Testing the Standard Model of Cosmology Using BAO data

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Future of Large Scale Structure Formation

(Present)t

Standard Model of Cosmology

Universe is Flat

Universe is Isotropic

Universe is Homogeneous (large scales)

Dark Energy is Lambda (w=-1)

Power-Law primordial spectrum (n_s=const)

Dark Matter is cold

All within framework of FLRW

Standard Model of Cosmology
Vanilla Model

- Homogeneous and Isotropic FLRW Flat Lambda Cold Dark Matter Universe (LCDM) with power–law form of the primordial spectrum
- It has 6 main parameters:

$$\Omega_b$$

$$\Omega_m$$

$$H_0$$

$$\tau$$

$$A_s$$

$$n_s$$

Era of Precision Cosmology ?

Cosmological Parameters from WMAP

WMAP Cosmological Parameters
Model: lcdm+sz+lens
Data: wmap5

$10^2\Omega_b h^2$	2.273 ± 0.062	$1 - n_s$	$0.037^{+0.015}_{-0.014}$
$1 - n_s$	$0.0081 < 1 - n_s < 0.0647$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	0.457 ± 0.022
C_{220}	5756 ± 42	$d_A(z_{\rm eq})$	14279^{+186}_{-189} Mpc
$d_A(z_*)$	14115^{+188}_{-191} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.41 \pm 0.11) \times 10^{-9}$
h	$0.719^{+0.026}_{-0.027}$	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
$k_{\rm eq}$	0.00968 ± 0.00046	$\ell_{\rm eq}$	136.6 ± 4.8
ℓ_*	$302.08^{+0.83}_{-0.84}$	n_s	$0.963^{+0.014}_{-0.015}$
Ω_b	0.0441 ± 0.0030	$\Omega_b h^2$	0.02273 ± 0.00062
Ω_c	0.214 ± 0.027	$\Omega_c h^2$	0.1099 ± 0.0062
Ω_Λ	0.742 ± 0.030	Ω_m	0.258 ± 0.030
$\Omega_m h^2$	0.1326 ± 0.0063	$r_{\rm hor}(z_{\rm dec})$	286.0 ± 3.4 Mpc
$r_s(z_d)$	153.3 ± 2.0 Mpc	$r_s(z_d)/D_v(z = 0.2)$	0.1946 ± 0.0079
$r_s(z_d)/D_v(z = 0.35)$	0.1165 ± 0.0042	$r_s(z_*)$	146.8 ± 1.8 Mpc
R	1.713 ± 0.020	σ_8	0.796 ± 0.036
A_{SZ}	$1.04^{+0.96}_{-0.69}$	t_0	13.69 ± 0.13 Gyr
τ	0.087 ± 0.017	θ_*	0.010400 ± 0.000029
θ_*	0.5959 ± 0.0017 °	t_*	380081^{+5843}_{-5841} yr
$z_{\rm dec}$	1087.9 ± 1.2	z_d	1020.5 ± 1.6
$z_{\rm eq}$	3176^{+151}_{-150}	$z_{\rm reion}$	11.0 ± 1.4
z_*	1090.51 ± 0.95		

Table from LAMBDA website

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.
- This needs proper investigation, using advanced statistical methods, high performance computational facilities and high quality observational data.

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All within framework of FLRW

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	$0.5986 \pm 0.0017\ ^\circ$
z_r	14.6 ± 2.0

Power-Law (PL)

WMAP Cosmological Parameters
Model: lcdm
Data: wmap

$10^2\Omega_b h^2$	2.229 ± 0.073
$\Delta^2_{\mathcal{R}}(k=0.002/\mathrm{Mpc})$	$(23.5 \pm 1.3) \times 10^{-10}$
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	$0.5952 \pm 0.0021\ ^\circ$
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}	$1.06^{+0.62}_{-0.65}$
t_0	13.97 ± 0.20 Gyr
τ	0.101 ± 0.031
θ_A	$0.5940 \pm 0.0021\ ^\circ$
z_r	12.8 ± 2.8

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).

