Lambda or Not Lambda

Arman Shafieloo

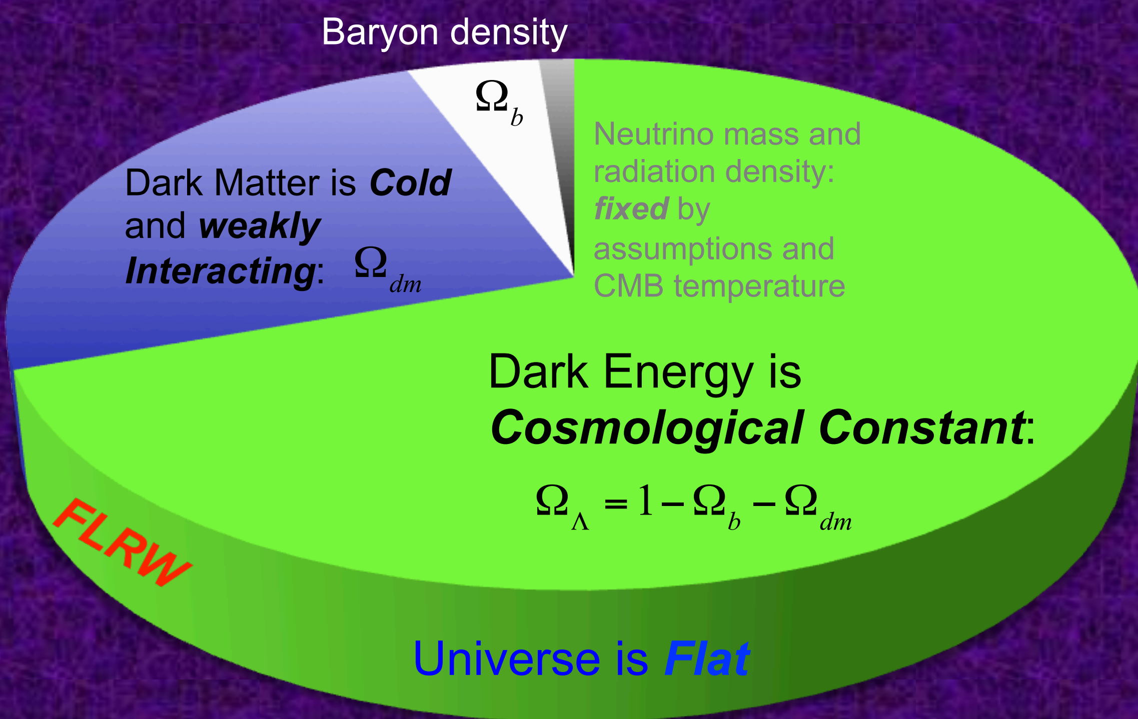
Korea Astronomy and Space Science Institute

2nd APCTP-TUS Workshop on Dark energy

Tokyo University of Science, August 2-5 2015

Standard Model of Cosmology

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

τ

Hubble Parameter and the Rate of Expansion

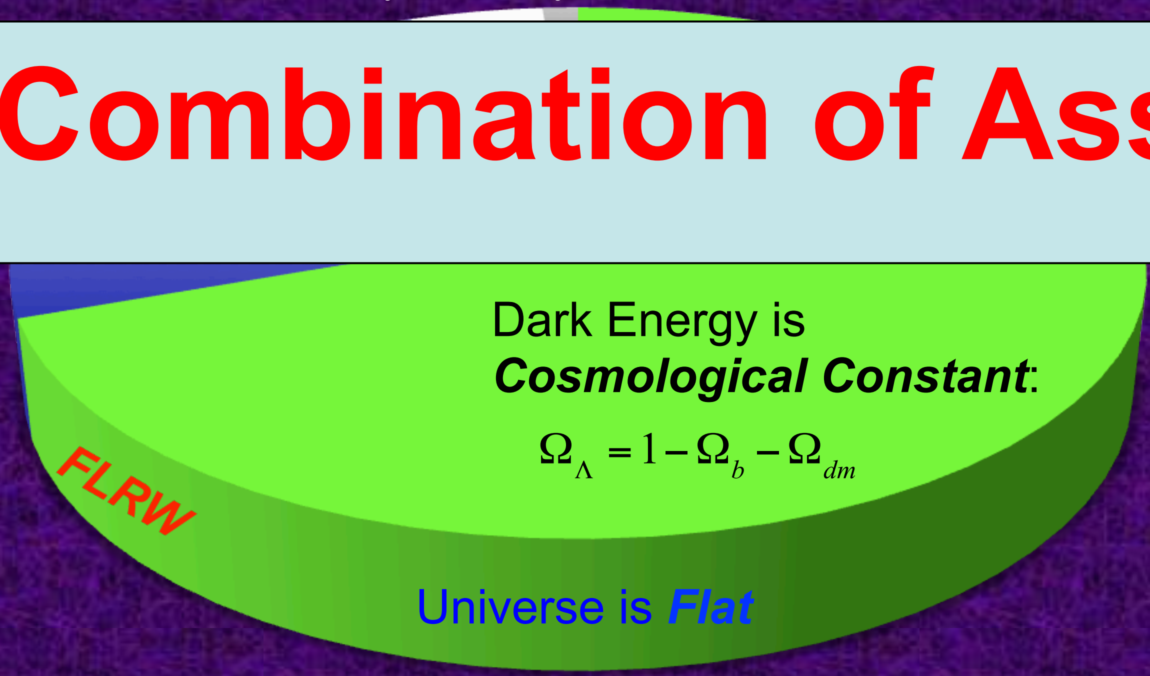
H_0

Standard Model of Cosmology

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

Baryon density

Combination of Assumptions



n_s, A_s

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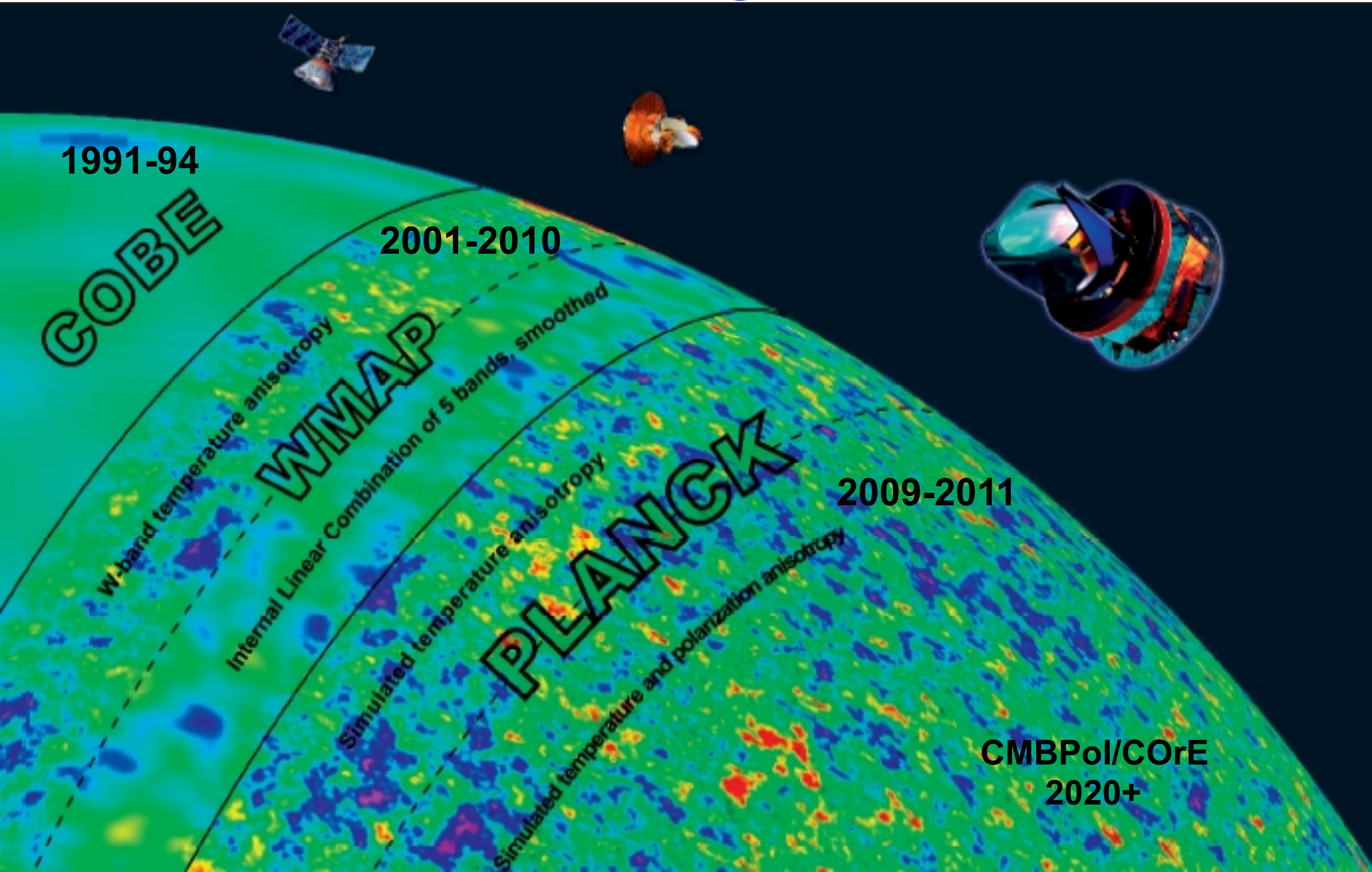
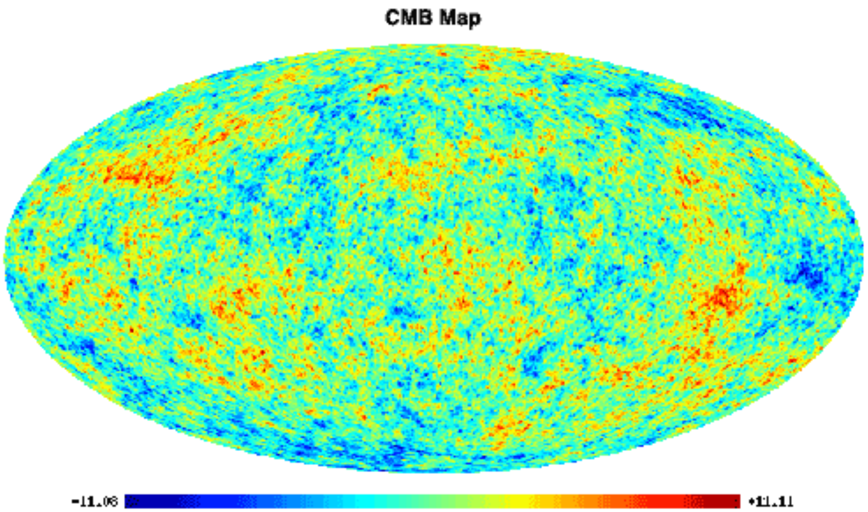
Why such assumptions?
Hints from Cosmological Observations



