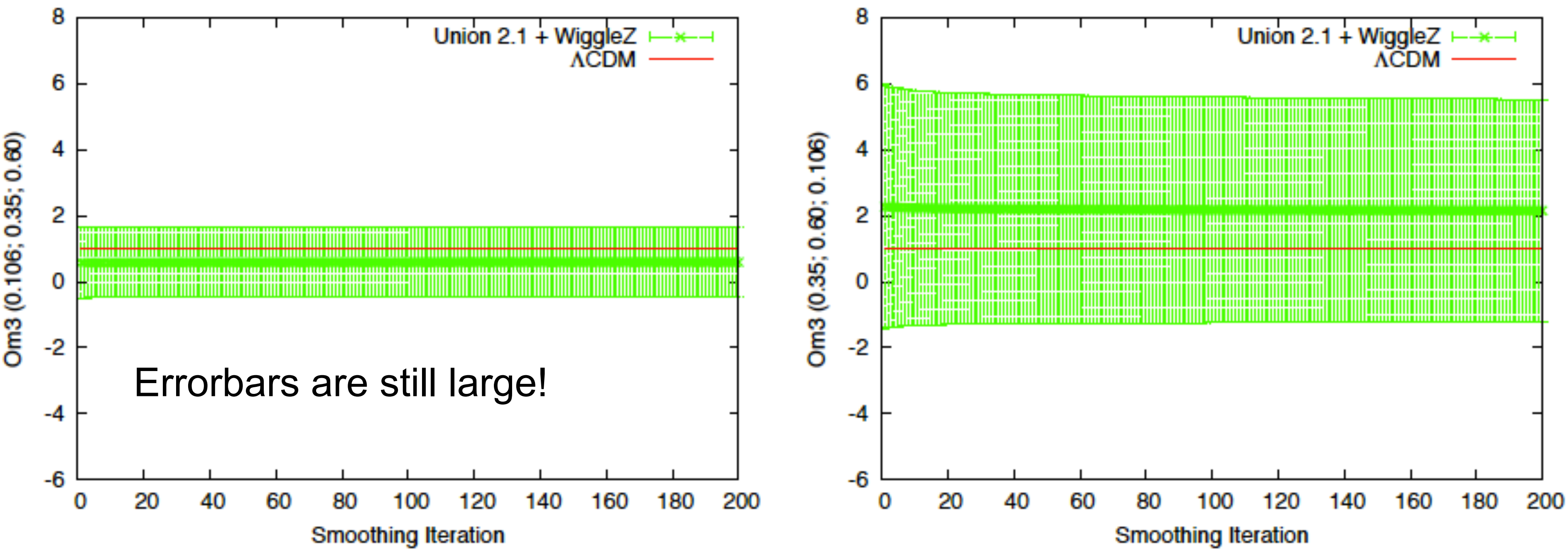
$$z_1 = 0.2, z_2 = 0.35$$

Om3 = 1 only for Flat LCDM model

$$Om3(z_1; z_2; z_3) = \frac{H(z_2; z_1)^2 - 1}{x_2^3 - x_1^3} \Big/ \frac{H(z_3; z_1)^2 - 1}{x_3^3 - x_1^3}, \quad \text{where} \quad x = 1 + z,$$