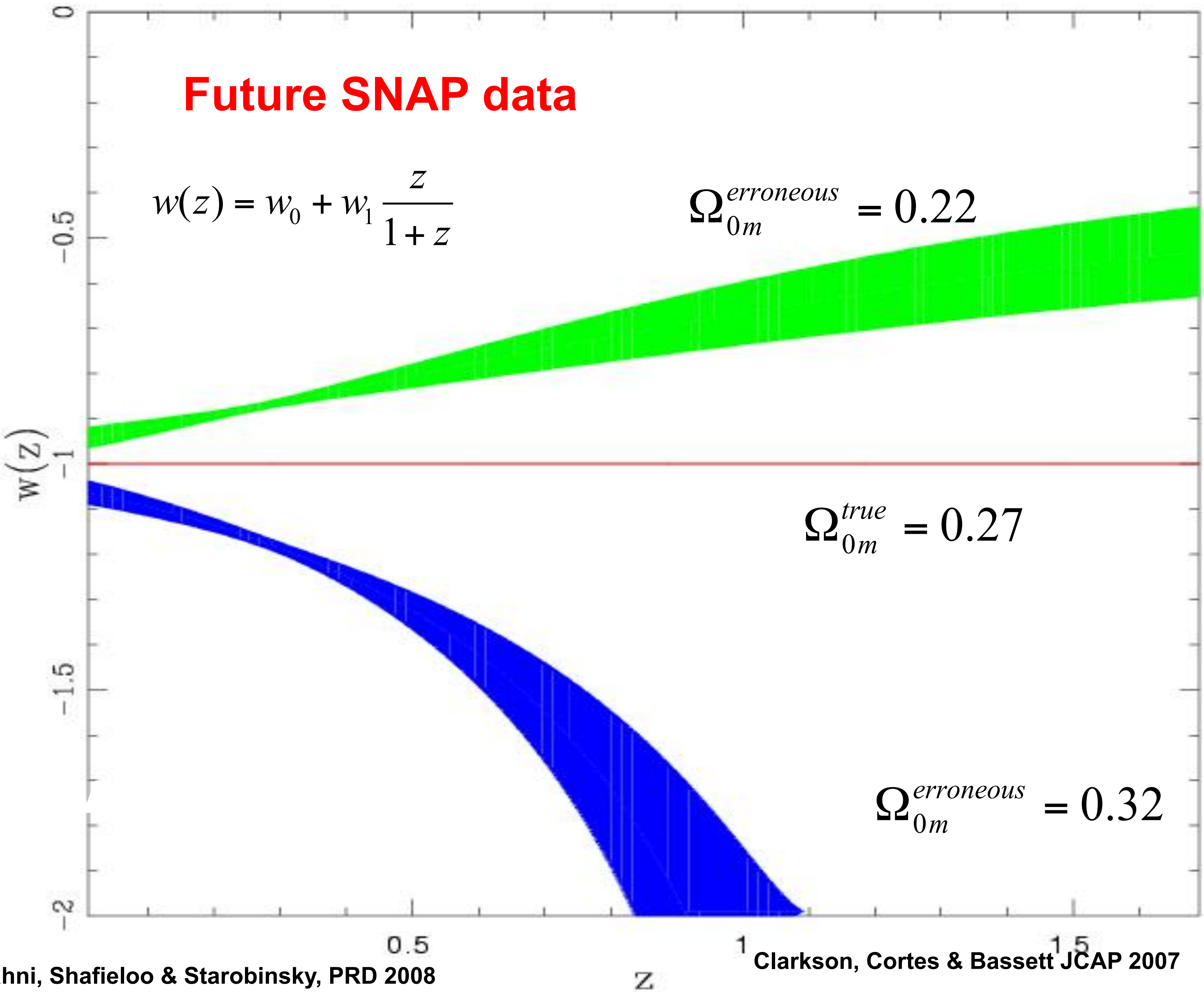
Assumptions from the early universe can affect reconstruction of the late universe.

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

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

Quite tricky to work with

Shafieloo et al, MNRAS 2006 ; Shafieloo MNRAS 2007



Sahni, Shafieloo & Starobinsky, PRD 2008

Clarkson, Cortes & Bassett JCAP 2007

Shafieloo & Clarkson PRD 2010

Late Universe and Dark Energy Models

- Lambda-CDM: The most favorite model
- Brane Models
- Quintessence and Quiessence Models
- Phantoms, Ghosts, demons
- Modified Gravity
- etc...

$$\frac{H^2(z)}{H_0^2} = \left[\Omega_{0M}(1+z)^3 + \Omega_{DE}\exp[\int 3\left(1+w(z)\right)\frac{dz}{1+z}]\right]$$

Dark Energy Parameterizations

$$F = \frac{L}{4\pi d_L^2}$$

Supernovae Ia as Standardized Candles

$$\Delta\theta = \frac{\Delta\chi}{d_A(z)}$$

BAO as standard ruler

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

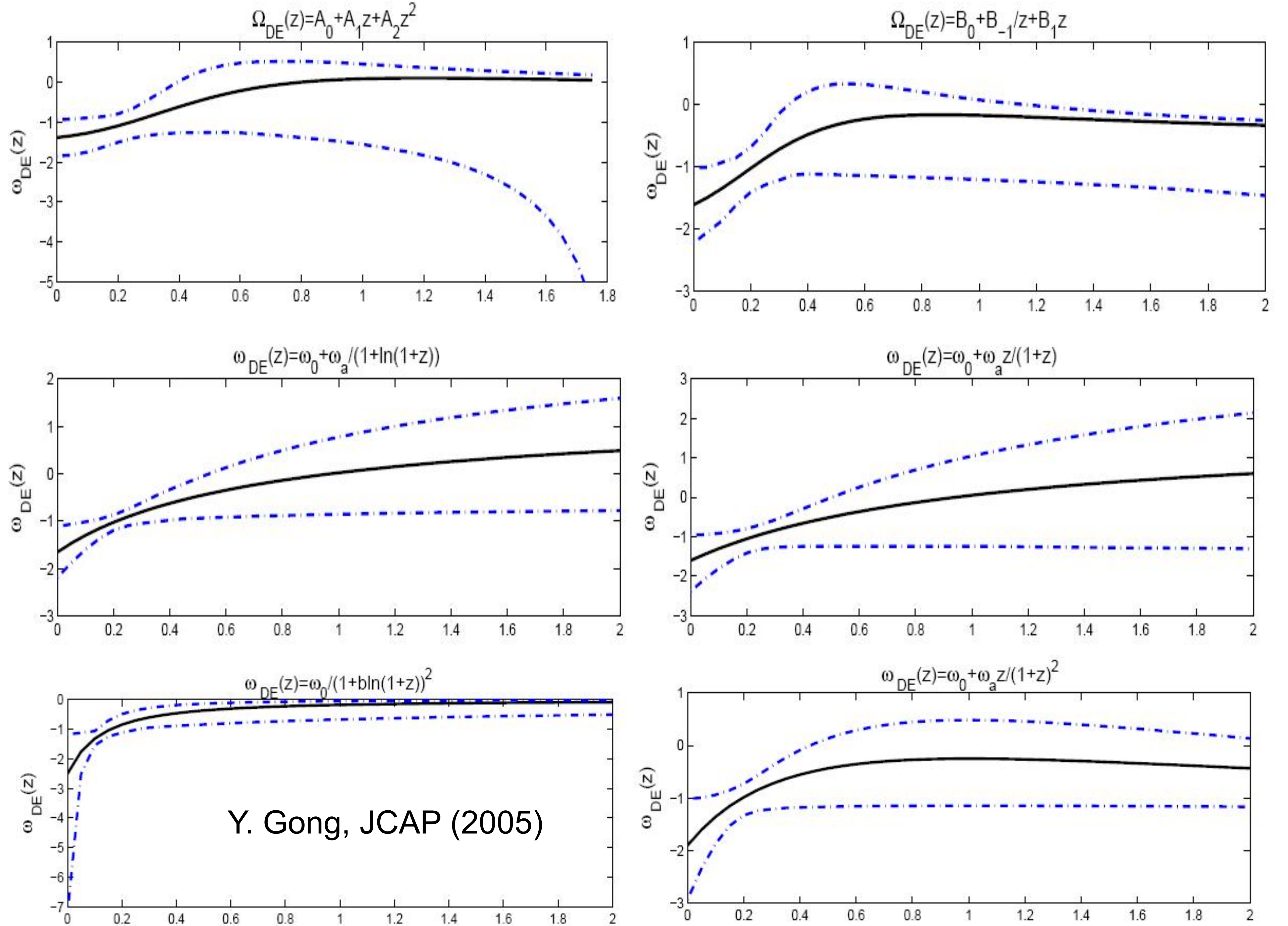
$$d_A(z) = (1+z)^{-1}\int_0^z \frac{dz'}{H(z')}$$