Statistics of CMB

CMB Anisotropy Sky map => Spherical Harmonic decomposition



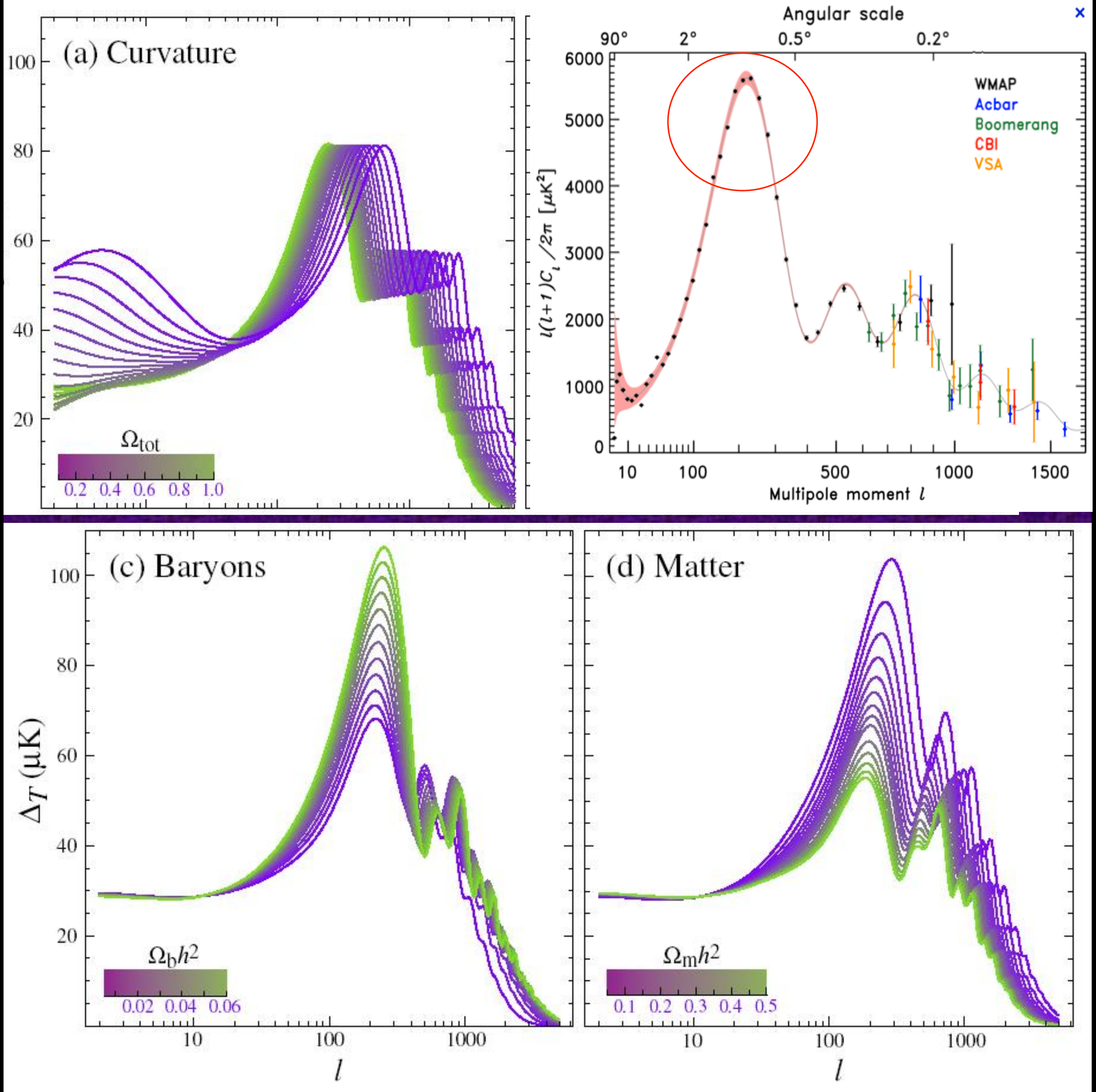
$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

$$\langle a_{lm}\, a^{*}_{l'm'} \rangle = C_l\ \delta_{ll'} \delta_{mm'}$$

Gaussian Random field => Completely specified by

angular power spectrum $l(l+1)C_l$:

Power in fluctuations on angular scales of $\sim \pi/l$



Sensitivity of the CMB acoustic temperature spectrum to four fundamental cosmological parameters.

