Looking for evidences beyond the standard model of cosmology

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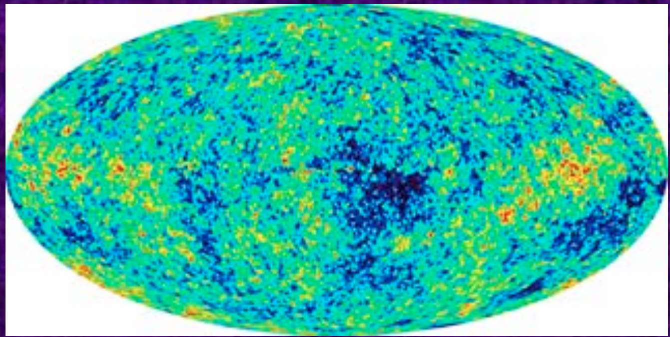
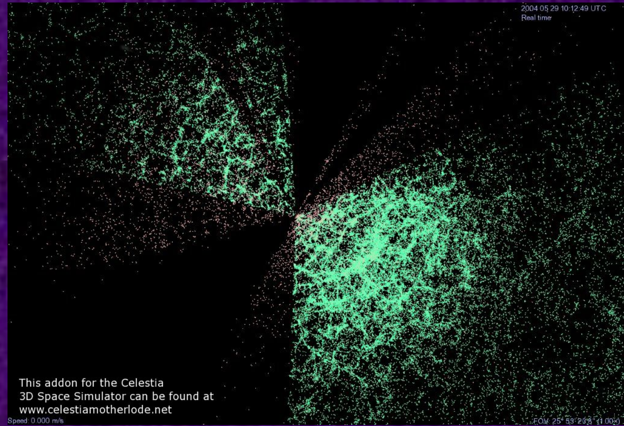
Cosmology, from ***fiction*** to being ***science*****….**



Cosmic Microwave Background (CMB)

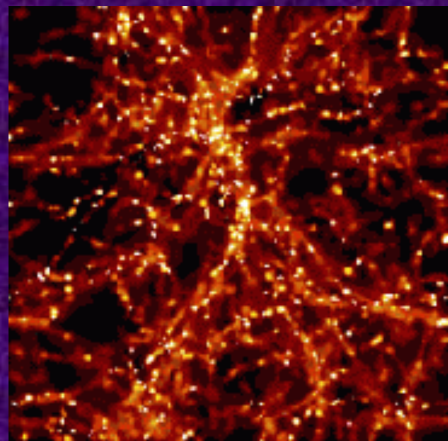


Large-scale structure

Cosmological Observations

Gravitational Lensing

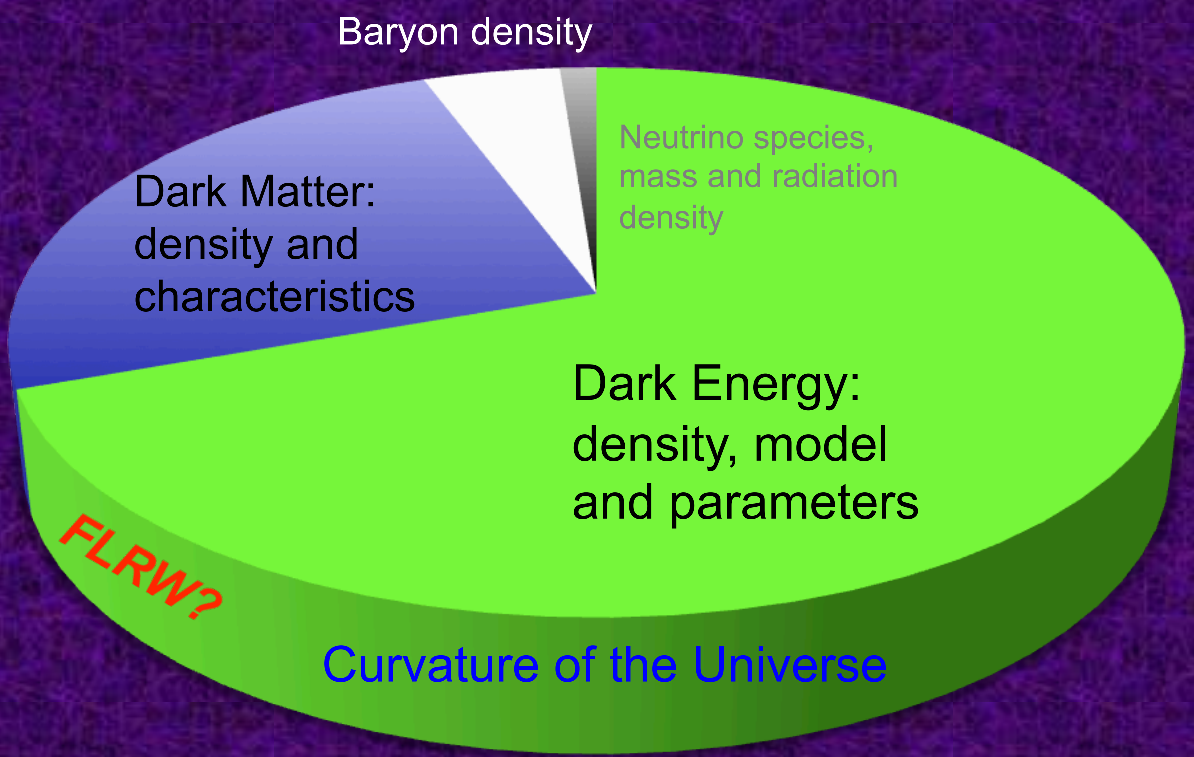
Type Ia supernovae



Lyman Alpha Forest

Era of Precision Cosmology

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



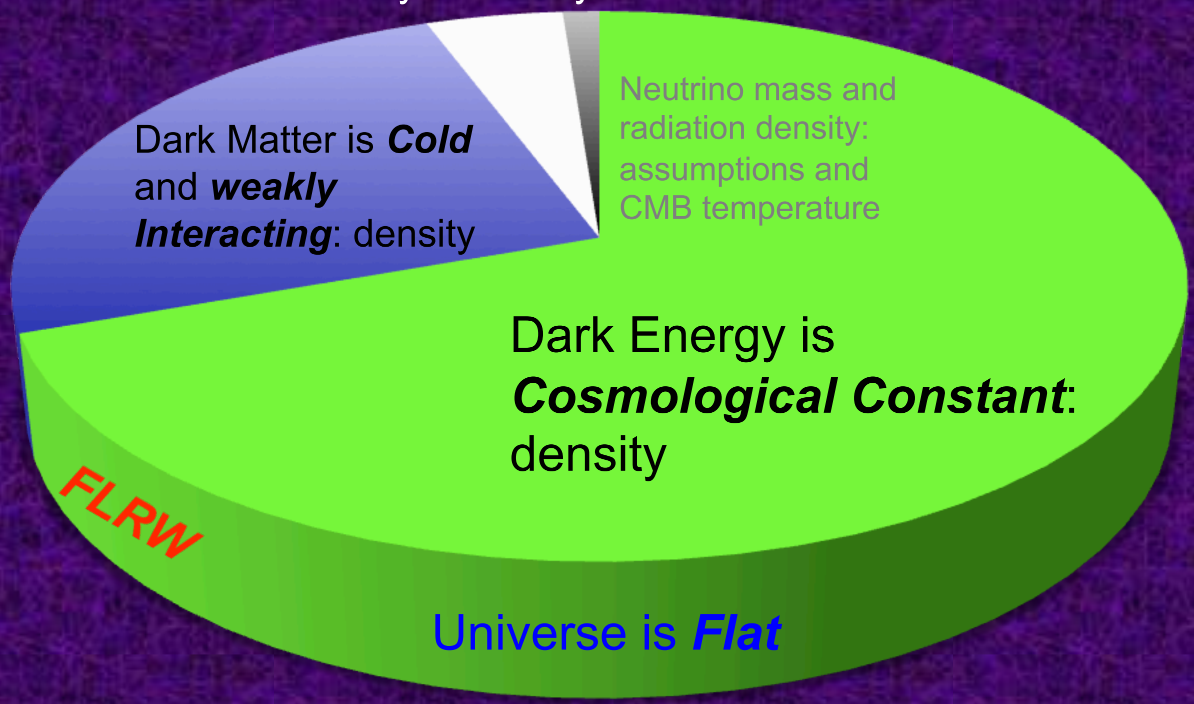
Initial Conditions:
Form of the Primordial Spectrum and Model of Inflation and its Parameters

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***

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Hubble Parameter and the Rate of Expansion

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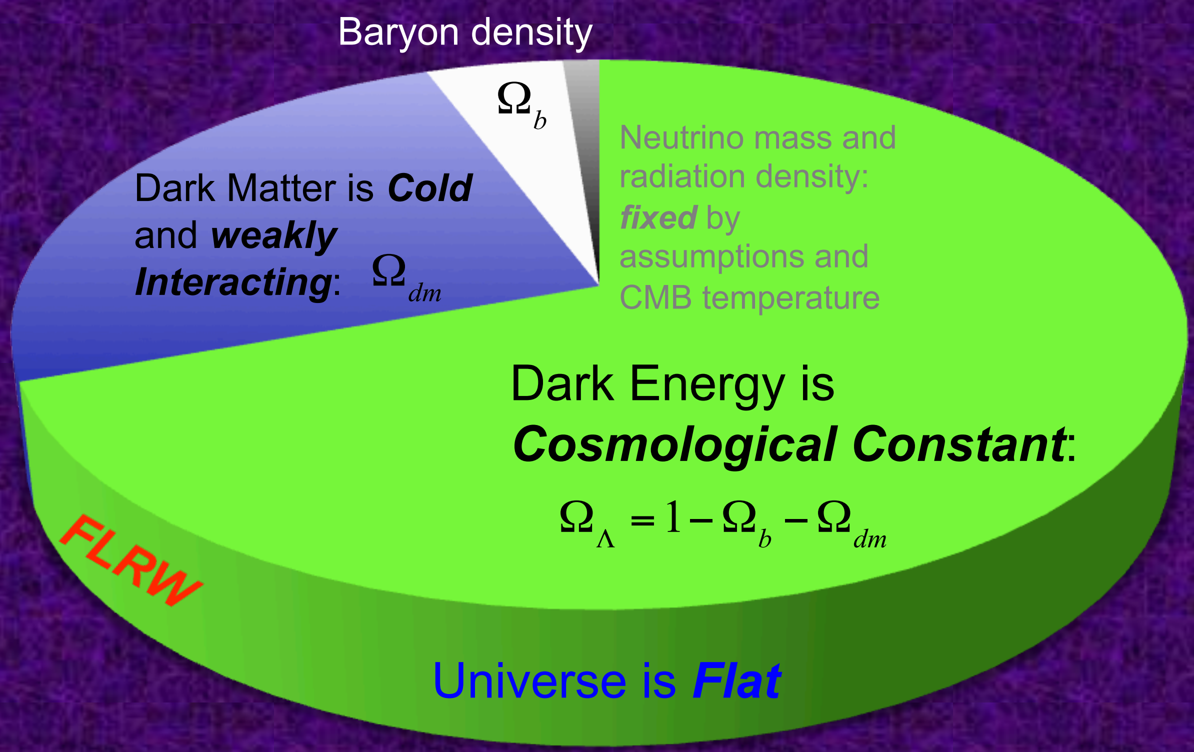
Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.