$$\frac{H^2(z)}{H^2{}_0} = \left[\Omega_{0M}(1+z)^3 + (1-\Omega_{0M})X(z)\right]$$

1. Fitting functions for d_l(z)
2. Fitting functions for DE density
3. Fitting functions for EOS

Most general form

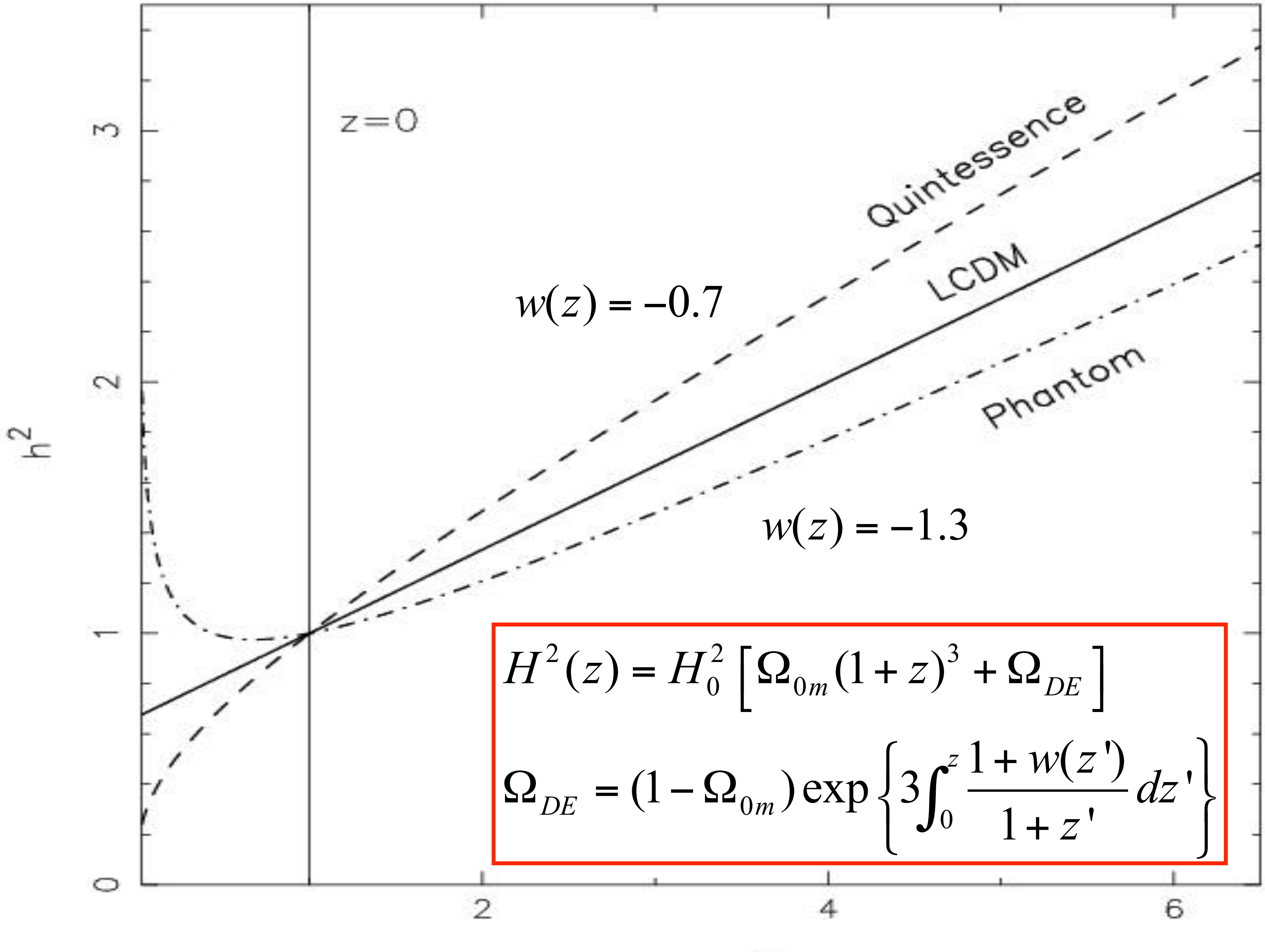
$$\frac{H^2(z)}{H^2{}_0} = \left[\Omega_{0M}(1+z)^3 + (1-\Omega_{0M})\exp[\int 3\left(1+w(z)\right)\frac{dz}{1+z}]\right]$$