Characteristics of Om3

Om is constant only for Flat LCDM model
Om3 is equal to one for Flat LCDM model

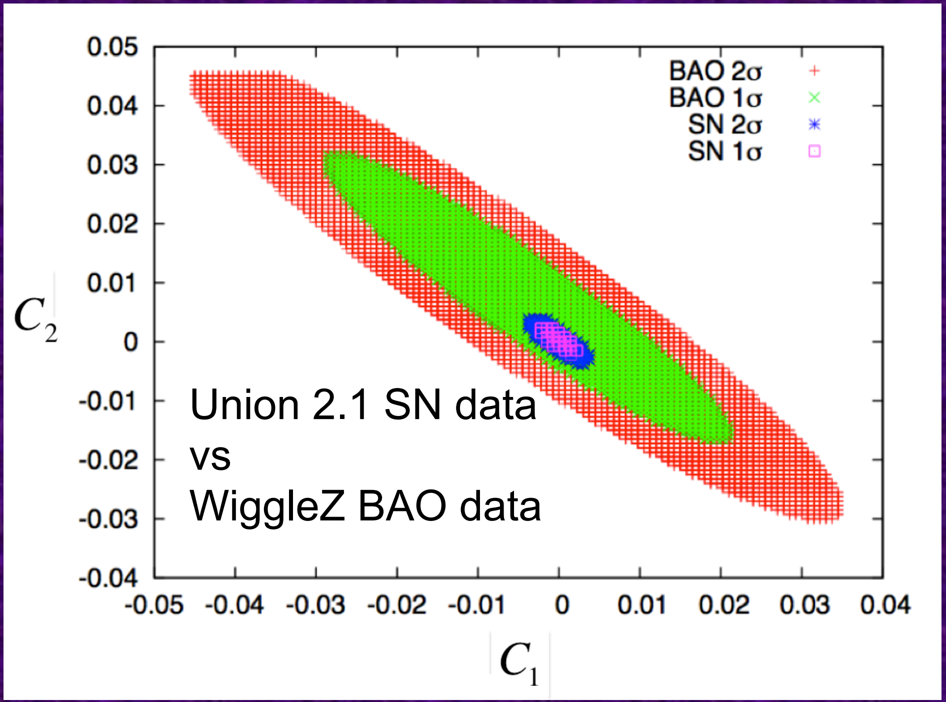


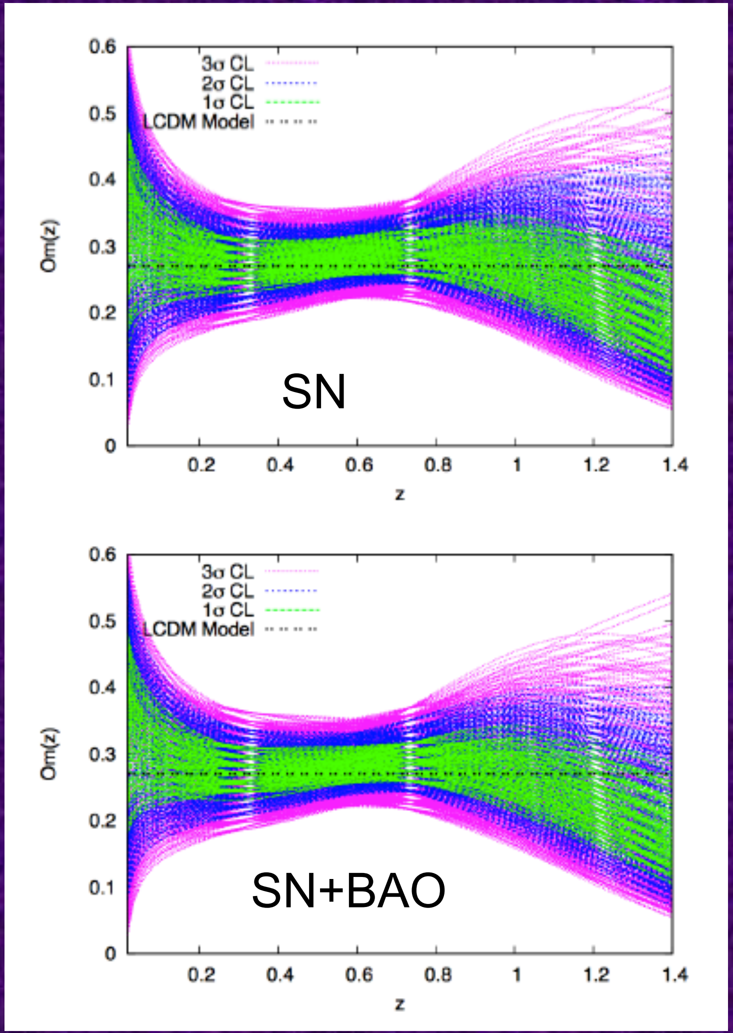
$$Om3(z_1;z_2;z_3) = \frac{H(z_2;z_1)^2 - 1}{x_2^3 - x_1^3} \Big/ \frac{H(z_3;z_1)^2 - 1}{x_3^3 - x_1^3}, \quad \text{where} \quad x = 1 + z,$$