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

$$n_s, A_s$$

Epoch of reionization

$$\tau$$

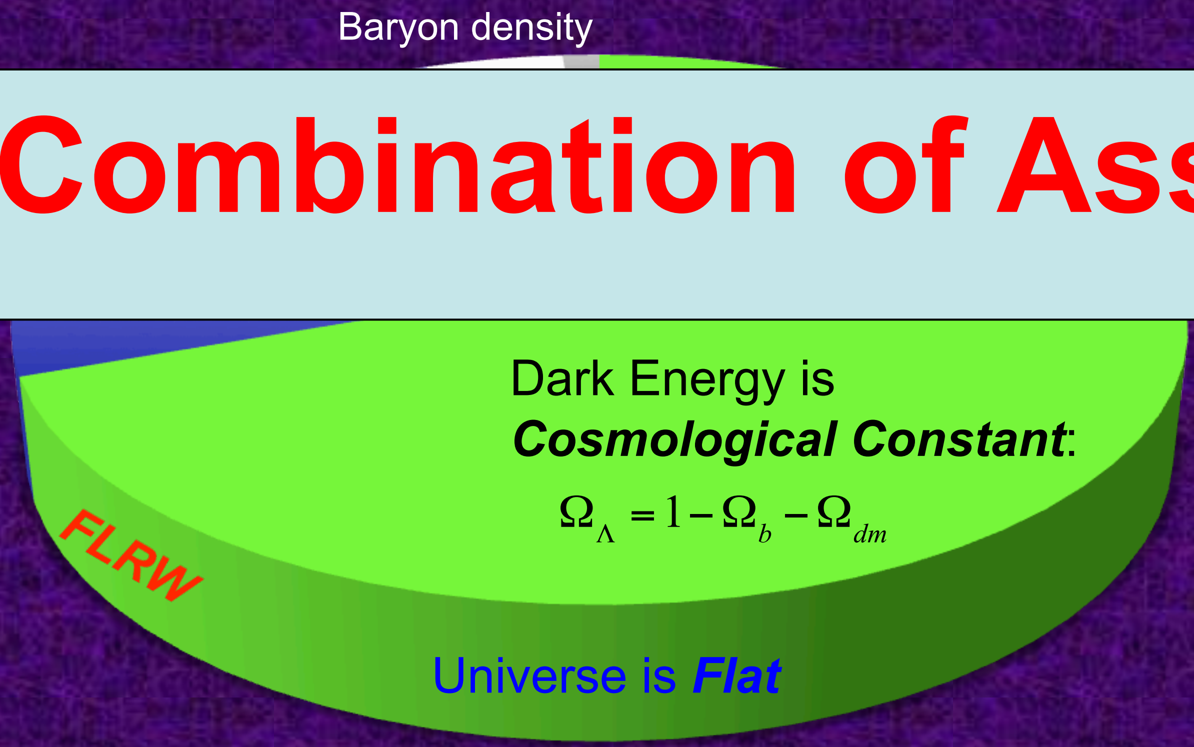
Hubble Parameter and the Rate of Expansion

$$H_0$$

Standard Model of Cosmology

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

Combination of Assumptions



n_s, A_s

Epoch of reionization

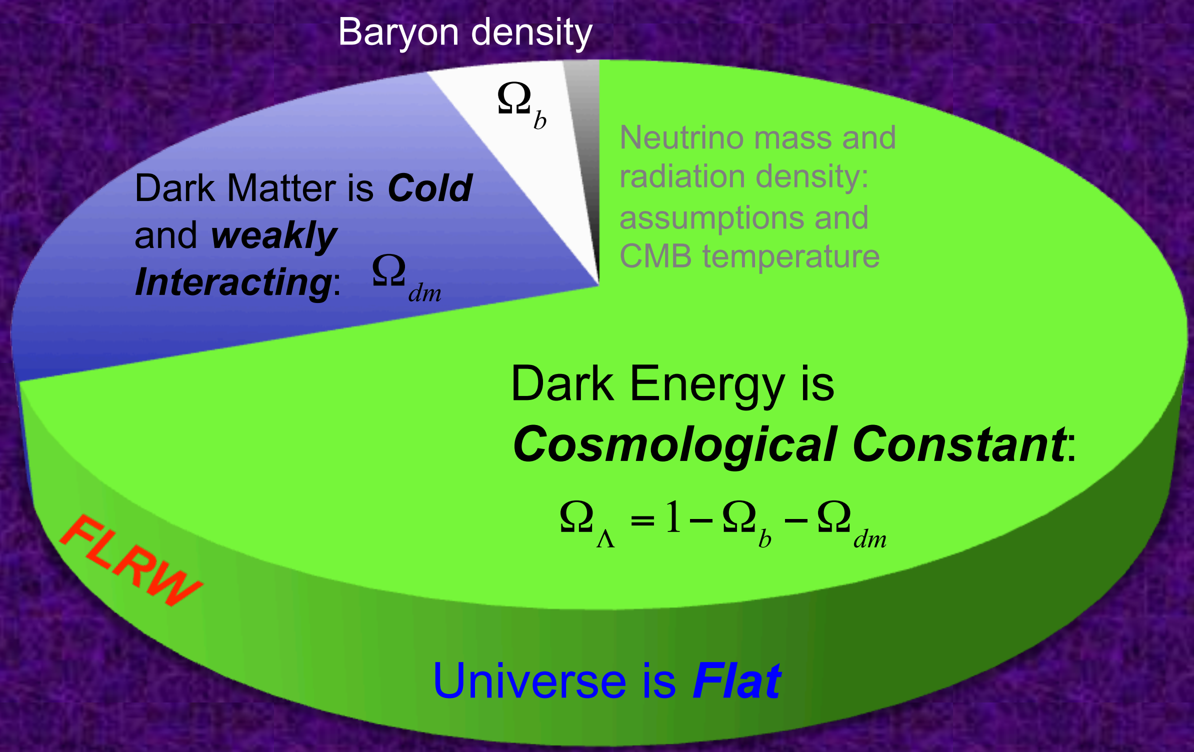
τ

Hubble Parameter and the Rate of Expansion

H_0

Standard Model of Cosmology

combination of *reasonable* assumptions, but.....



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 might 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.

(Present)

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

Dark Energy in 2017

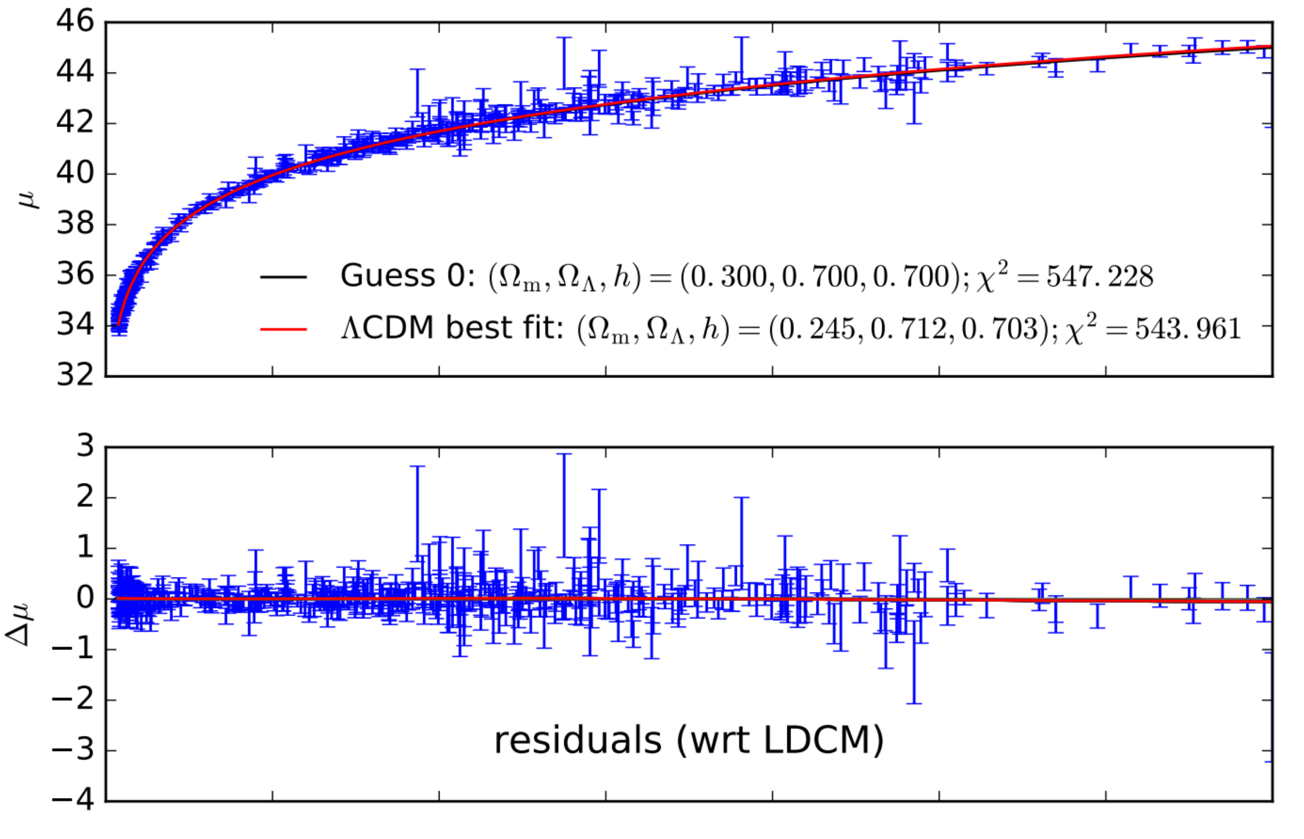
SN

Almost 20 years after discovery of the acceleration of the universe:

From 60 Supernovae Ia at cosmic distances, we now have ~800 published distances, with better precision, better accuracy, out to z=1.5. ***Accelerating universe in proper concordance to the data.***