$\Omega_{DE}(z)=A_0+A_1z+A_2z^2$
$\Omega_{DE}(z)=B_0+B_{-1}/z+B_1z$
$\omega_{DE}(z)=\omega_0+\omega_a/(1+\ln(1+z))$
$\omega_{DE}(z)=\omega_0+\omega_a z/(1+z)$
$\omega_{DE}(z)=\omega_0/(1+b\ln(1+z))^2$
$\omega_{DE}(z)=\omega_0+\omega_a z/(1+z)^2$
$\omega_{DE}(z)$
Y. Gong, JCAP (2005)

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



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

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

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

Om diagnostic

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

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

arXive:0807.3548

Also look at:

C. Zunckel & C. Clarkson, PRL 2008

arXive:0807.4304

Om(z) is constant only for FLAT LCDM model

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

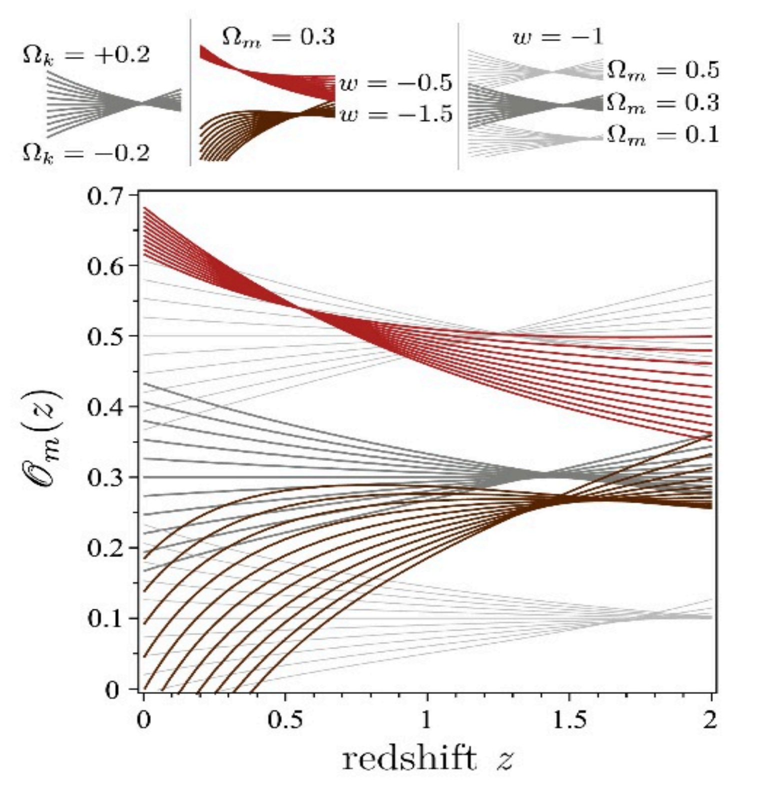
$$w<-1 \rightarrow Om(z)<\Omega_{0m}$$

$$w>-1 \rightarrow Om(z)>\Omega_{om}$$

LCDM

Phantom

Quintessence



We Only Need h(z)

To find cosmological quantities and parameters there are two general approaches:

1. Parametric methods

Easy to confront with cosmological observations to put constrains on the parameters, but the results are highly biased by the assumed models and parametric forms.

2. Non Parametric methods

Difficult to apply on the raw data, but the results will less biased and more reliable and independent of theoretical models or parametric forms.

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Non Parametric methods of Reconstruction

Usually involves binning and smoothing

$$\boxed{F = \frac{L}{4\pi d_L^2}}$$

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

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

$$\frac{H^2(z)}{H^2_0} = \left[\Omega_{0M}(1+z)^3 + (1-\Omega_{0M})\exp[\int 3\left(1+w(z)\right)\frac{dz}{1+z}]\right]$$

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

Method of Smoothing

A. Shafieloo, U. Alam, V. Sahni, A. Starobinsky, MNRAS (2006)
A. Shafieloo, MNRAS (2007)
A. Shafieloo & C. Clarkson PRD (2010)