A. Shafieloo, V. Sahni & A. A. Starobinsky, PRD 2012

BAO data still has low quality

Using BAO distance ratios



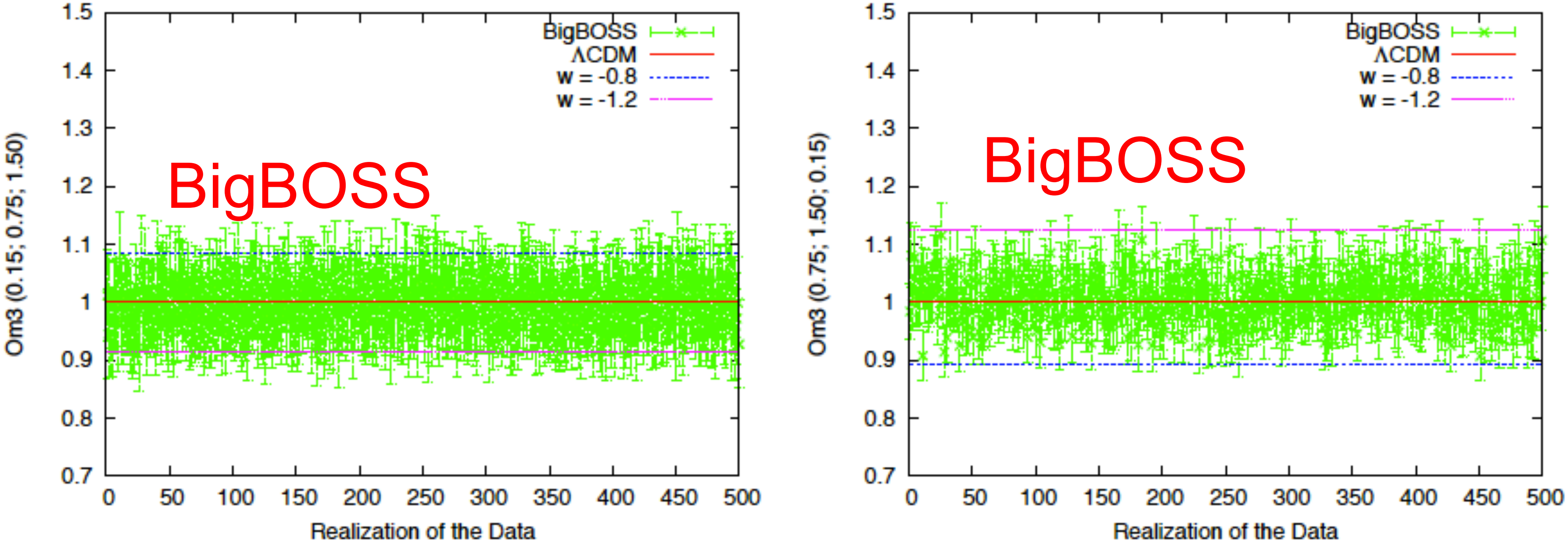


Constraining the expansion history of the universe using Crossing Statistic

A. Shafieloo, JCAP (a) 2012
A. Shafieloo, JCAP (b) 2012

Characteristics of Om3

Om is constant only for Flat LCDM model
Om3 is equal to one for Flat LCDM model

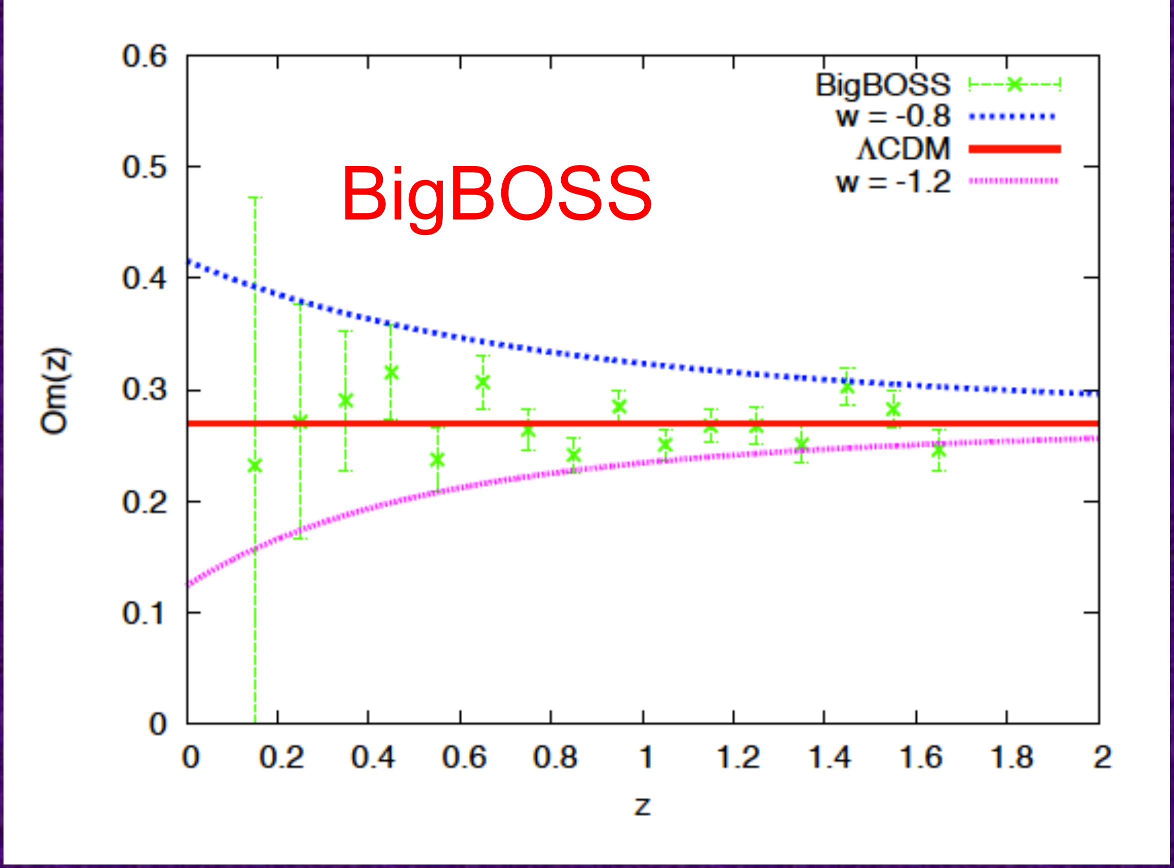


$$Om3(z_1; z_2; z_3) = \frac{H(z_2; z_1)^2 - 1}{x_2^3 - x_1^3} \Big/ \frac{H(z_3; z_1)^2 - 1}{x_3^3 - x_1^3}, \quad \text{where} \quad x = 1 + z,$$

A. Shafieloo, V. Sahni & A. A. Starobinsky, PRD 2012

Characteristics of Om3

Om is constant only for Flat LCDM model
Om3 is equal to one for Flat LCDM model



Assuming perfect estimation of the distance to the last scattering surface and 2% uncertainty for H0

$$Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1}$$

A. Shafieloo, V. Sahni & A. A. Starobinsky, PRD 2012

Summary

- Om3 is introduced as a null test of LCDM. Om3 is independent of H0 and distance to the last scattering surface hence independent of the biases from the early universe and measurements of H0.

- Om3 can be derived directly using BAO observables.

- BAO links the early and late universe. It is currently providing us with more and more valuable information about the universe but its still poor.

- *Challenging the standard model is more affordable and realistic than trying to reconstruct the underlying model of the universe.*

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cosmopd2012@apctp.org (deadline 31st December 2012)

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The position is initially for two years, with the possibility of a third year depending on the research performance, mutual agreement or funding situation. The starting date of the appointment is negotiable, but no later than the end of 2013.

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