JLA Compilation

L'Huillier & Shafieloo JCAP 2017

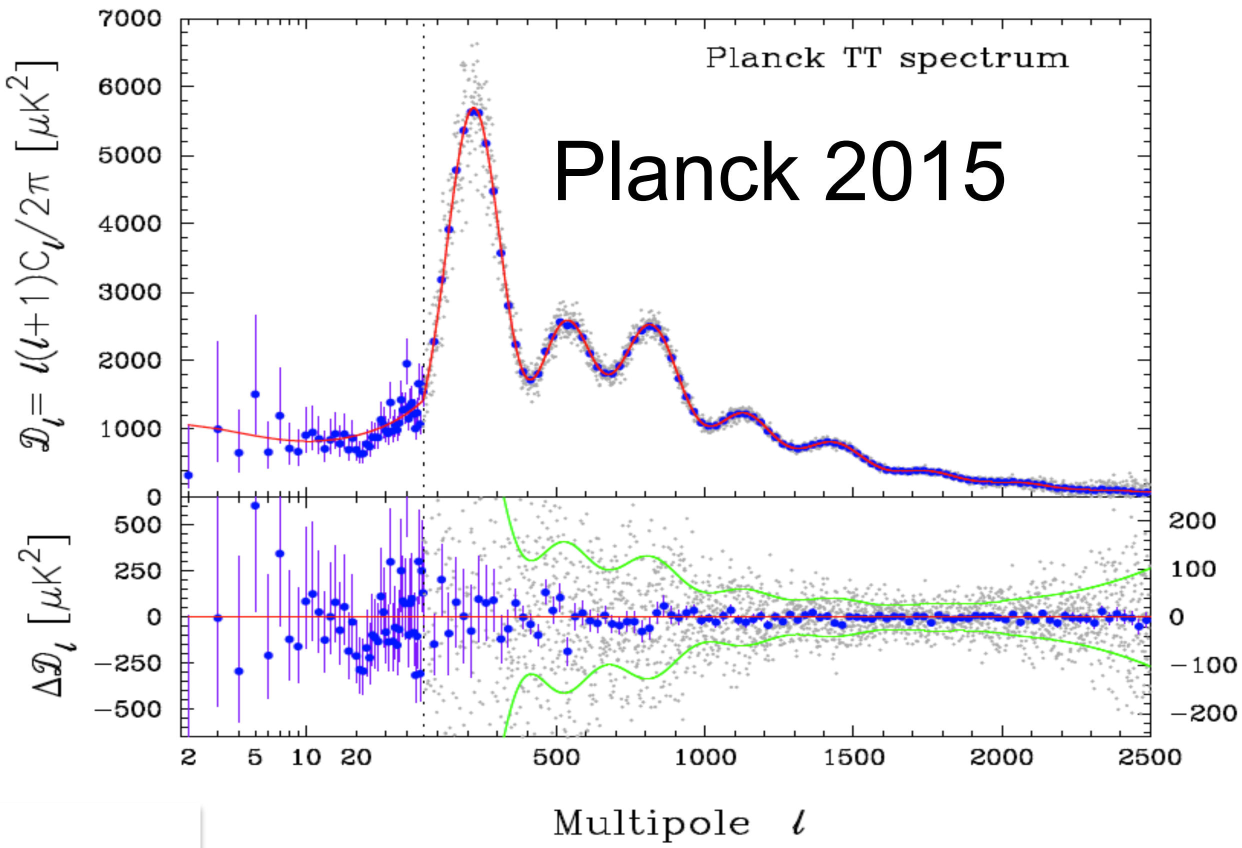


Dark Energy in 2017

CMB

Almost 20 years after discovery of the acceleration of the universe:

CMB directly points to acceleration. Didn't even have acoustic peak in 1998!

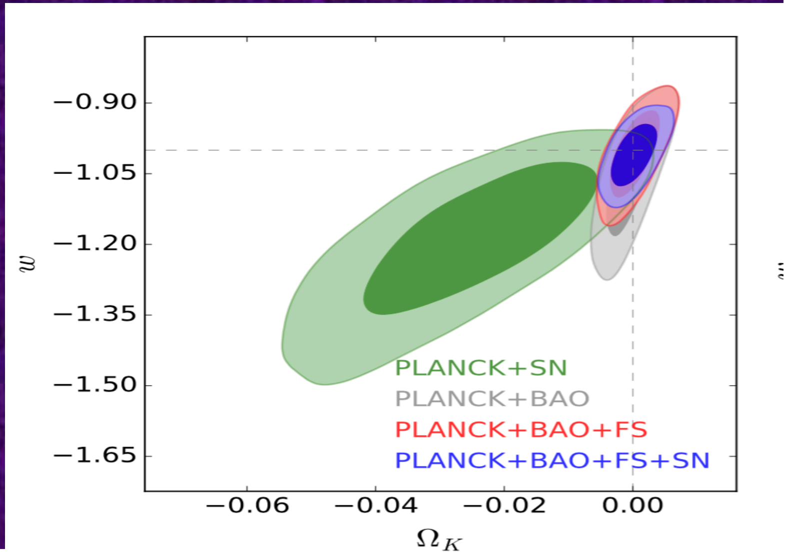


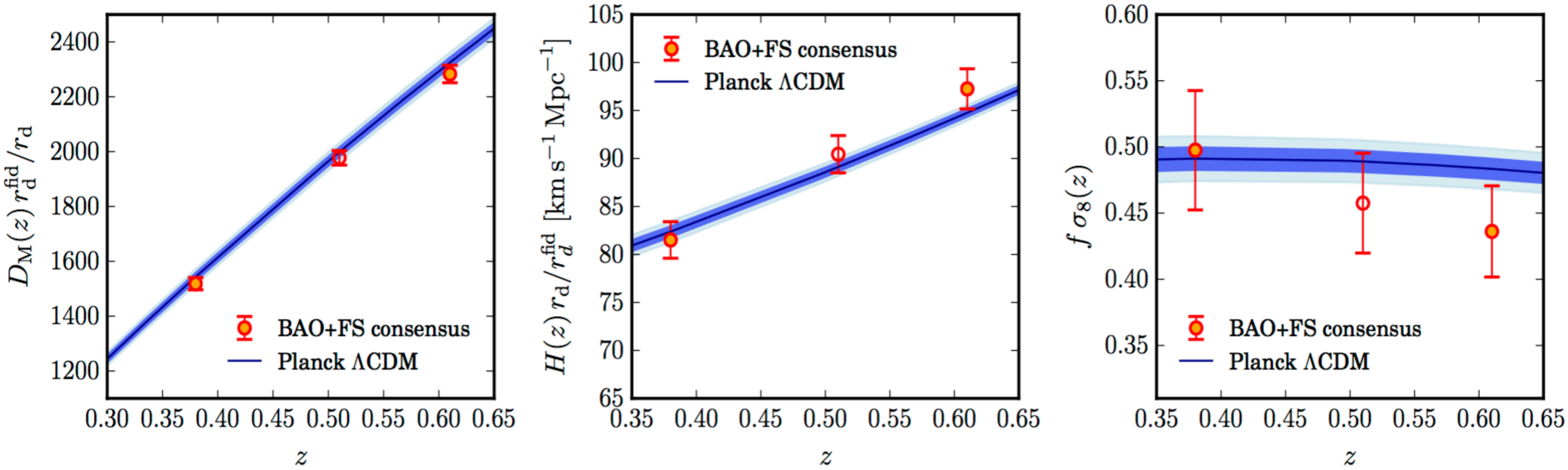
Dark Energy in 2017

LSS

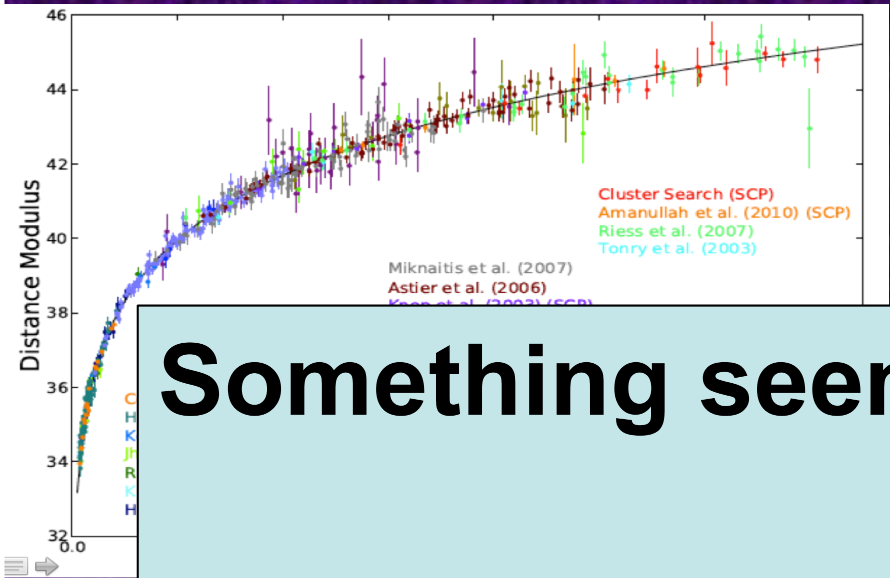
Almost 20 years after discovery of the acceleration of the universe:

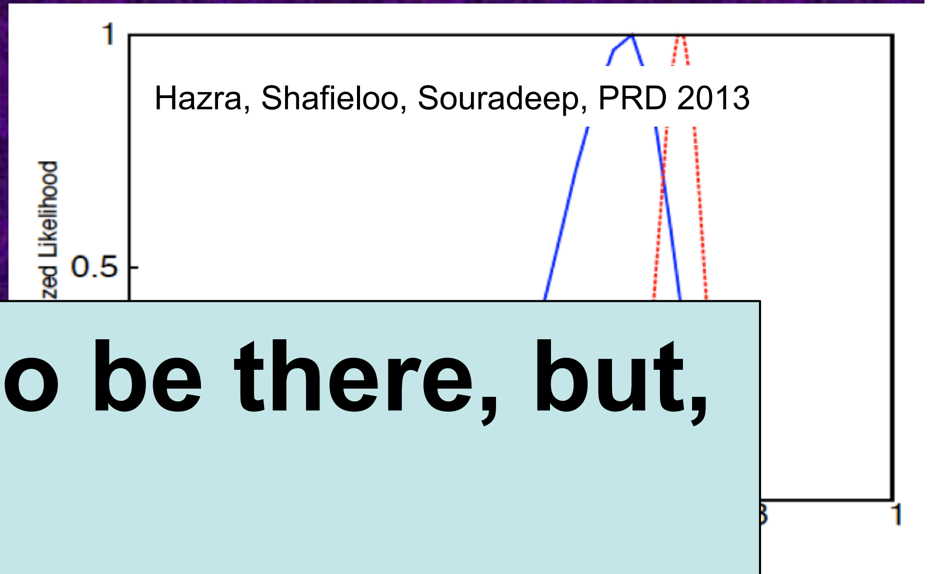
BOSS collaboration (2016),
arXiv:Alam et al, 1607.03155