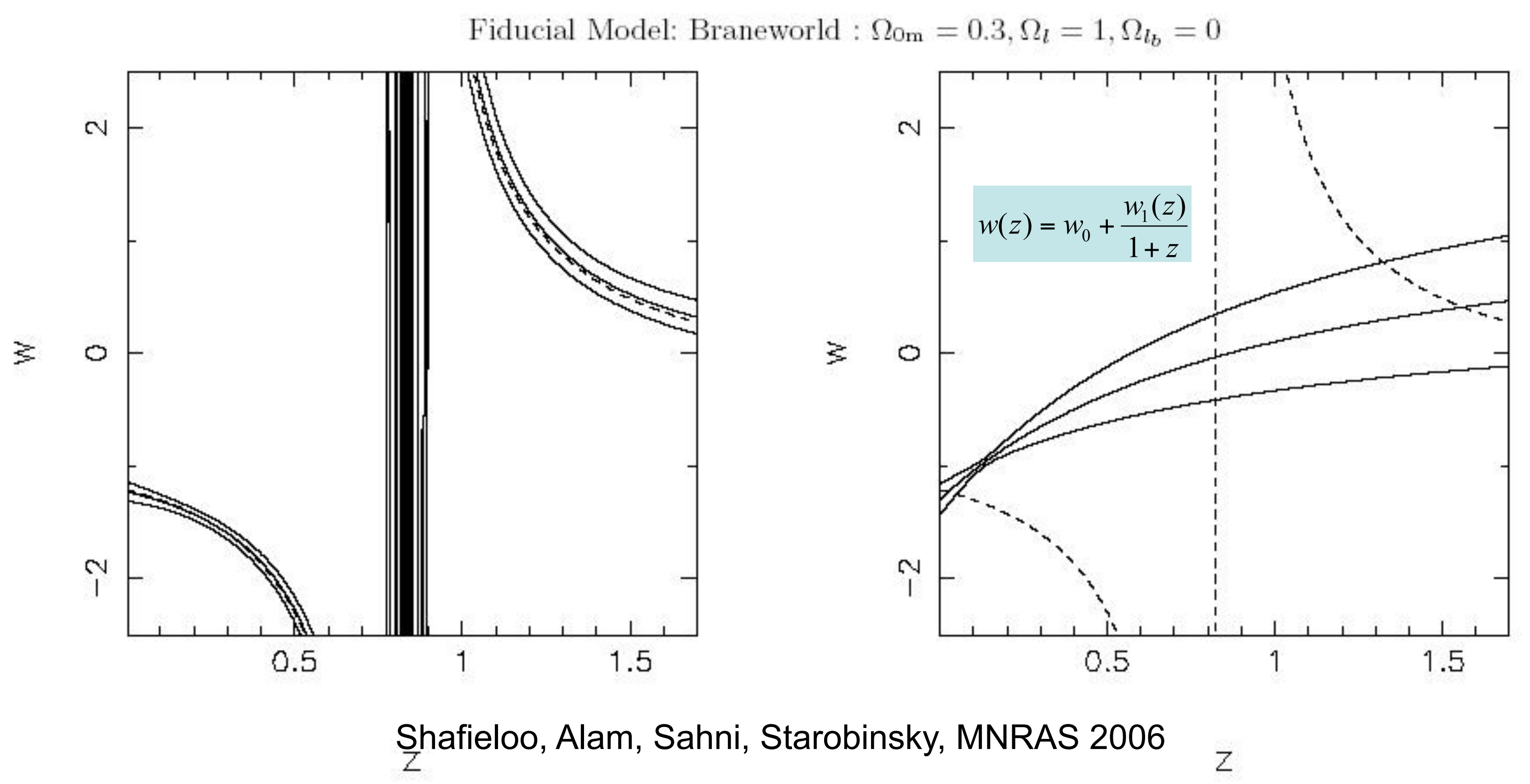
$$\ln d_L(z,\Delta) = \ln d_L(z)^g + N(z)\sum_i [\ln d_L(z_i) - \ln d_L(z_i)^g]\exp\left[-\frac{\ln^2(\frac{1+z_i}{1+z})}{2\Delta^2}\right](\frac{1}{\sigma_{\ln d_L(z_i)}})^2$$

$$N(z)^{-1} = \sum_i \exp\left[-\frac{\ln^2(\frac{1+z_i}{1+z})}{2\Delta^2}\right](\frac{1}{\sigma_{\ln d_L(z_i)}})^2$$

Smoothing function
(error-sensitive)