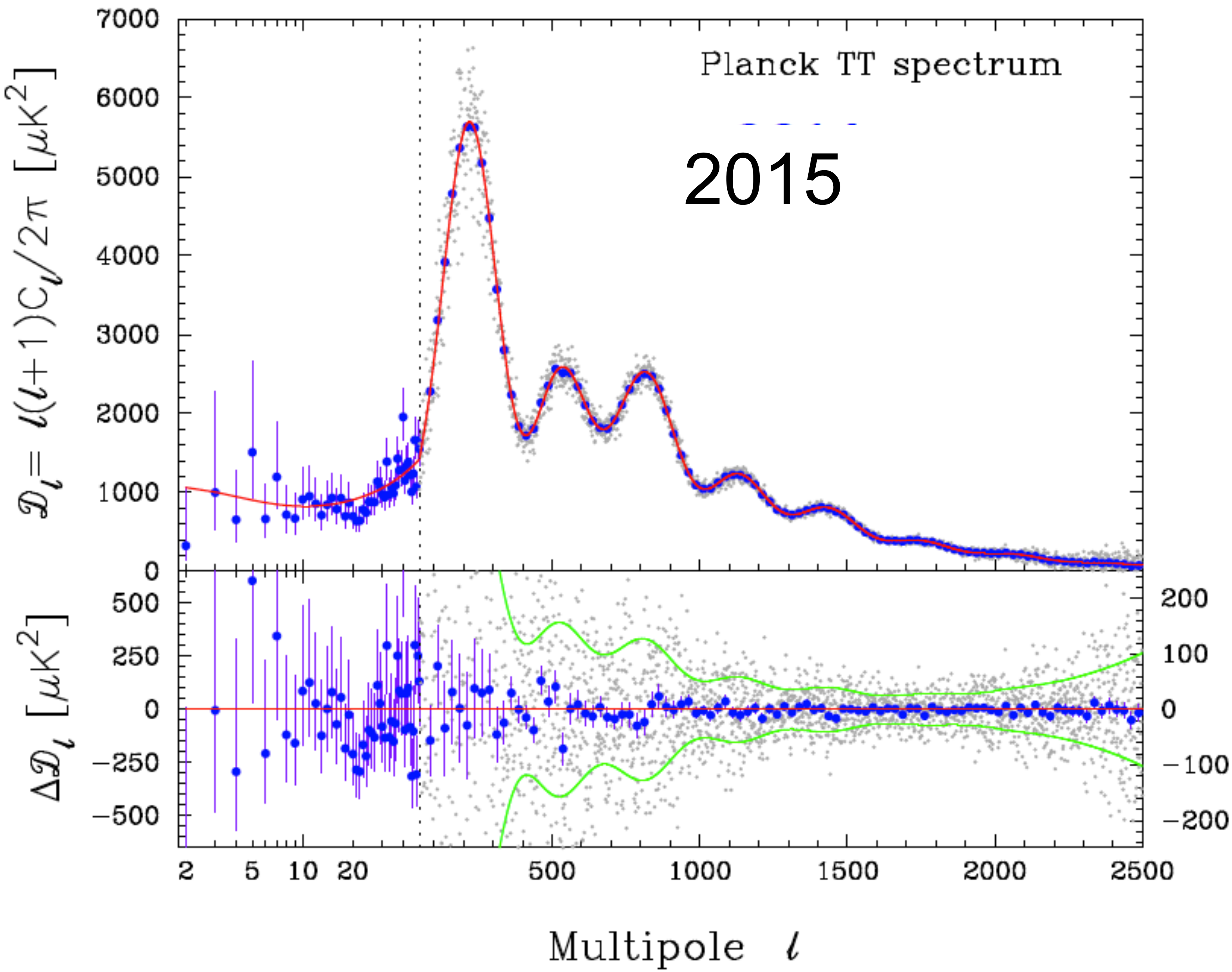
Total density

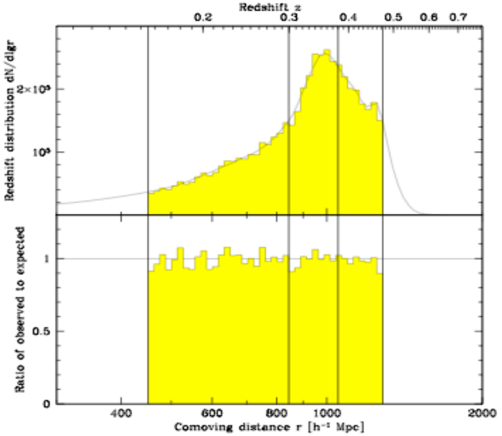
Dark Energy

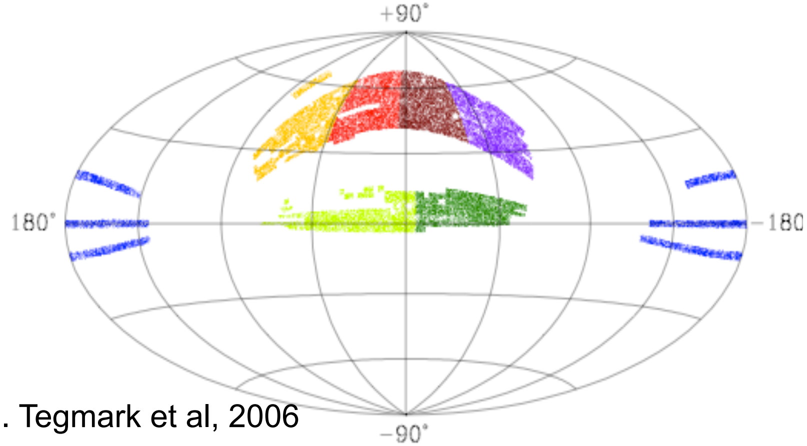
Baryon density and

Matter density.

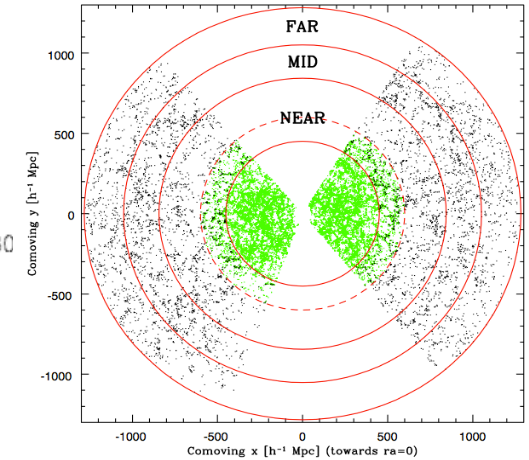
From Hu & Dodelson, 2002


Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
7000
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell$ [μK^2]
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500
Multipole ℓ



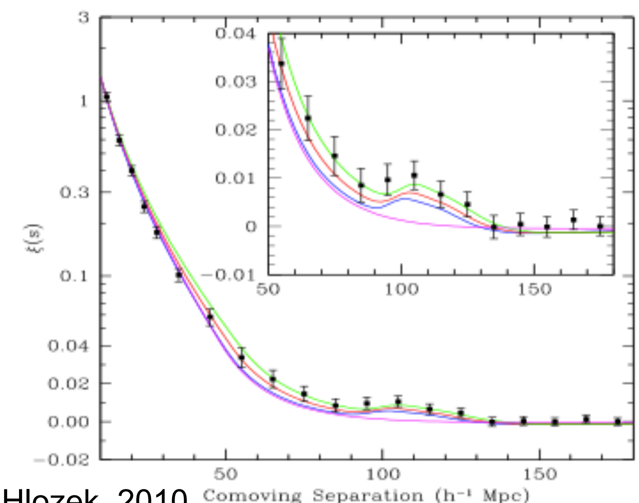


M. Tegmark et al, 2006



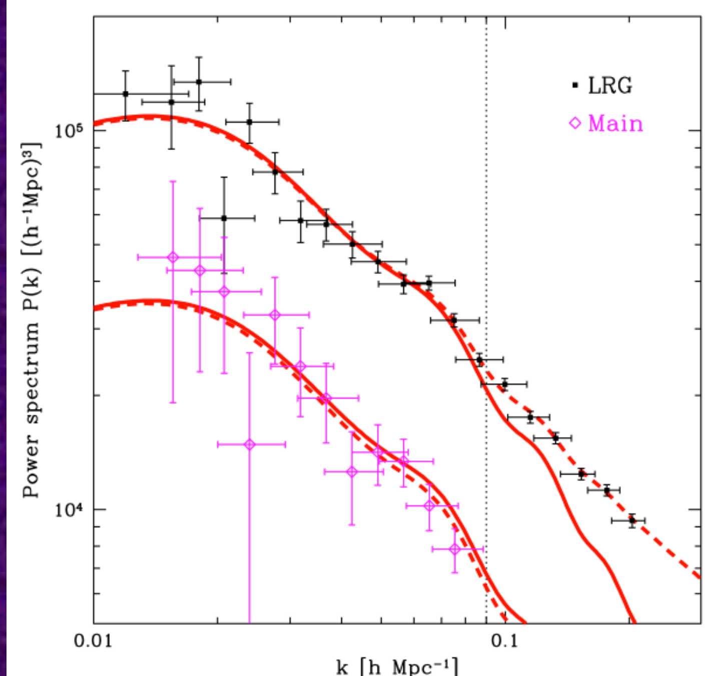
Large Scale Structure Data and Distribution of Galaxies

$$P(k) = \int_{-\infty}^{\infty} \xi(r) \exp(-ikr) r^2 dr \, .$$



Bassett & Hlozek, 2010

Fig. 1.1. The Baryon Acoustic Peak (BAP) in the correlation function – the BAP is visible in the clustering of the SDSS LRG galaxy sample, and is sensitive to the matter density (shown are models with $\Omega_m h^2 = 0.12$ **(top)**, 0.13 **(second)** and 0.14 **(third)**, all with $\Omega_b h^2 = 0.024$). The bottom line without a BAP is the correlation function in the pure CDM model, with $\Omega_b = 0$. From Eisenstein *et al.*, 2005 (52).



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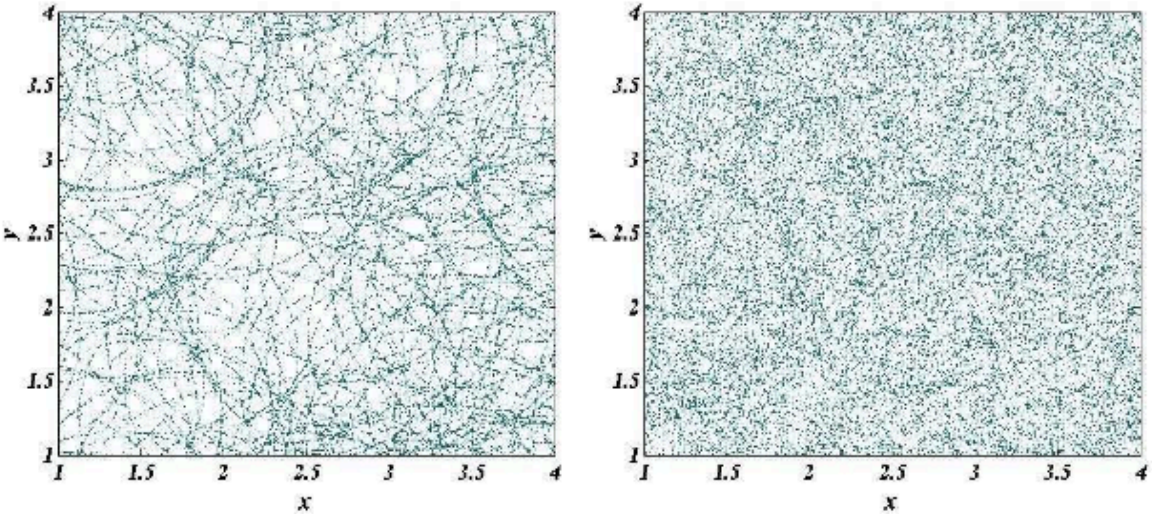
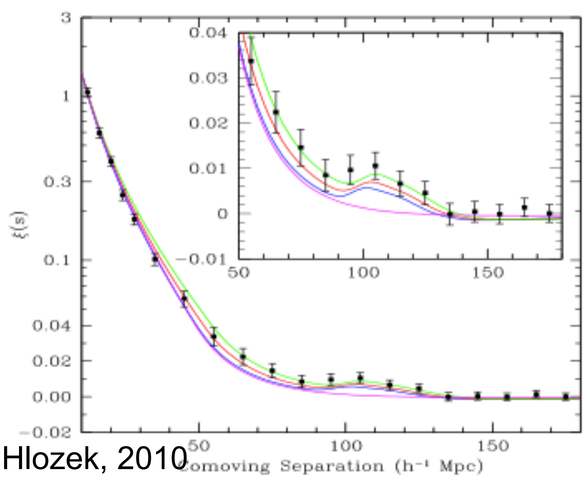


Fig. 1.5. Rings of power superposed. Schematic galaxy distribution formed by placing the galaxies on rings of the same characteristic radius L. The preferred radial scale is clearly visible in the left hand panel with many galaxies per ring. The right hand panel shows a more realistic scenario - with many rings and relatively few galaxies per ring, implying that the preferred scale can only be recovered statistically.