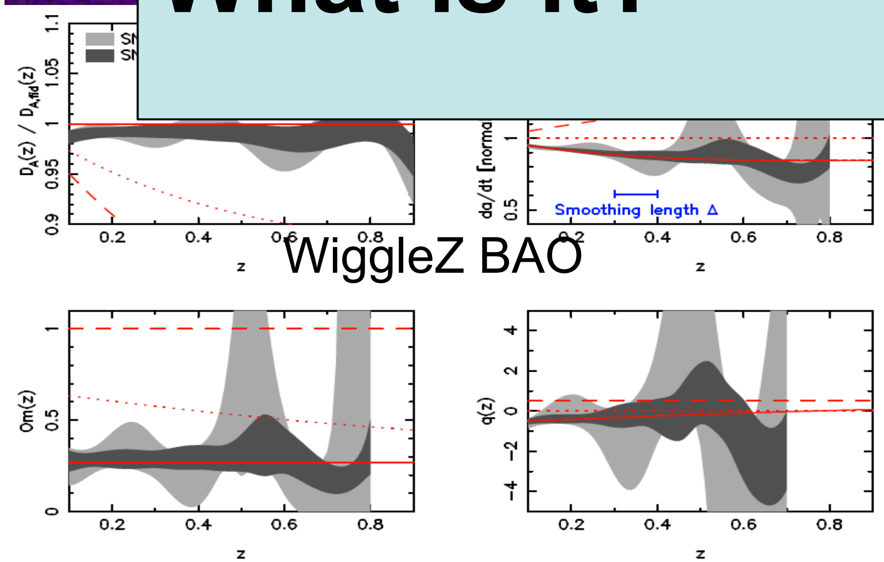
Accelerating Universe, Now

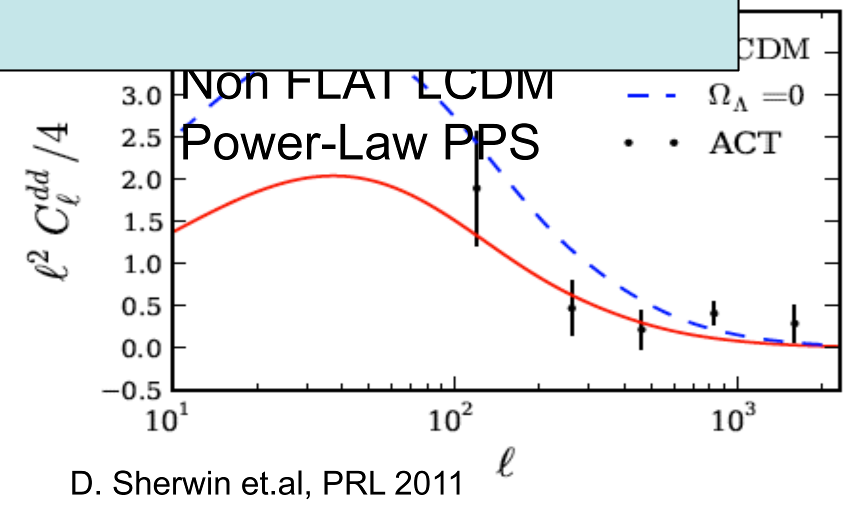




Something seems to be there, but,

What is it?





Dark Energy Models

- Cosmological Constant
- Quintessence and k-essence (scalar fields)
- Exotic matter (Chaplygin gas, phantom, etc.)
- Braneworlds (higher-dimensional theories)
- Modified Gravity
- ……

But which one is really responsible for the acceleration of the expanding universe?!

Reconstructing Dark Energy

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 ***properly*** on the raw data, but the results will be less biased and more reliable and independent of theoretical models or parametric forms.

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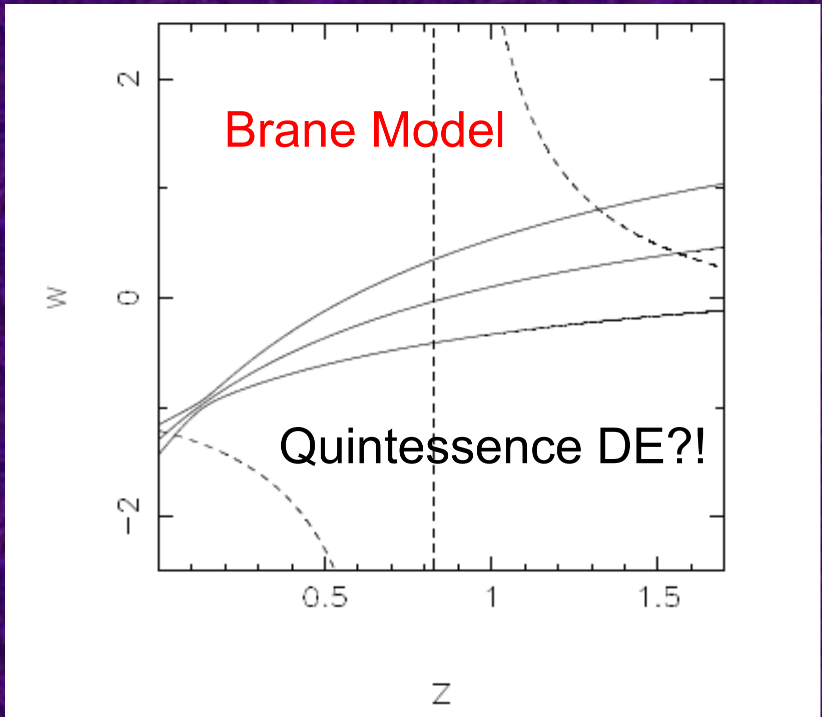
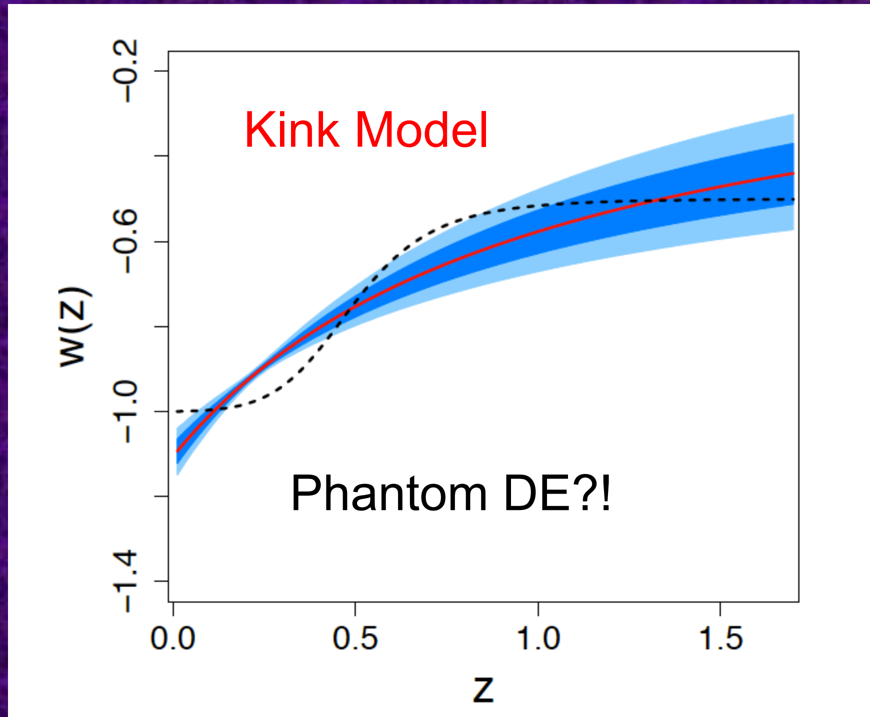
Problems of Dark Energy Parameterizations (model fitting)





Shafieloo, Alam, Sahni & Starobinsky, MNRAS 2006

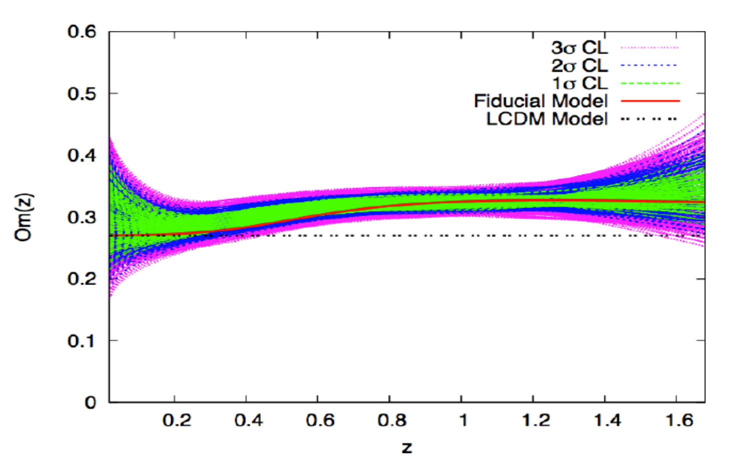
Holsclaw et al, PRD 2011

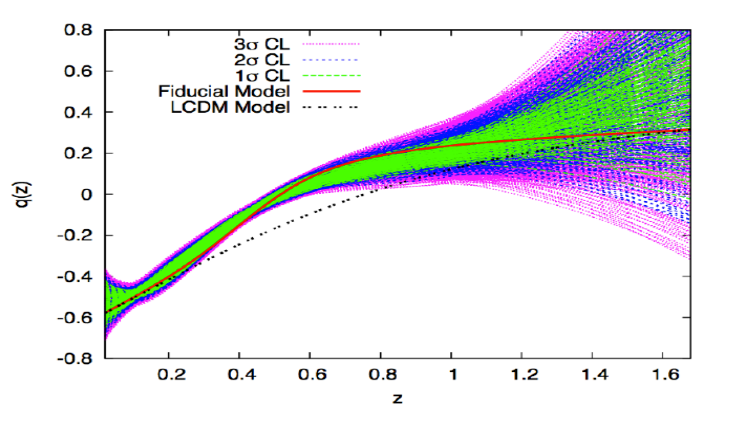
$$w(z) = w_0 + w_a \frac{z}{1+z}.$$

Chevallier-Polarski-Linder ansatz (CPL).