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

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

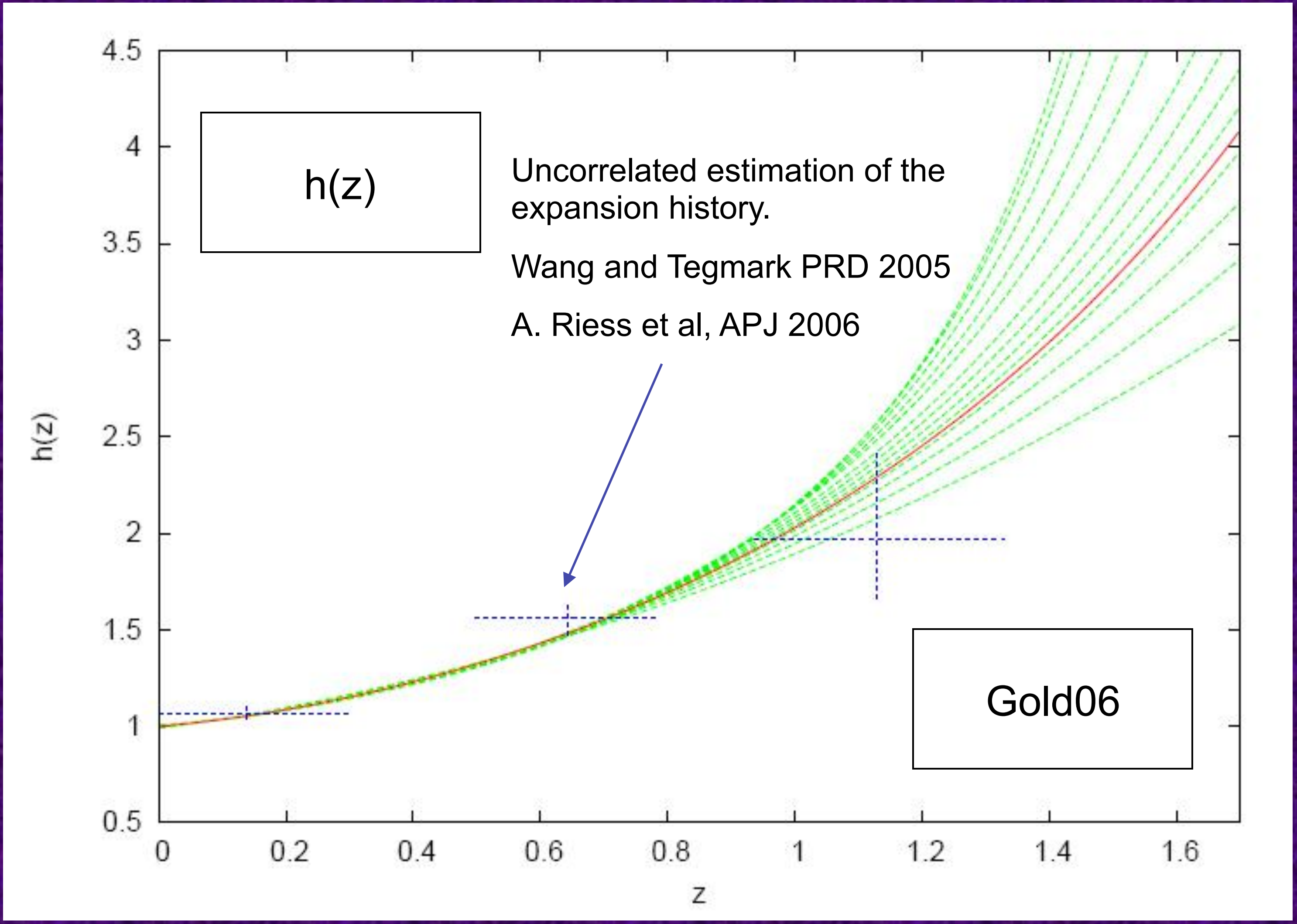


Shafieloo, Alam, Sahni, Starobinsky, MNRAS 2006

Reconstructed **w(z)** by **smoothing method**

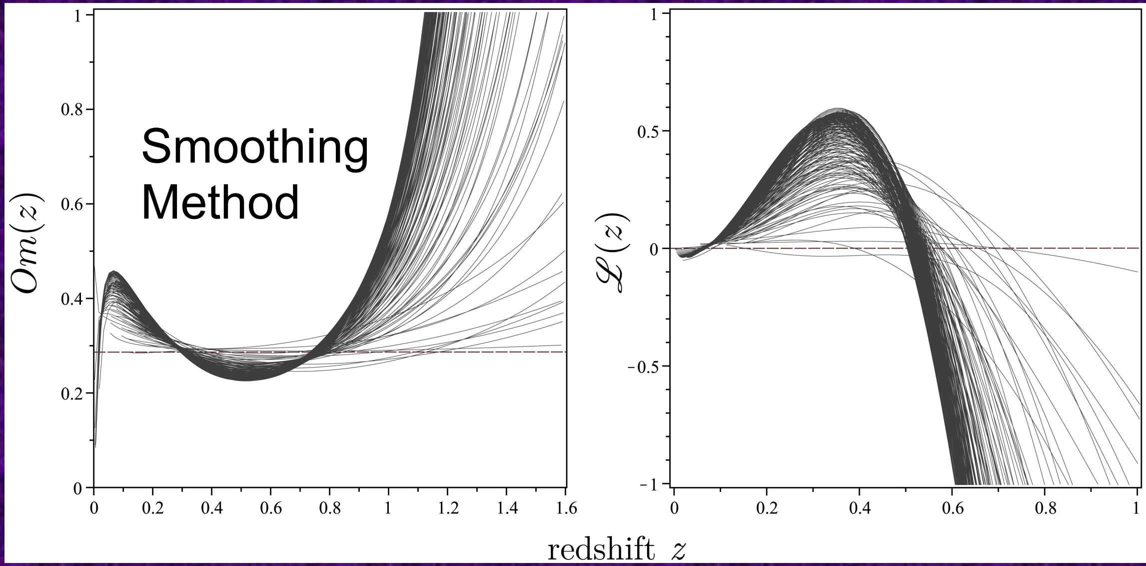
Reconstructed **w(z)** by using CPL fit.

Chevallier et al (2001) and Linder (2003)



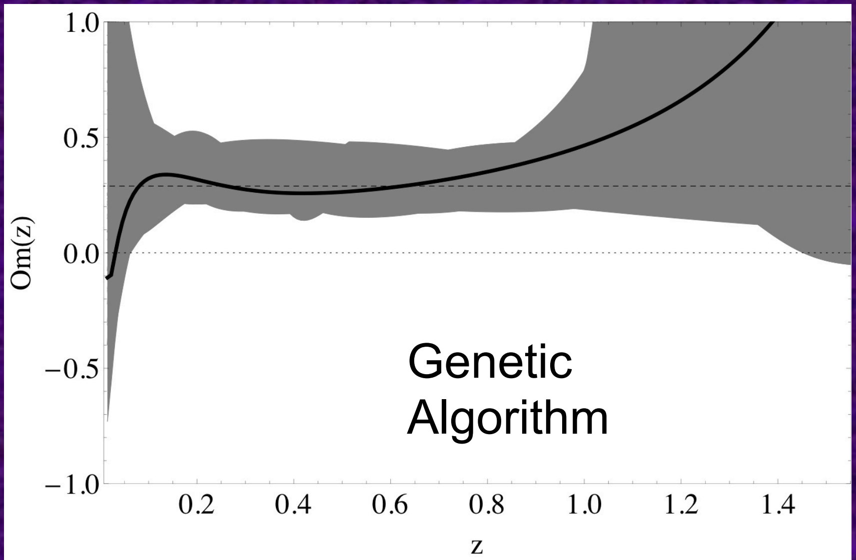
A. Shafieloo, MNRAS 2007

Model Independent Reconstruction of the Expansion History of the Universe as a Null Test for the Cosmological Constant