$$P(k) = \int_{-\infty}^{\infty} \xi(r) \exp(-ikr) r^2 dr \, .$$



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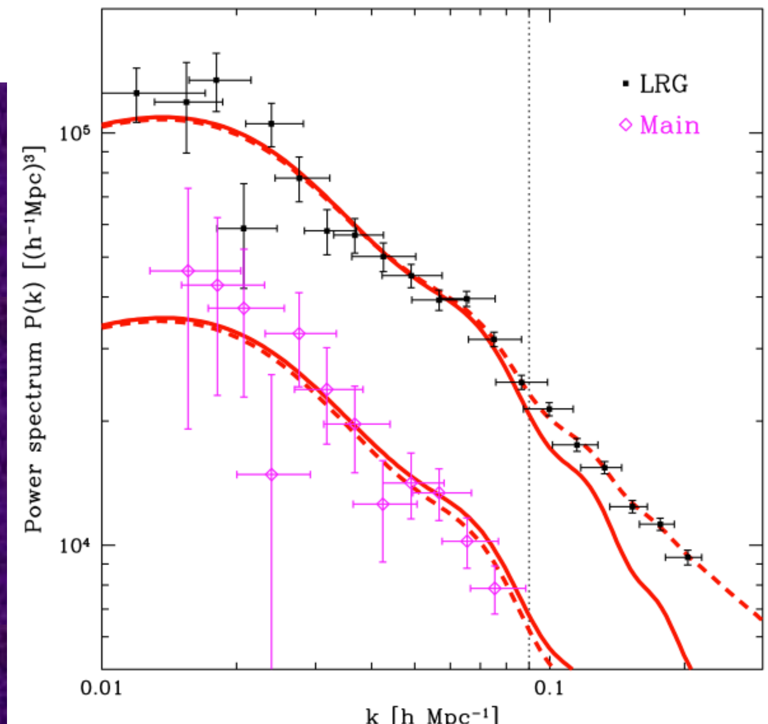
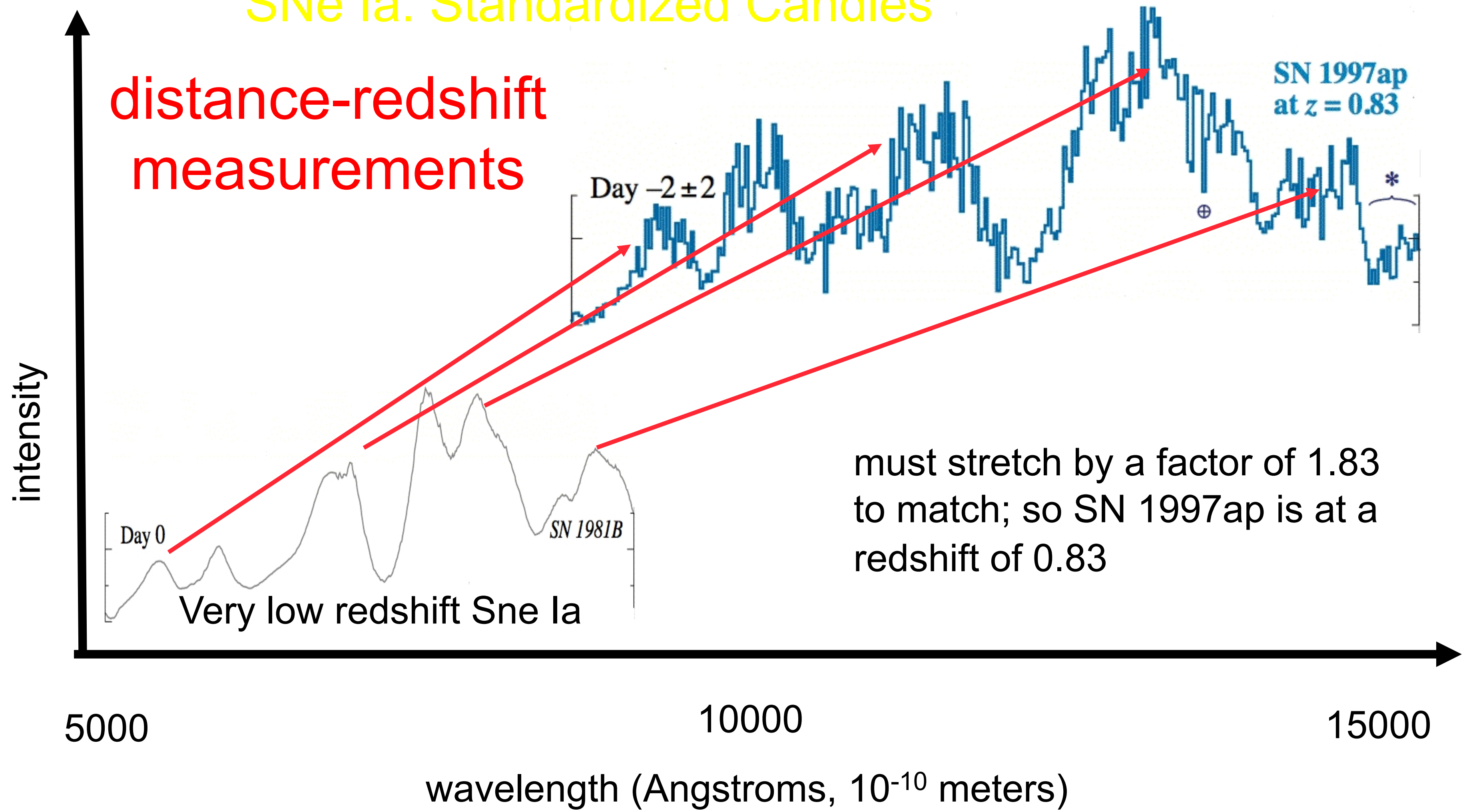