Model independent reconstruction of the expansion history

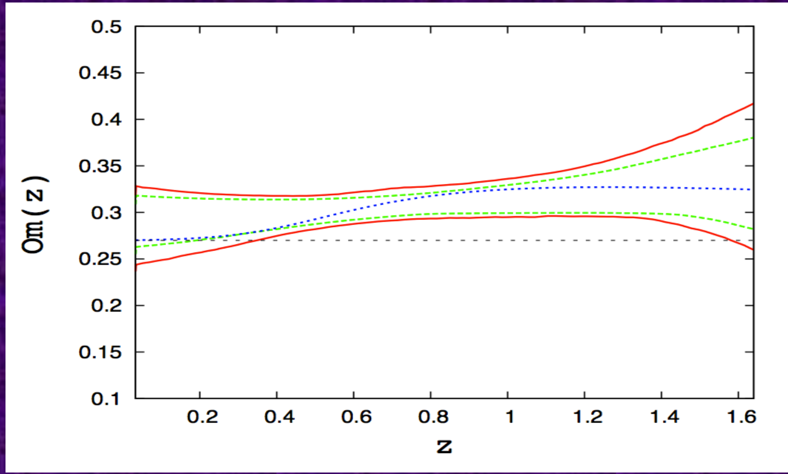
Crossing Statistic + Smoothing

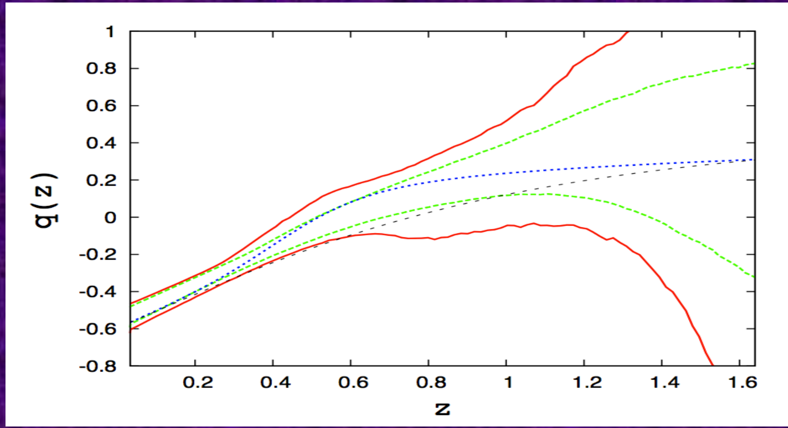




Shafieloo, JCAP (b) 2012

Gaussian Processes





Shafieloo, Kim & Linder, PRD 2012

Dealing with observational uncertainties in matter density (and curvature)

- Small uncertainties in the value of matter density affects the reconstruction exercise quiet dramatically.
- Uncertainties in matter density is in particular bound to affect the reconstructed w(z).

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

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

Full theoretical picture:

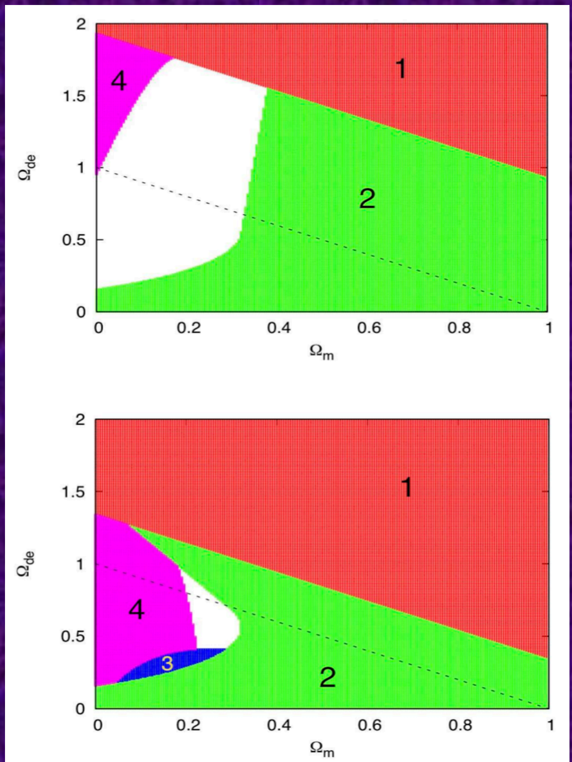
Cosmographic Degeneracy

$$\boxed{d_l(z)} = \frac{1+z}{\sqrt{1-\Omega_m-\Omega_{de}}}\sinh\left(\sqrt{1-\Omega_m-\Omega_{de}}\int_0^z \frac{dz'}{h(z')}\right)$$

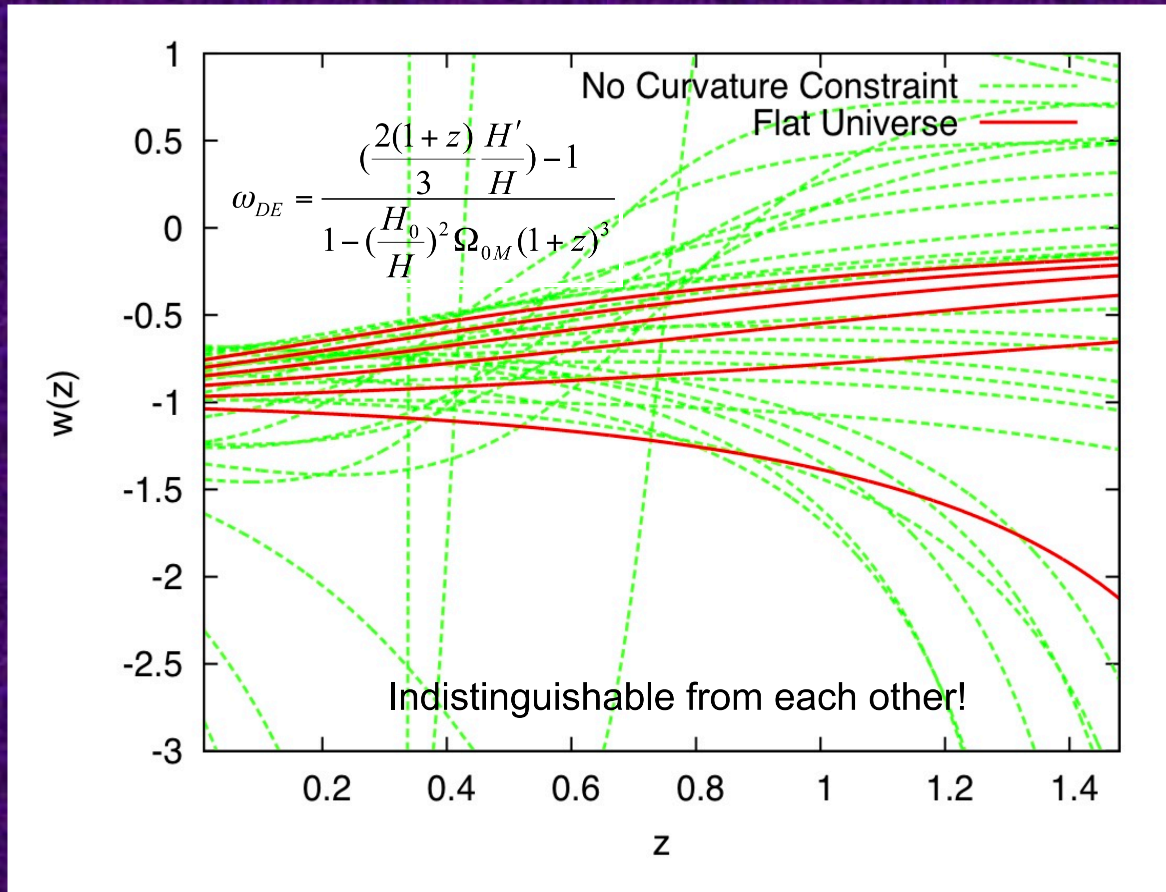
$$\begin{aligned} h(z)^2 &\equiv [H(z)/H_0]^2 \equiv (\dot{a}/a)^2 \\ &= \Omega_m(1+z)^3 + (1-\Omega_m-\Omega_{de})(1+z)^2 \\ &\quad + \Omega_{de}\exp\left[3\int_0^z \frac{dz'}{1+z'}[1+w(z')]\right], \end{aligned}$$

Cosmographic Degeneracy

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



Shafieloo & Linder, PRD 2011



Reconstruction & ***Falsification***

Considering (low) quality of the data and cosmographic degeneracies we should consider a new strategy sidewise to reconstruction: **Falsification.**

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

But, How?

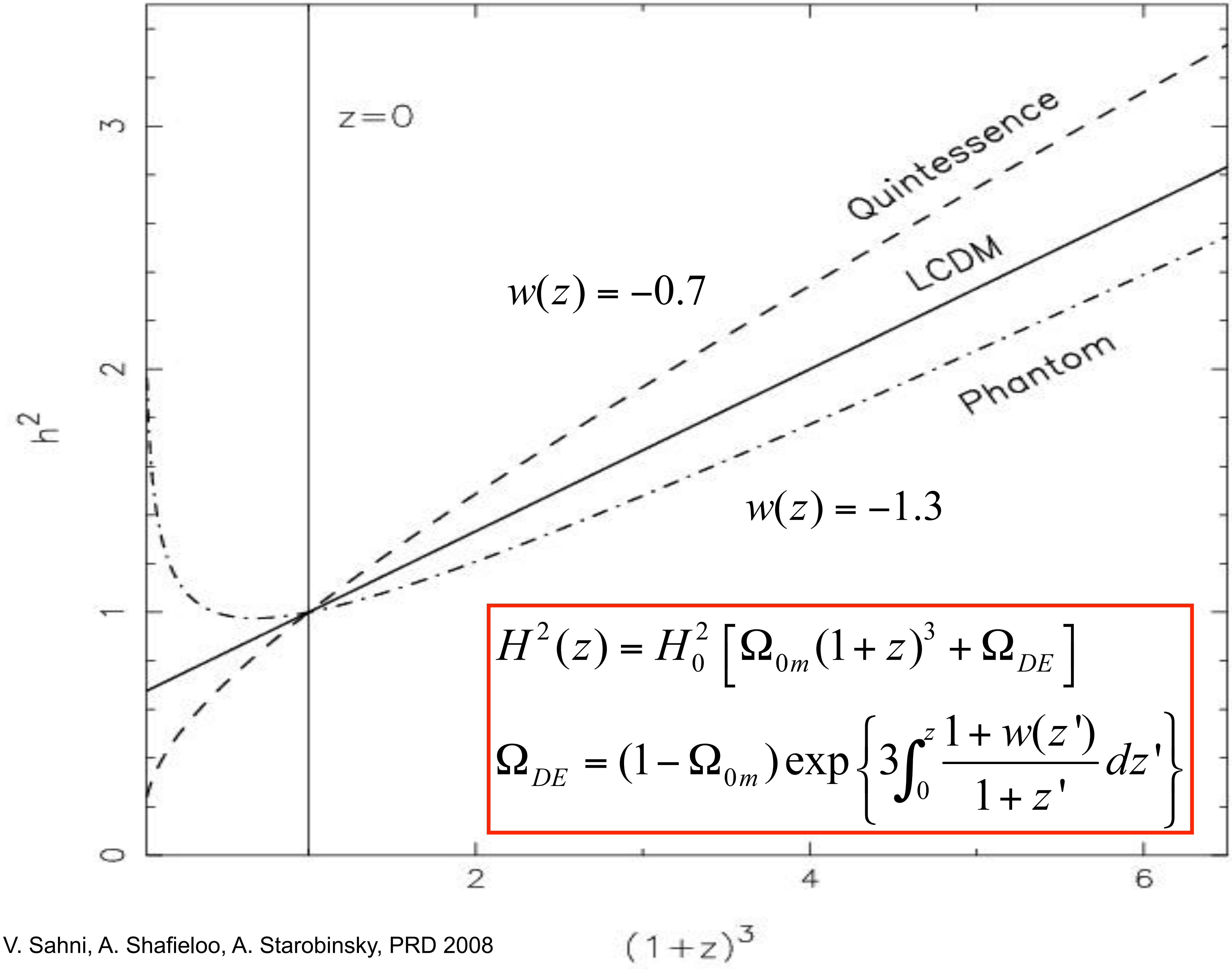
We should look for special characteristics of the standard model and relate them to observables.