Shafieloo & Clarkson, PRD 2010

Nesseris & Shafieloo, MNRAS 2010



Model Independent Reconstruction of H(z)

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

Smoothing Supernovae data

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

Real time cosmology

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

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Volume distance from baryon acoustic oscillation measurements

Deriving h(z) from BAO

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

Observable

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

Effective dilation distance

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

Comoving sound horizon at baryon drag epoch

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

Deriving h(z) from BAO

$$\boxed{\mathscr{R}(z)} = \frac{r_s(z_{CMB})}{D_V(z)}$$

Observable BAO

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Observable CMB

Deriving h(z) from BAO

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

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

Deriving h(z) from BAO

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

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

Percival et. al. 2010

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

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

LAMBDA website

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

$$H_0 = 73.8 \pm 2.4$$

Riess et. al. 2011

$$\sigma_{h(z)}{}^2 = \left[\frac{\partial h(z)}{\partial H_0}\right]^2 \sigma_{H_0}{}^2 + \left[\frac{\partial h(z)}{\partial D_V(z)}\right]^2 \sigma_{D_V(z)}{}^2$$

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

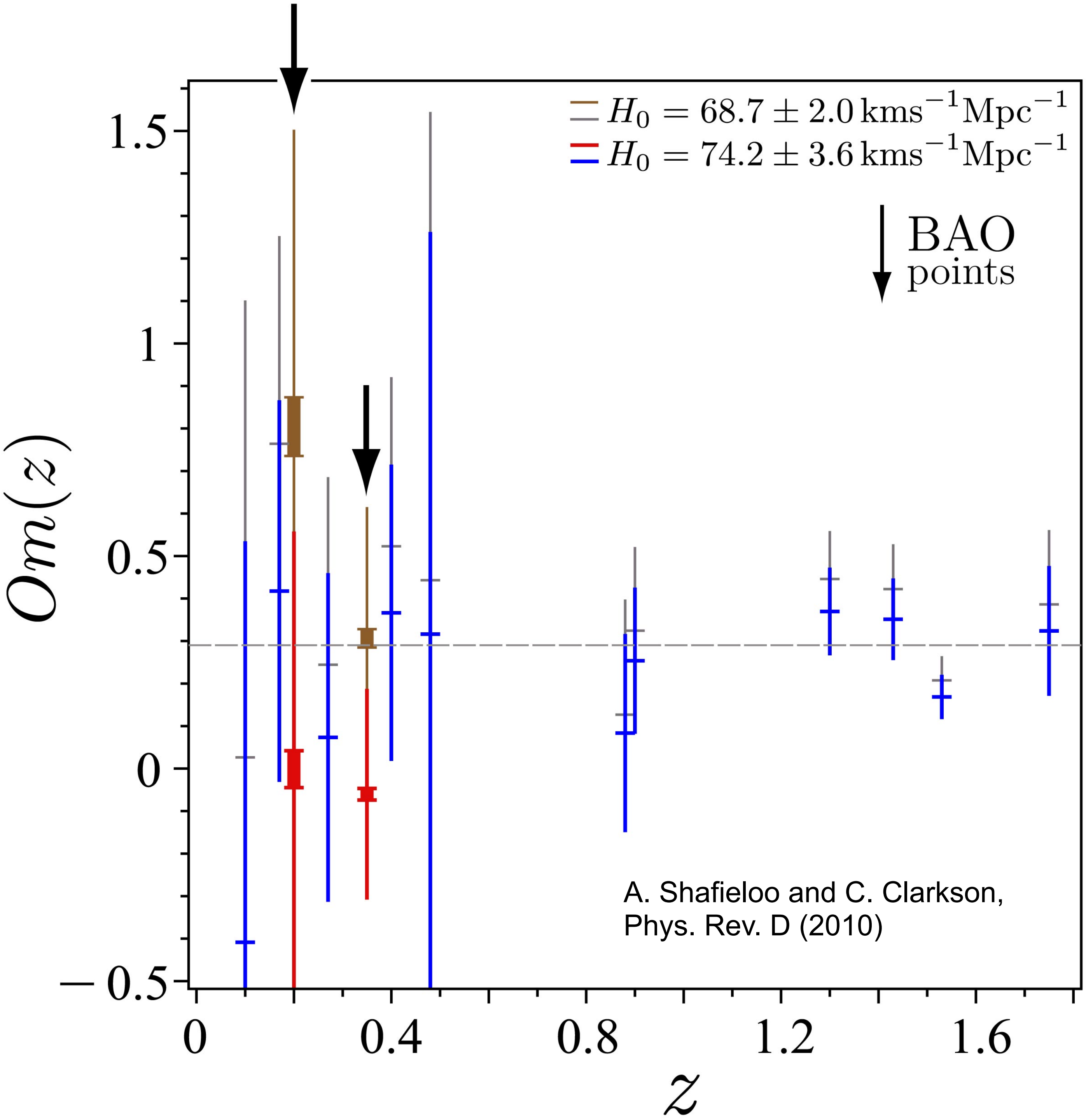
$$\sigma_{h(z)}{}^2 = \left[\frac{\partial h(z)}{\partial H_0}\right]^2 \sigma_{H_0}{}^2 + \left[\frac{\partial h(z)}{\partial D_V(z)}\right]^2 \sigma_{D_V(z)}{}^2$$