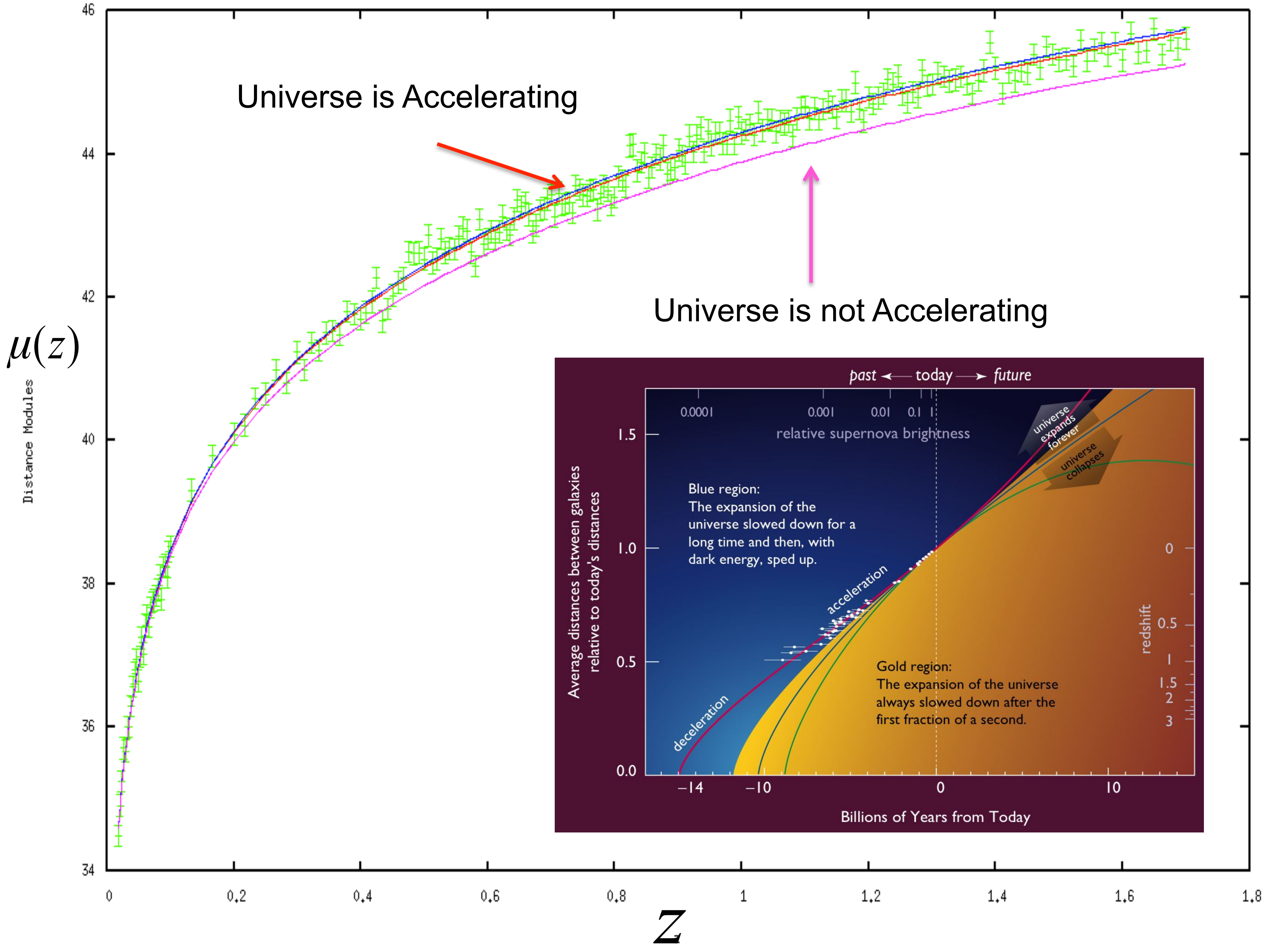
Measuring Distances in Astronomy

SNe Ia: Standardized Candles

distance-redshift measurements



must stretch by a factor of 1.83 to match; so SN 1997ap is at a redshift of 0.83



Universe is Accelerating
Universe is not Accelerating
μ(z)
Distance Modules
Z
46
44
42
40
38
36
34
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
past ← today → future
0.0001
0.001
0.01
0.1
1
relative supernova brightness
universe expands forever
universe collapses
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.
acceleration
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Gold region:
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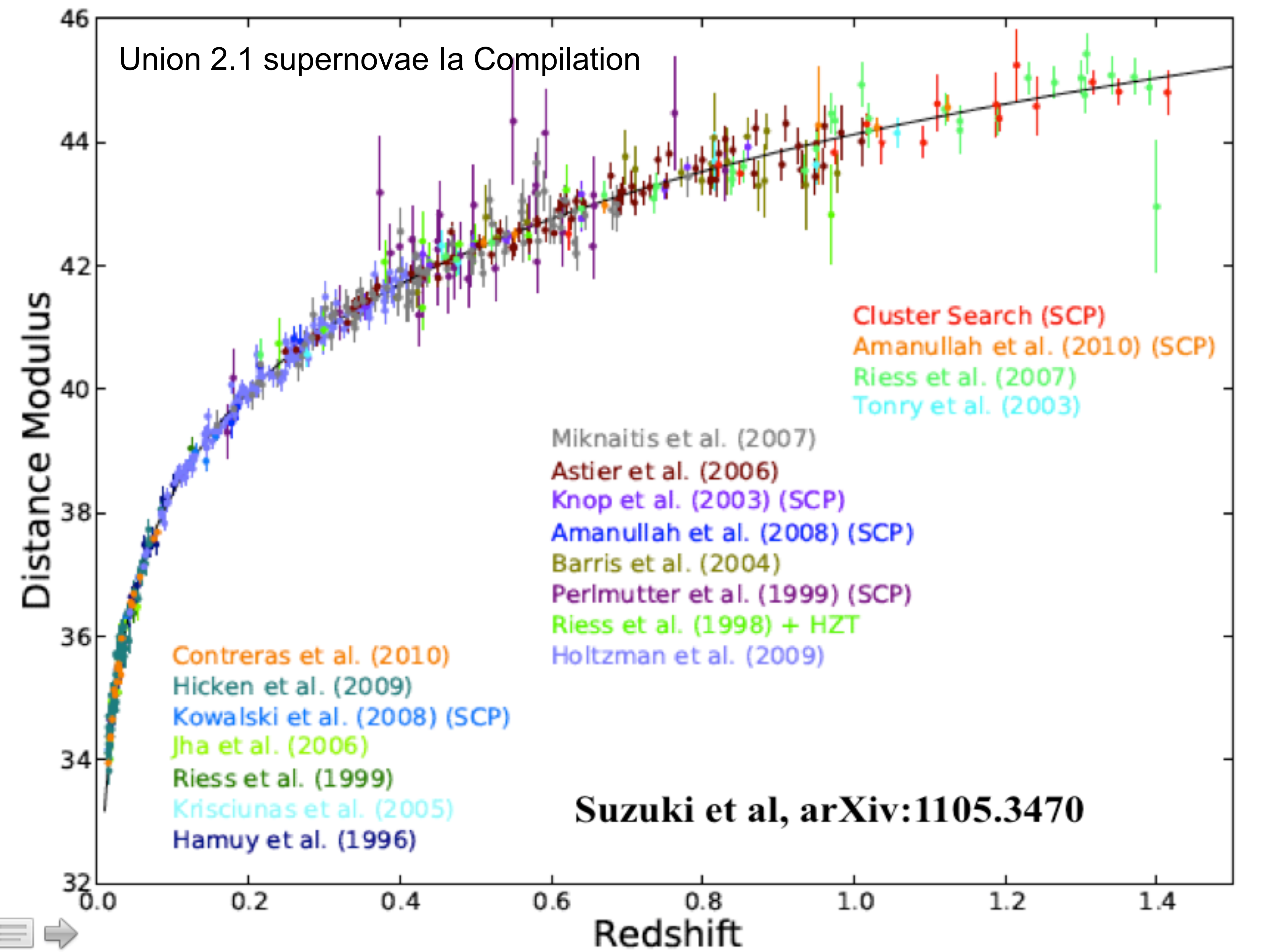
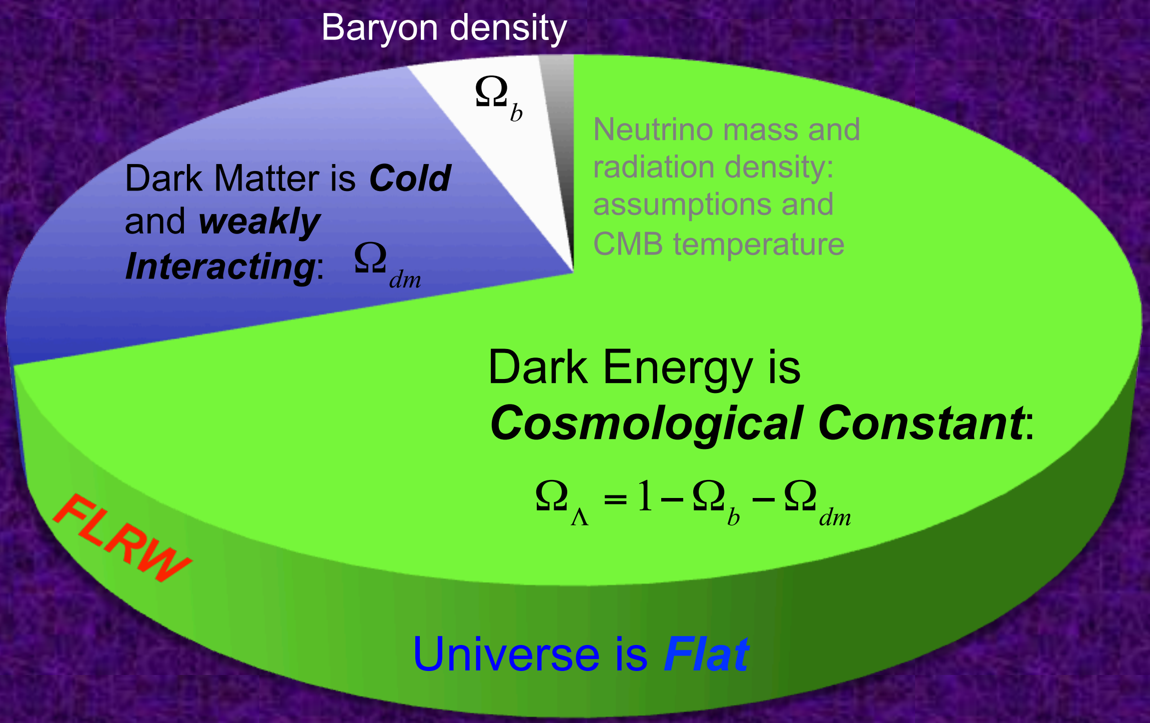
Average distances between galaxies relative to today's distances
1.5
1.0
0.5
0.0
−14
−10
0
10
Billions of Years from Today
redshift
0
0.5
1
1.5
2
3


Union 2.1 supernovae Ia Compilation
Distance Modulus
Redshift
46
44
42
40
38
36
34
32
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)
Suzuki et al, arXiv:1105.3470

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)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

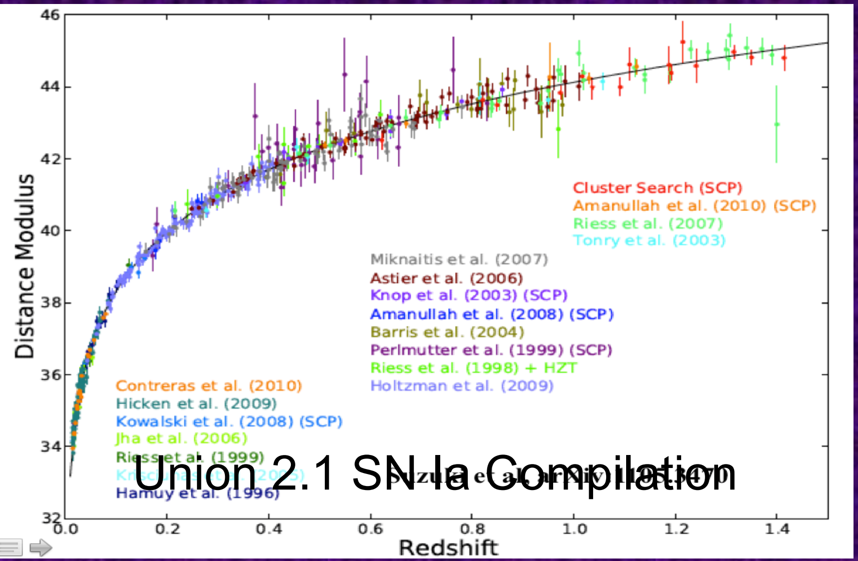
Era of Accelerating Universe

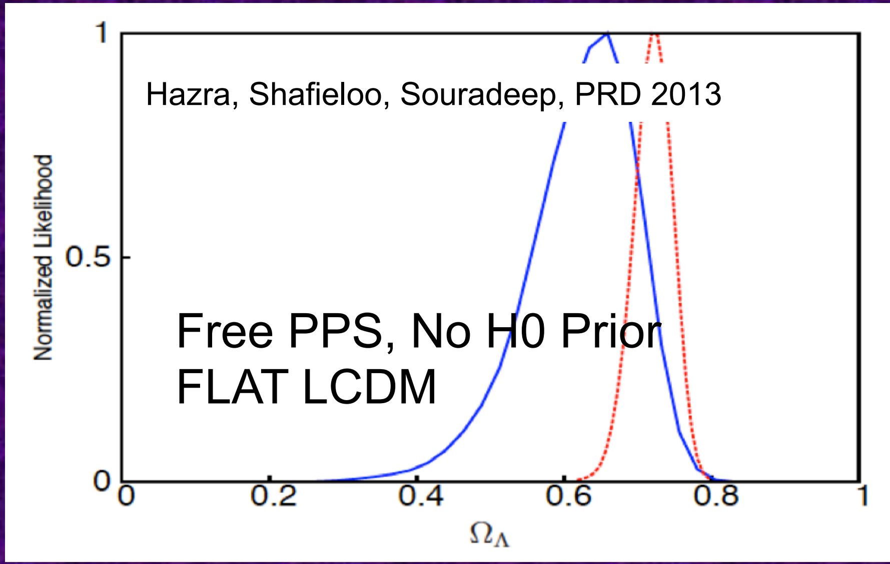
- Mid 90’s: Indirect evidences were seen in the distribution of the galaxies where SCDM could not explain the excess of power at large scales.