Falsification of Cosmological Constant

- 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



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

Falsification: Null Test of Lambda

Om diagnostic

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

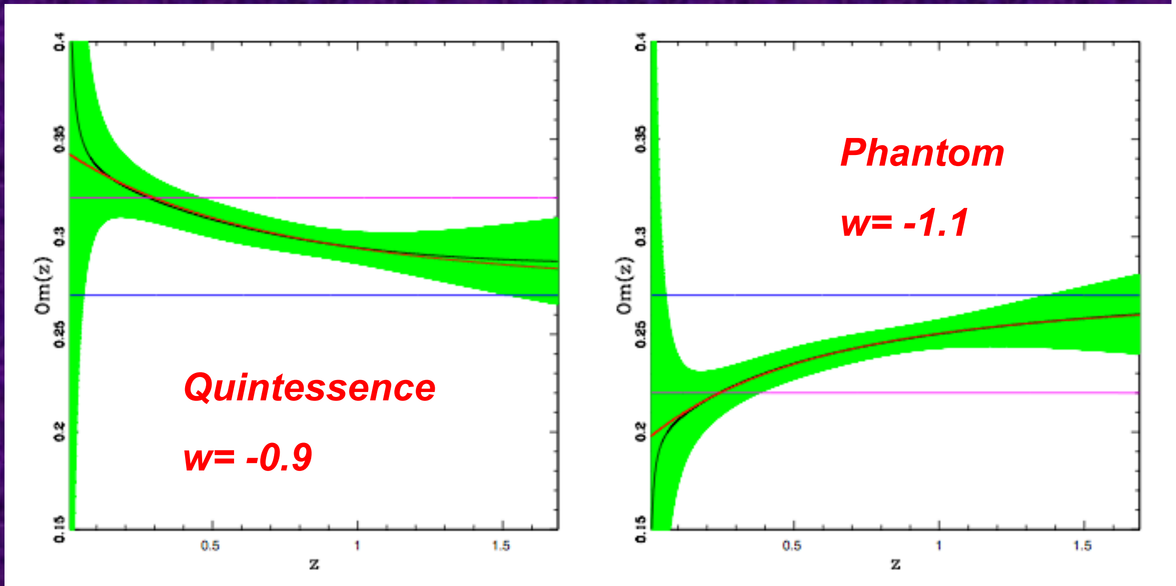
We Only Need h(z)

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

Om(z) is constant only for FLAT LCDM model

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

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



SDSS III DR-12 / BOSS Collaboration
Y. Wang et al, arXiv:1607.03154

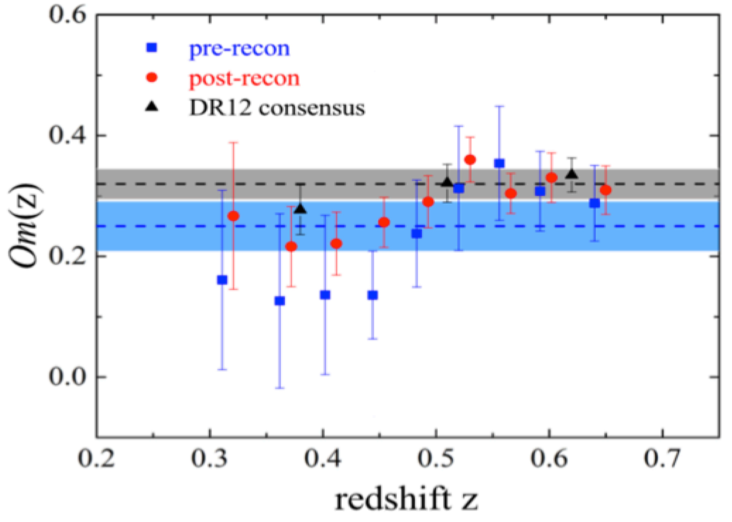


Figure 17. The $Om(z)$ values converted by our measurements on Hubble parameter in 9 redshift bins.

Om diagnostic is very well established

WiggleZ collaboration
C. Blake et al, MNRAS 2011

SDSS III Collaboration
L. Samushia et al, MNRAS 2013

Deviations from ΛCDM and GR 13

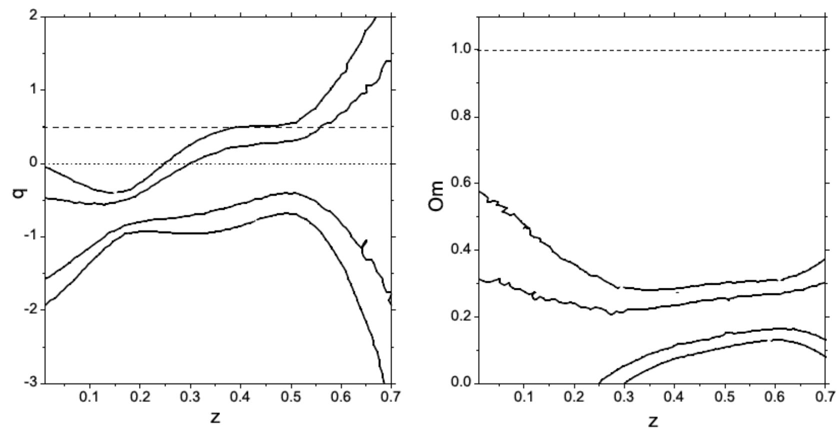


Figure 12. Confidence levels (1σ and 2σ) for the deceleration parameter as a function of redshift and Om(z) reconstructed from the compilation of geometric measurements in tables 2 and 3. H_0 is marginalised over with an HST prior. The dotted line in the left panel demarcates accelerating expansion (below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

10 *Blake et al.*

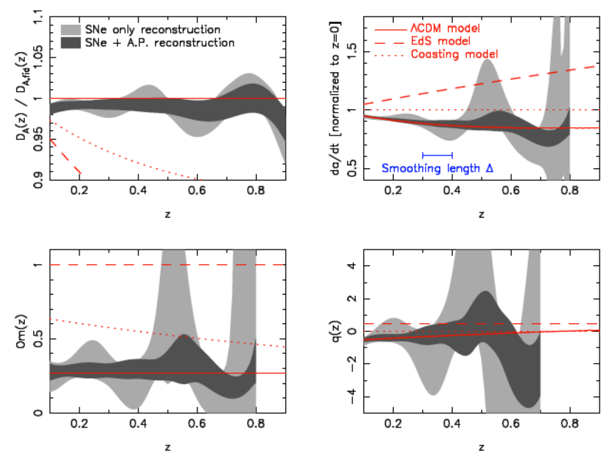


Figure 6. This Figure shows our non-parametric reconstruction of the cosmic expansion history using Alcock-Paczynski and supernovae data. The four panels of this figure display our reconstructions of the distance-redshift relation $D_A(z)$, the expansion rate $\dot{a}/H_0$, the Om(z) statistic and the 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 $q(z)$].

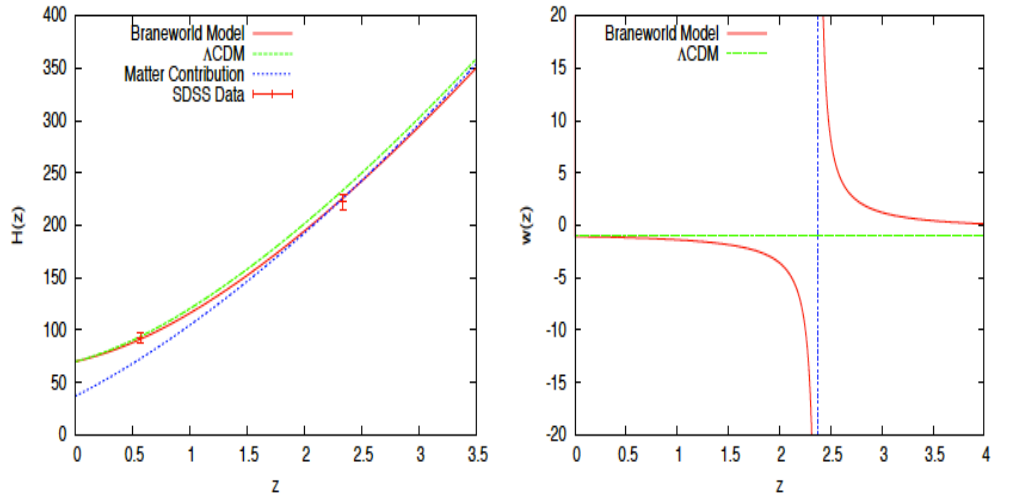
Omh2

Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

$$Omh2(z_1,z_2) = \frac{H^2(z_2) - H^2(z_1)}{(1+z_2)^3 - (1+z_1)^3} = \Omega_{0m} H_0^2$$

Only for LCDM

Sahni, Shafieloo, Starobinsky, ApJ Lett 2014



$Omh^2 = 0.1426 \pm 0.0025$ LCDM +Planck+WP

$$Omh^2(z_1; z_2) = 0.124 \pm 0.045$$
$$Omh^2(z_1; z_3) = 0.122 \pm 0.010$$
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BAO+H0

H(z = 0.00) = 70.6 \pm 3.3 km/sec/Mpc
H(z = 0.57) = 92.4 \pm 4.5 km/sec/Mpc
H(z = 2.34) = 222.0 \pm 7.0 km/sec/Mpc

Omh2

Important discovery if no systematic in the SDSS Quasar BAO data

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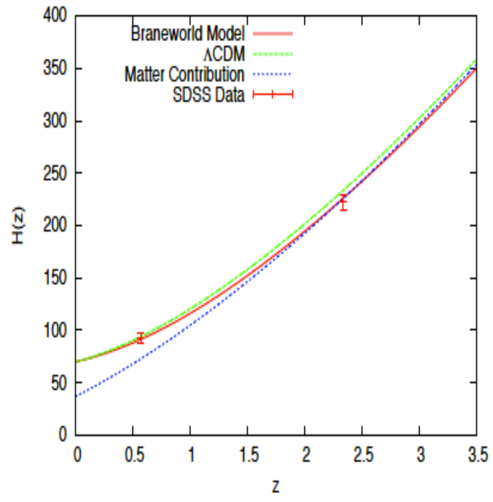