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

Om diagnostic

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

Reconstruction of Om(z)



Alcock-Paczynski Measurement

- An Alcock-Paczynski measurement can be applied to cosmological objects as well as an isotropic process such as the 2-point statistics of galaxy clustering (Ballinger et al. 1996)

$$\Delta z = L_0 H(z)/c$$

$$\Delta\theta = L_0/[(1+z)D_A(z)]$$

$$\Delta z/\Delta\theta = (1+z)D_A(z)H(z)/c,$$

Scale Distortion Parameter

C. Blake et. al, in prepration, WiggleZ Survey: Alcock-Paczynski measurement

$$F(z) = (1+z)D_A(z)H(z)/c$$

Amplitude of systematic errors in measurements of the scale distortion parameter F(z) in four redshift slices relative to its fiducial value F_fid (FLCDM with matter density of 0.27), marginalized over the growth rate and galaxy bias b^2.

Combining the information from supernovae data and AP measurements

Smoothing method reconstruct D_A(z) using supernovae data in a model independent way.

(Shafieloo et al 2006, Shafieloo 2007, Shafieloo and Clarkson 2010)

Assumption of curvature (here assuming flat universe) allow us to relate h(z) and distance measurements.

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

AP measurements of distortion parameter F(z) put additional constraints on the reconstructed results through consistency check between the D_A(z) and H(z).

$$F(z) = (1+z)D_A(z)H(z)/c$$

Smoothing method can be modified to include SN Ia and AP measurements simultaneously to reconstruct the expansion history of the universe.

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

C. Blake et. al, in prepration

(Present)t

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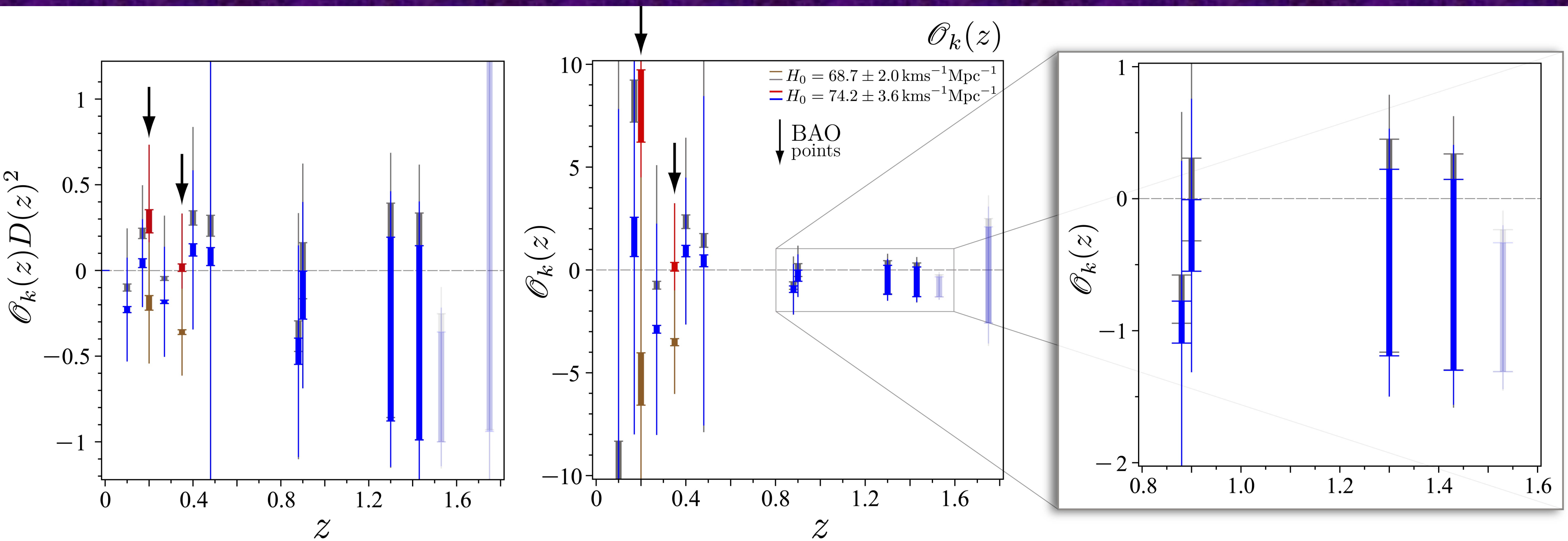
All within framework of FLRW

Universe is Flat? FLRW metric?



$$d_L(z) = \frac{c(1+z)}{H_0\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k}\int_0^z \mathrm{d}z' \frac{H_0}{H(z')}\right)$$

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

$$d_L = (1+z)^2 d_A$$

$$\Omega_k = \frac{[h(z)D'(z)]^2 - 1}{[D(z)]^2} = \mathscr{O}_k(z)$$

Shafieloo & Clarkson, PRD 2010

Conclusion

- BAO links the early and late universe. It is currently providing us with more and more valuable information about the universe.
- The current standard model of cosmology seems to work fine confronting with BAO data.
- This does not mean all the other models are wrong.
- It is important to analyze the data in a model independent way.
- Challenging the standard model is more affordable and realistic than trying to reconstruct the underlying model of the universe.
- Future data will break many degeneracies and probably we can distinguish between many models. We should wait and see how long the standard model can survive.

Coming soon!

$$\Omega_3$$

A new diagnostic of dark energy, tailored to fit BAO data