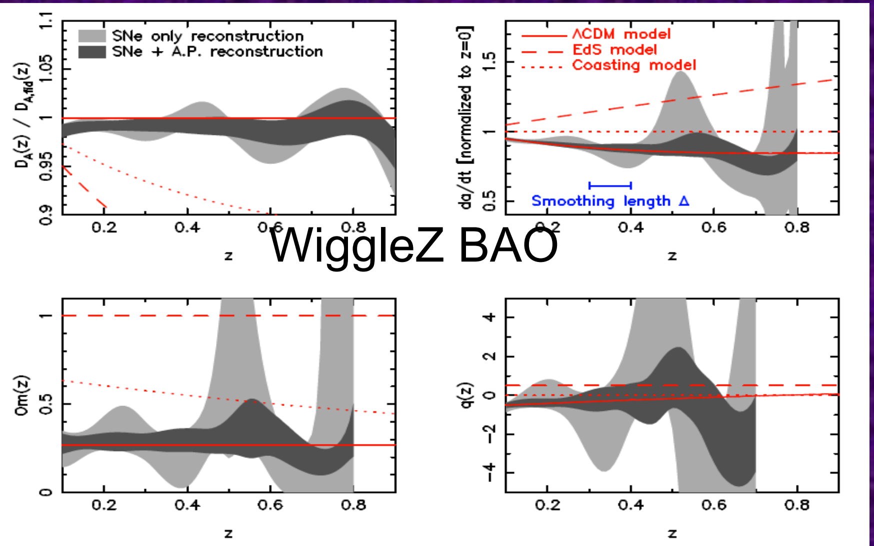
- 1998: Direct evidence came by Supernovae Type Ia Observations. *Going to higher redshifts, supernovae are fainter than expected. One can explain this only (?!=Nobel Prize) by considering an accelerating universe.*

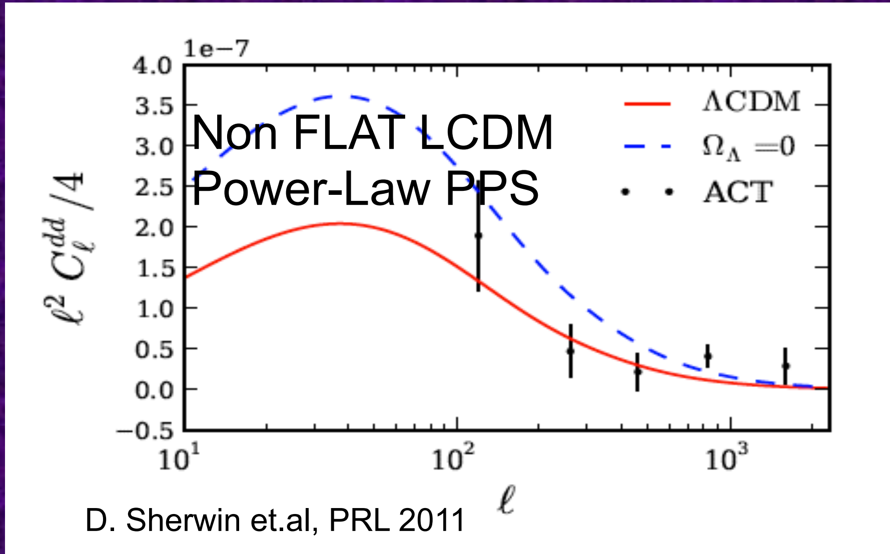
Accelerating Universe, Now-2015

Or better to say, ruling out zero-Lambda Universe

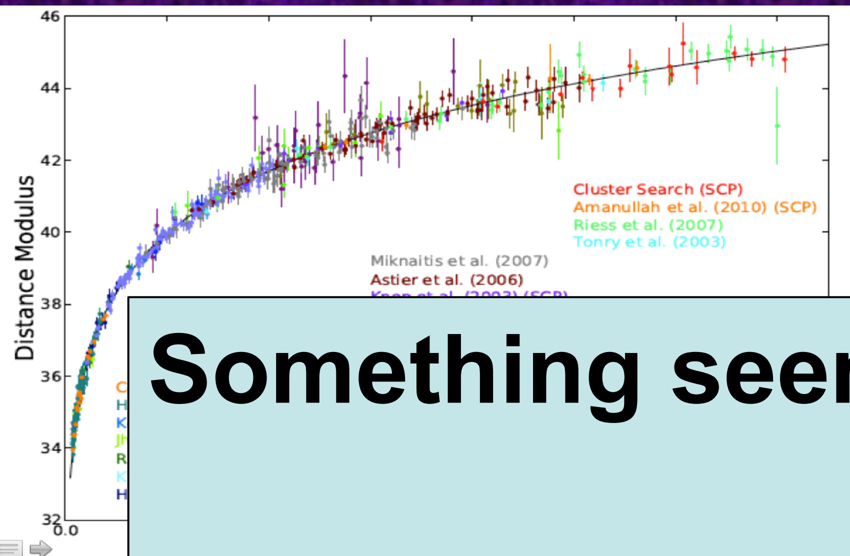


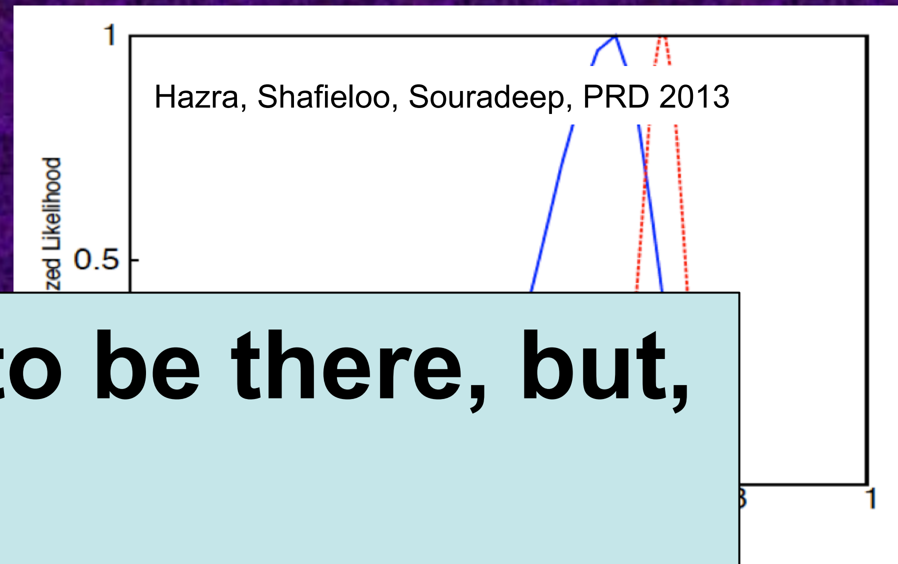






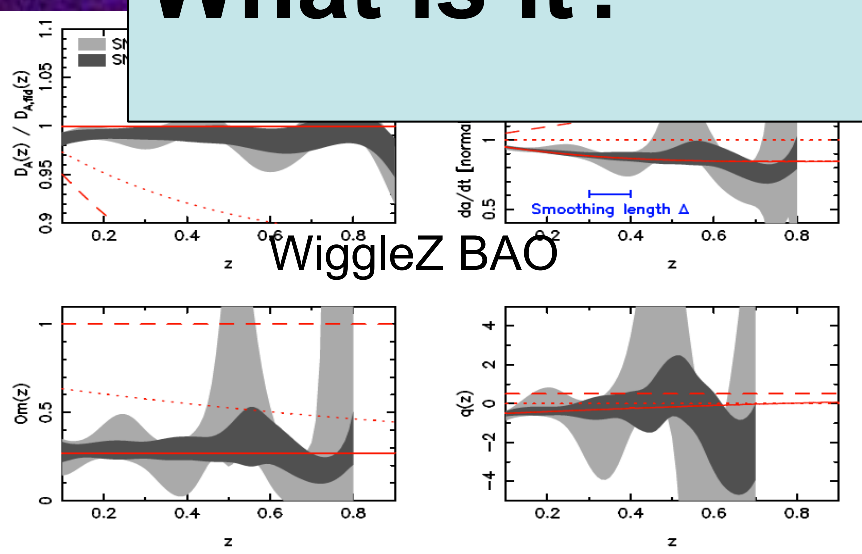
Accelerating Universe, Now

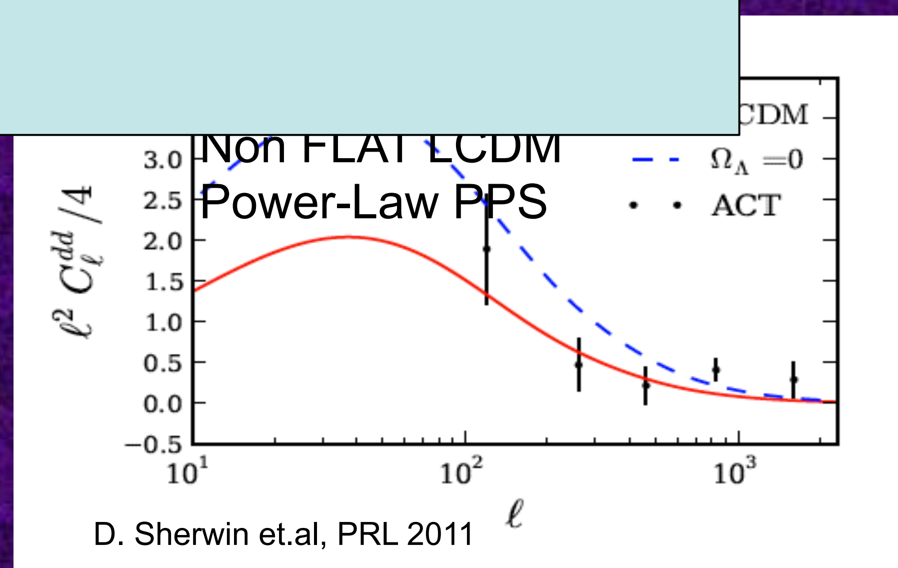




Something seems to be there, but,

What is it?