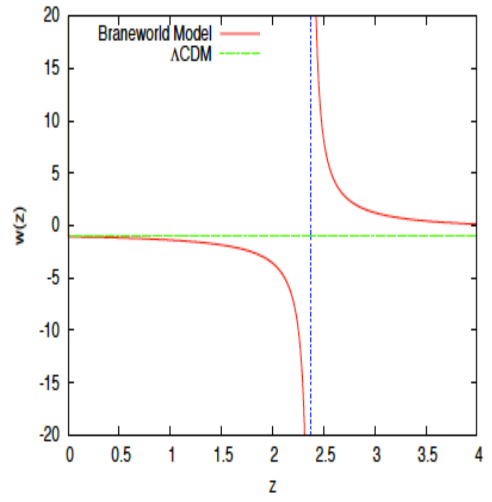

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2017 Omh2

No systematic yet found,

Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

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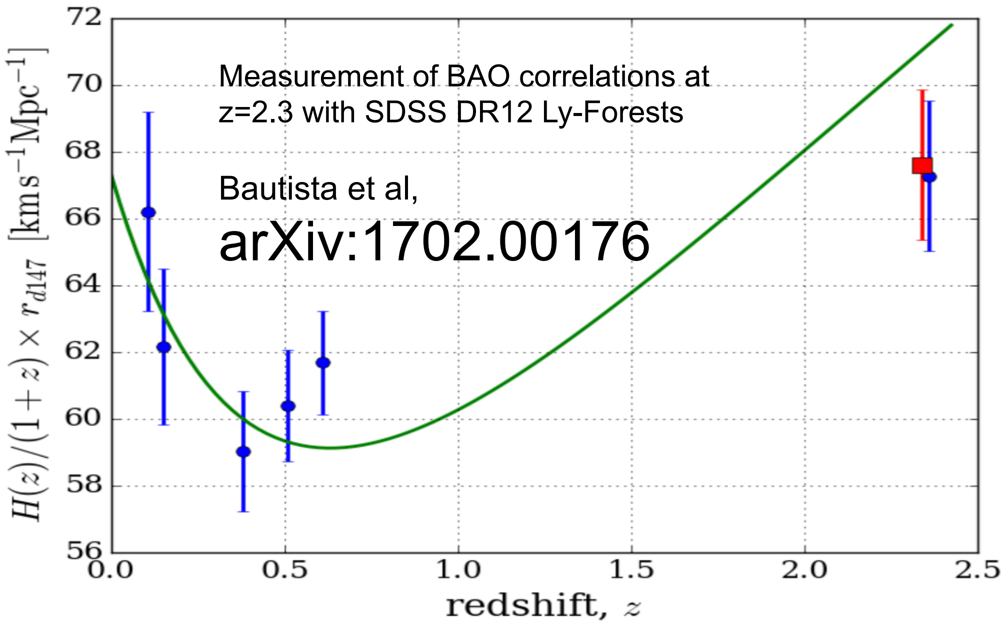

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2017 Omh2

No systematic yet found,
Results Persistent!

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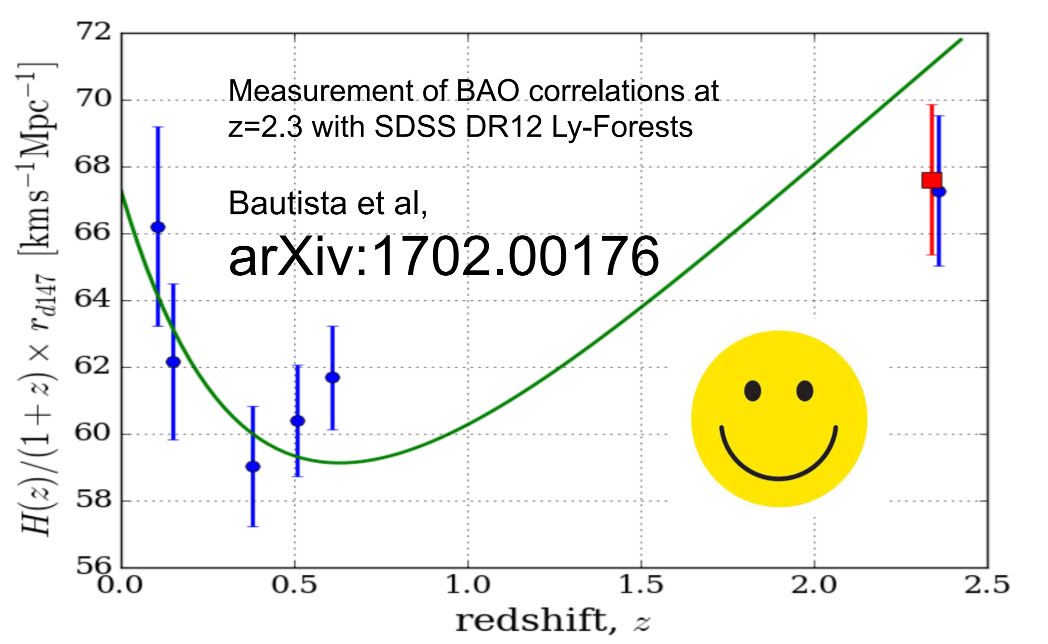

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What if we combine different cosmology data?

Do we still see evidence for dark energy evolution?

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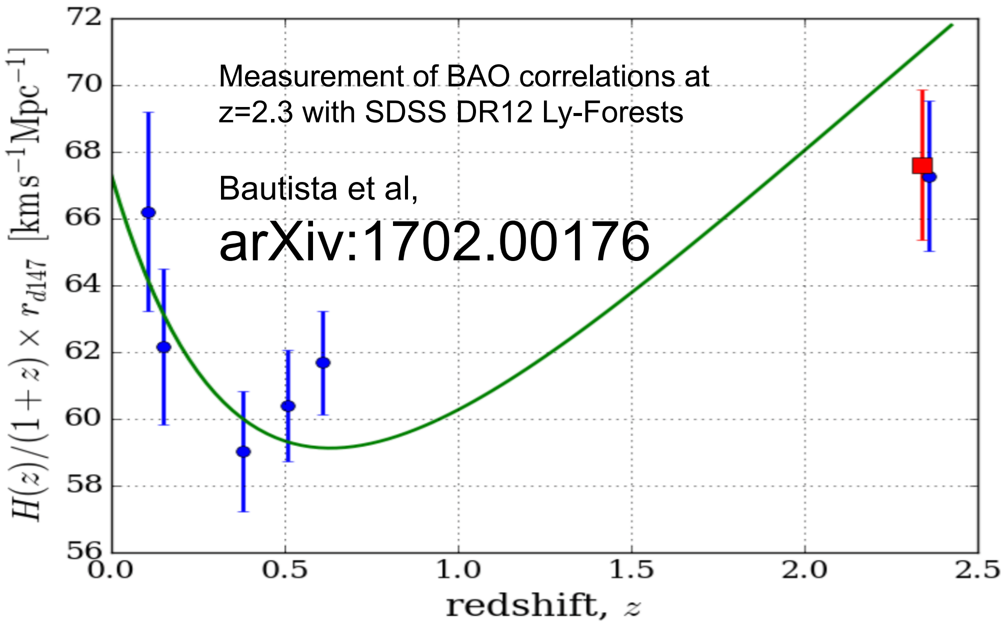

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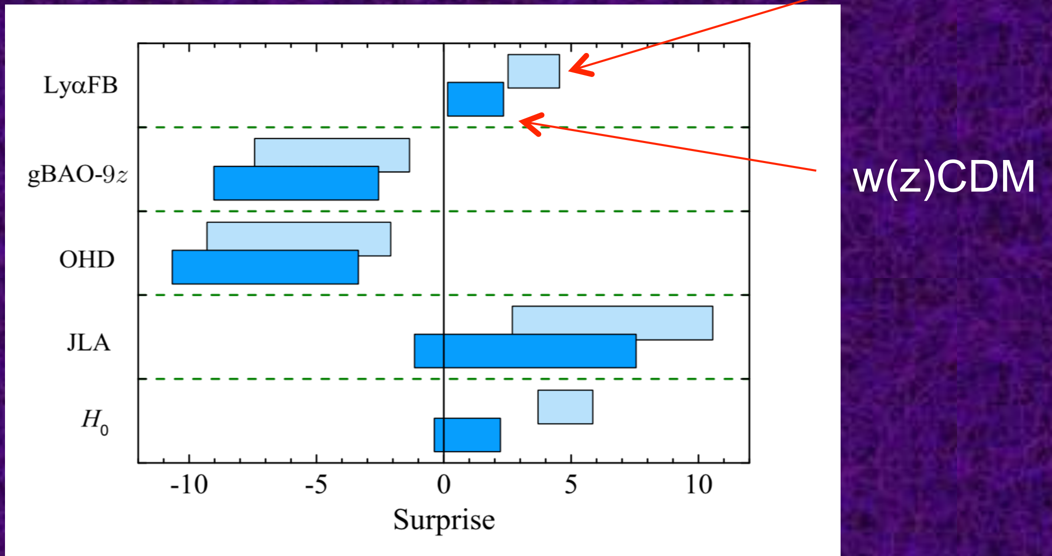
The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: Examining the observational evidence for dynamical dark energy

Gong-Bo Zhao,[1,2,*] Marco Raveri,[3,4] Levon Pogosian,[5,2] Yuting Wang,[1,2] Robert G. Crittenden,[2] Will J. Handley,[6,7] Will J. Percival,[2] Jonathan Brinkmann,[8] Chia-Hsun Chuang,[9,10] Antonio J. Cuesta,[11] Daniel J. Eisenstein,[12] Francisco-Shu Kitaura,[13,14] Kazuya Koyama,[2] Benjamin L'Huillier,[15] Robert C. Nichol,[2] Matthew M. Pieri,[16] Sergio Rodriguez-Torres,[9,17,18] Ashley J. Ross,[19,2] Graziano Rossi,[20] Ariel G. Sánchez,[21] Arman Shafieloo,[15,22] Jeremy L. Tinker,[23] Rita Tojeiro,[24] Jose A. Vazquez,[25] and Hanyu Zhang[1]

arXiv:1701.08165

$$T \equiv \frac{S}{\Sigma} = \frac{(\theta_1-\theta_2)^T \mathcal{C}_1^{-1}(\theta_1-\theta_2) - \mathbf{Tr}\left(\mathcal{C}_2\mathcal{C}_1^{-1}+\mathbb{I}\right)}{\sqrt{\mathbf{Tr}\left(\mathcal{C}_2\mathcal{C}_1^{-1}+\mathbb{I}\right)^2}} ,$$



Acronym	Meaning	References
P15	The *Planck* 2015 CMB power spectra	[6]
JLA	The JLA supernovae	[28]
6dF	The 6dFRS (6dF) BAO	[29]
MGS	The SDSS main galaxy sample BAO	[30]
$P(k)$	The WiggleZ galaxy power spectra	[31]
WL	The CFHTLenS weak lensing	[32]
H_0	The Hubble constant measurement	[10]
OHD	$H(z)$ from galaxy age measurements	[33]
gBAO-3z	3-bin BAO from BOSS DR12 galaxies	[34]
gBAO-9z	9-bin BAO from BOSS DR12 galaxies	[35, 36]
LyαFB	The Lyα forest BAO measurements	[2, 9]
B	P15 + JLA + 6dF + MGS	
ALL12	The combined dataset used in [27]	
ALL16-3z	B+$P(k)$+WL+H_0+OHD+gBAO-3z+LyαFB	
ALL16	B+$P(k)$+WL+H_0+OHD+gBAO-9z+LyαFB	
DESI++	P15 + mock DESI BAO [49] + mock SN [50]	

Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

For LCDM; H0, LyFB and JLA measurements are in tension with the combined dataset, with tension values of T = 4.4, 3.5, 1.7.

The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: Examining the observational evidence for dynamical dark energy

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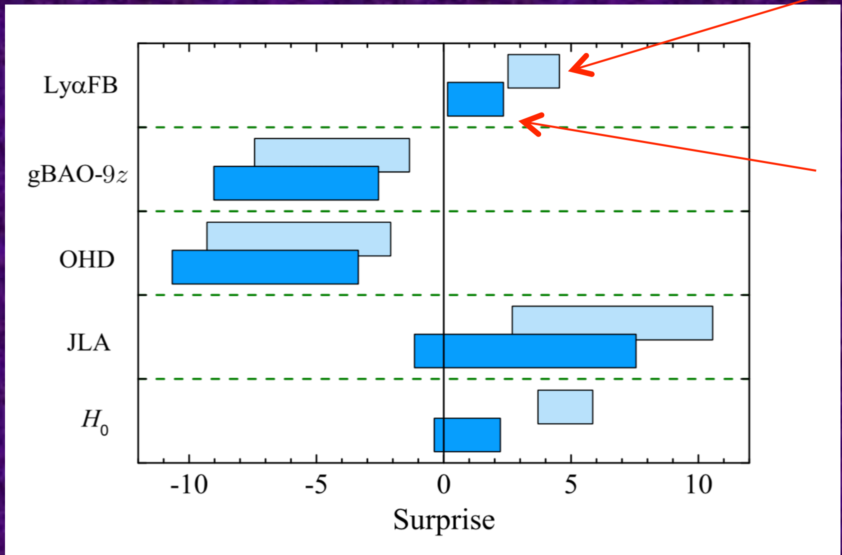
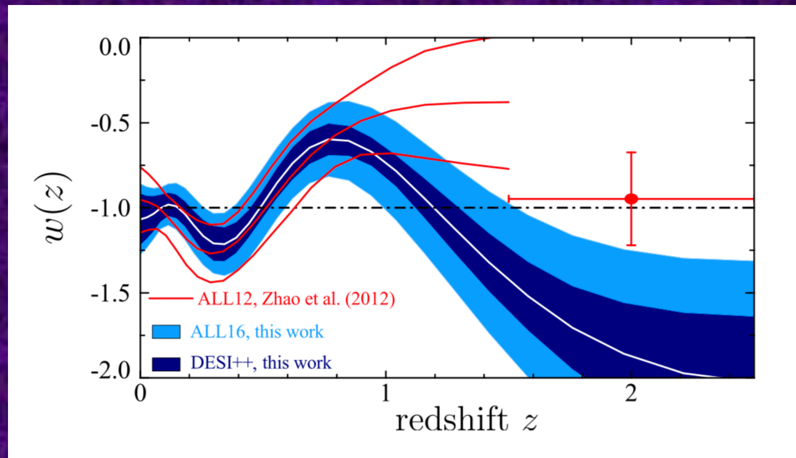
arXiv:1701.08165

$$T \equiv \frac{S}{\Sigma} = \frac{(\theta_1-\theta_2)^T \mathcal{C}_1^{-1}(\theta_1-\theta_2) - \mathbf{Tr}\left(\mathcal{C}_2\mathcal{C}_1^{-1}+\mathbb{I}\right)}{\sqrt{\mathbf{Tr}\left(\mathcal{C}_2\mathcal{C}_1^{-1}+\mathbb{I}\right)^2}},$$

LCDM

w(z)CDM





	P15	JLA	gBAO-9z	$P(k)$	WL	H_0	LyαFB	OHD
$\Delta\chi^2$	-0.7	-1.6	-2.8	$+1.1$	-0.1	-2.9	-3.7	-2.3

	ALL12	ALL16	DESI++
S/N	2.5σ	3.5σ	6.4σ
ΔAIC	-0.3	-4.3	-24.6
$\Delta\ln E$	-6.7 ± 0.3	-3.3 ± 0.3	11.3 ± 0.3

For LCDM; H0, LyFB and JLA measurements are in tension with the combined dataset, with tension values of T = 4.4, 3.5, 1.7.

Path to future:

Om3

A null diagnostic customized for reconstructing the properties of dark energy directly from BAO data

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

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

Observables

Shafieloo, Sahni, Starobinsky, PRD 2013

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

Characteristics of Om3

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

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

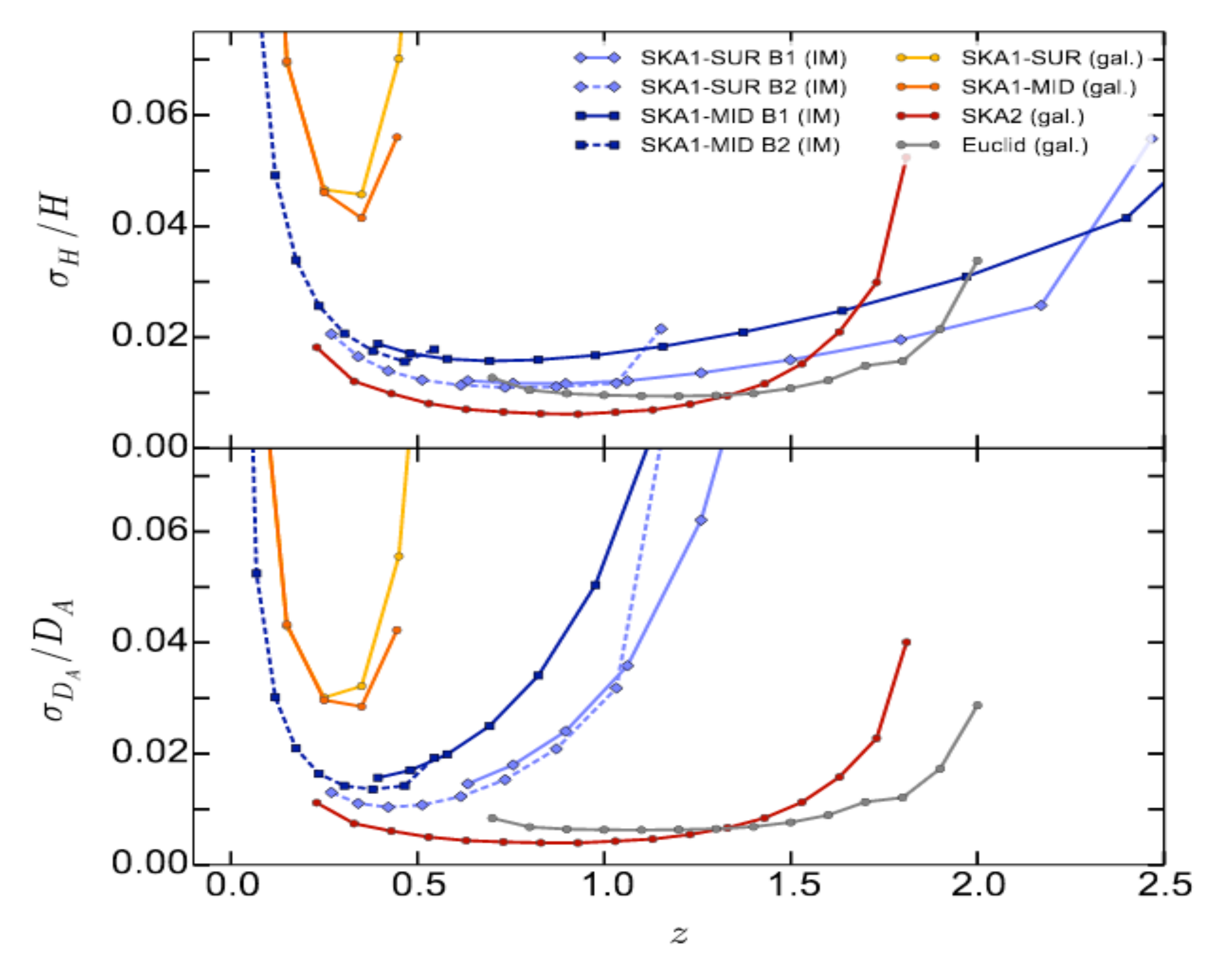
$$H(z_i; z_j) = \left(\frac{z_j}{z_i}\right)^2 \left[\frac{D(z_i)}{D(z_j)}\right]^2 \left[\frac{A(z_j)}{A(z_i)}\right]^3 = \frac{z_i}{z_j} \left[\frac{D(z_i)}{D(z_j)}\right]^2 \left[\frac{d(z_i)}{d(z_j)}\right]^3 ,$$

Om3 is independent of H0 and the early universe models and can be derived directly using BAO observables.

Shafieloo, Sahni, Starobinsky, PRD 2013

Future perspective

P. Bull et al,
1501.04088



- Om3 will show its power as it can be measured very precisely and used as a powerful litmus test of Lambda.

$$\sigma_{Om3} \approx 1.0 \times 10^{0} \left[WiggleZ \right]$$

$$\sigma_{Om3} \approx 2.0 \times 10^{-1} \left[DESI \right]$$

$$\sigma_{Om3} \approx 5.7 \times 10^{-1} \left[SKA1 - SUR(Gal) \right]$$

$$\sigma_{Om3} \approx 5.6 \times 10^{-1} \left[SKA1 - MID(Gal) \right]$$

$$\sigma_{Om3} \approx 4.0 \times 10^{-2} \left[SKA1 - MID(IM) \right]$$

$$\sigma_{Om3} \approx 2.5 \times 10^{-2} \left[SKA1 - SUR(IM) \right]$$

$$\sigma_{Om3} \approx 1.4 \times 10^{-2} \left[Euclid \right]$$

$$\sigma_{Om3} \approx 9.3 \times 10^{-3} \left[SKA2(Gal) \right]$$

Shafieloo, Sahni, Starobinsky, In Prep.

Conclusion

- The current standard model of cosmology seems to work fine but this does not mean all the other models are wrong. Data is not yet good enough to distinguish between various models.

- Using parametric methods and model fitting is tricky and we may miss features in the data. Non-parameteric methods of reconstruction can guide theorist to model special features.

- First target can be testing different aspects of the standard 'Vanilla' model. If it is not '*Lambda*' dark energy or power-law primordial spectrum then we can look further. It is possible to focus the power of the data for the purpose of the falsification. Next generation of astronomical/ cosmological observations, (DESI, Euclid, SKA, LSST, WFIRST etc) will make it clear about the status of the concordance model.

- ***Combination of different cosmological data hints towards some tension with LCDM model. If future data continues the current trend, we may have some exciting times ahead!***

Conclusion (Large Scales)

- We can (will) describe the constituents and pattern of the universe (soon). But still we do not understand it. Next challenge is to move from inventory to understanding, by the help of the new generation of experiments.