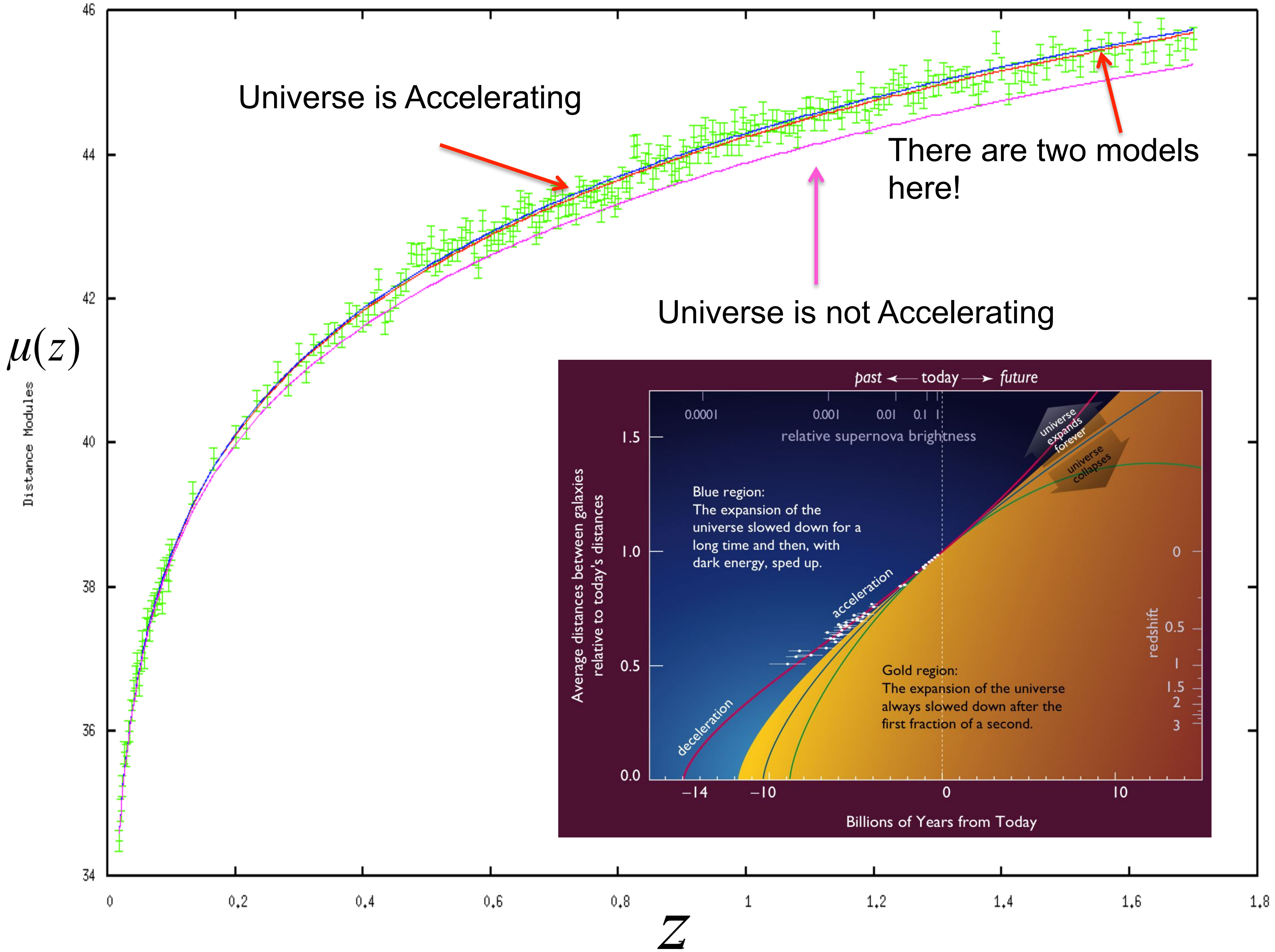




Dark Energy Models

- 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?!



Universe is Accelerating
There are two models here!
Universe is not Accelerating
μ(z)
Distance Modules
Z
46
44
42
40
38
36
34
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
past ← today → future
relative supernova brightness
0.0001
0.001
0.01
0.1
1
universe expands forever
universe collapses
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.
acceleration
deceleration
Gold region:
The expansion of the universe always slowed down after the first fraction of a second.
Average distances between galaxies relative to today's distances
redshift
Billions of Years from Today
−14
−10
0
10
0.0
0.5
1.0
1.5
3
2
1.5
1
0.5

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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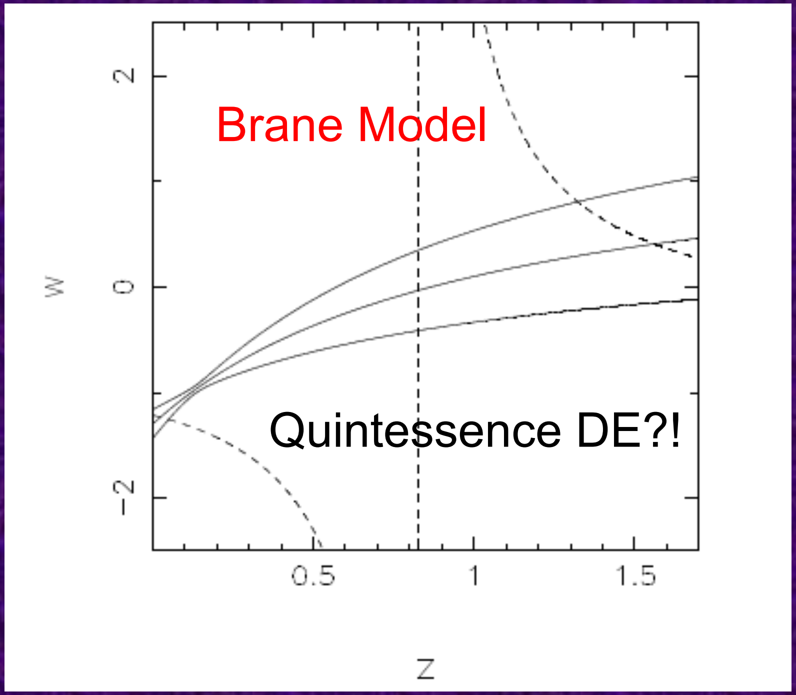
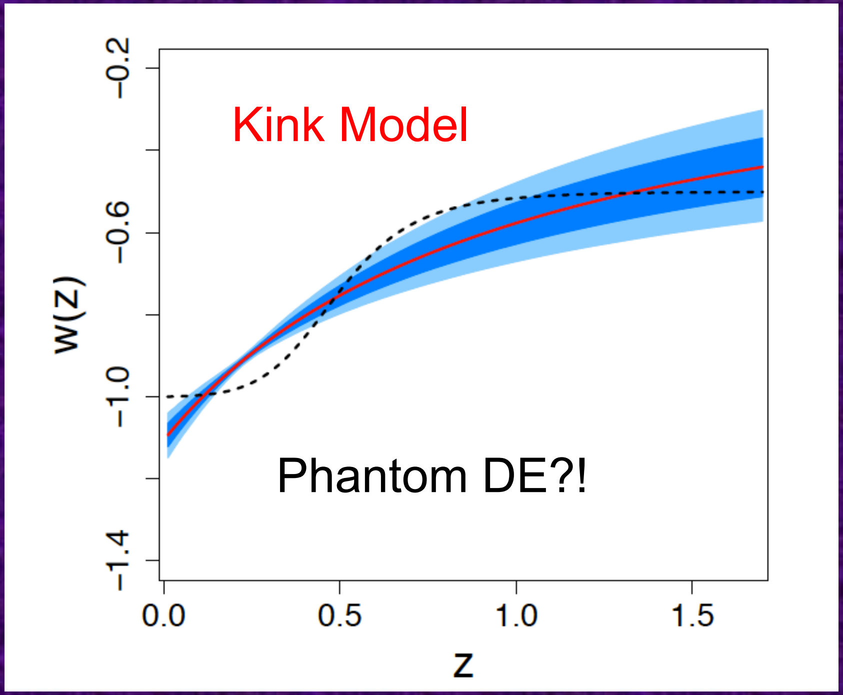
Problems of Dark Energy Parameterizations (model fitting)





Shafieloo, Alam, Sahni & Starobinsky, MNRAS 2006

Holsclaw et al, PRD 2011

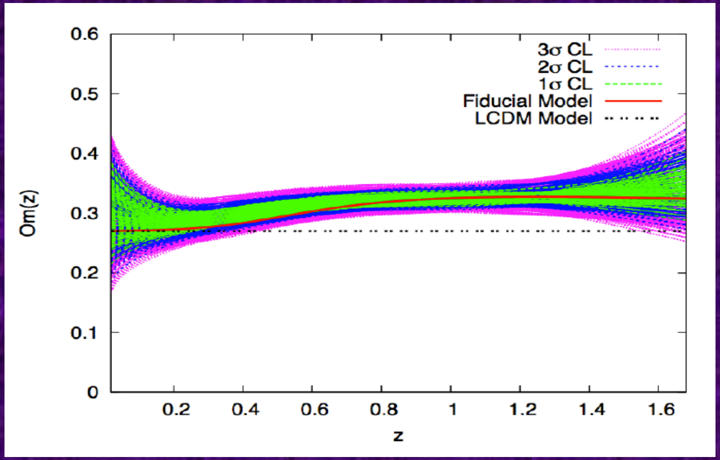
$$w(z) = w_0 - w_a \frac{z}{1+z}.$$

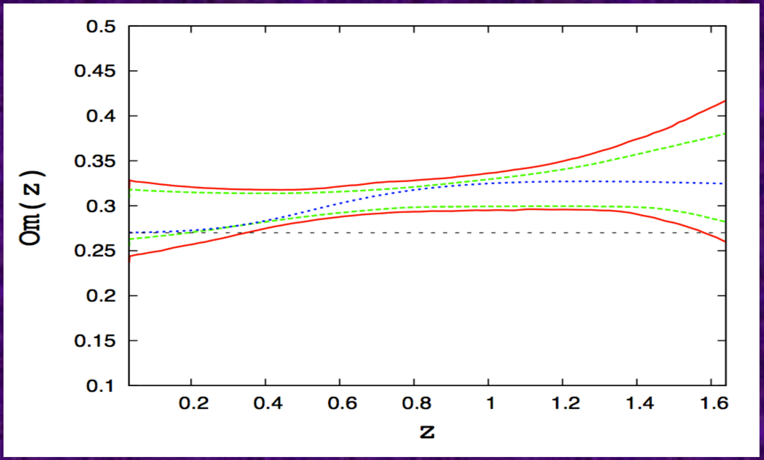
Chevallier-Polarski-Linder ansatz (CPL).

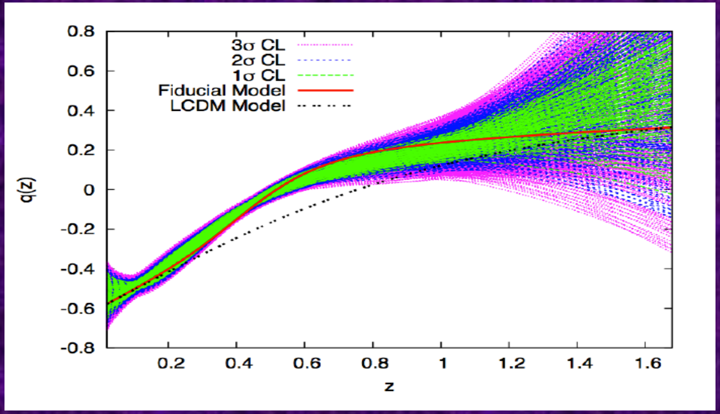
Model independent reconstruction of the expansion history

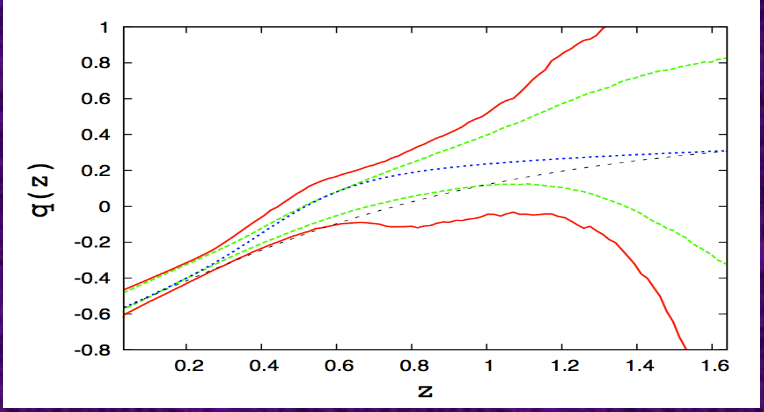
Crossing Statistic + Smoothing

Gaussian Processes









Shafieloo, JCAP (b) 2012

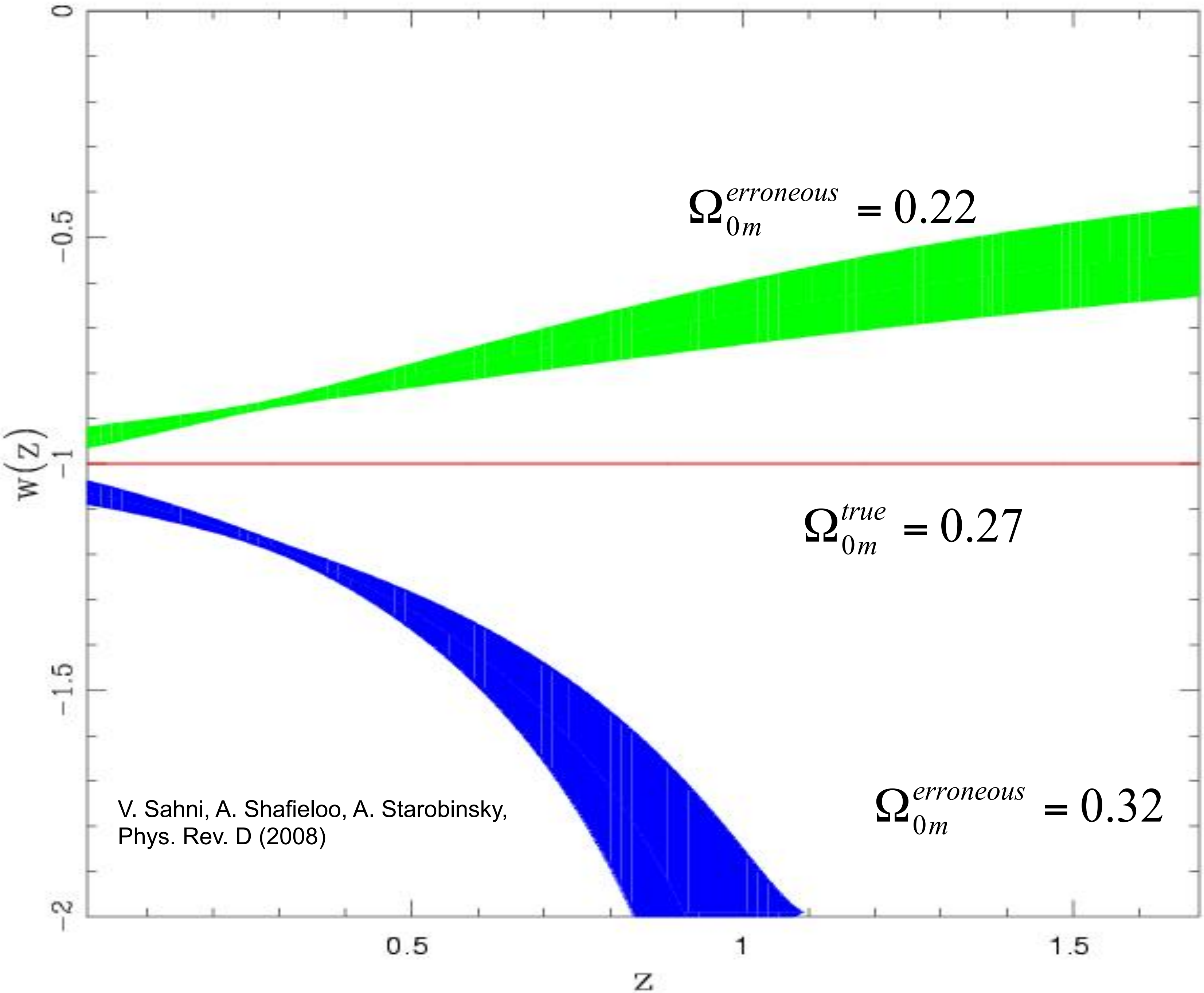
Shafieloo, Kim & Linder, PRD 2012

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).

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

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


$\Omega_{0m}^{erroneous} = 0.22$
$\Omega_{0m}^{true} = 0.27$
$\Omega_{0m}^{erroneous} = 0.32$
V. Sahni, A. Shafieloo, A. Starobinsky,
Phys. Rev. D (2008)
w(z)
z
0
−0.5
−1
−1.5
−2
0.5
1
1.5

Full theoretical picture:

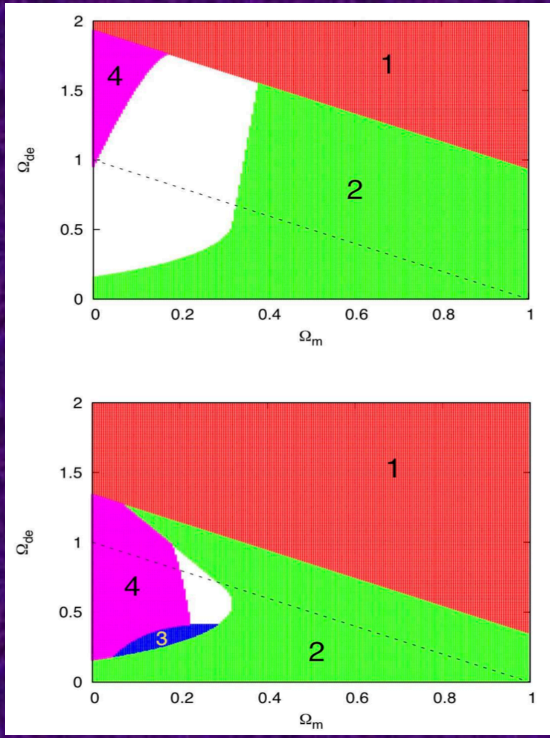
Cosmographic Degeneracy

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

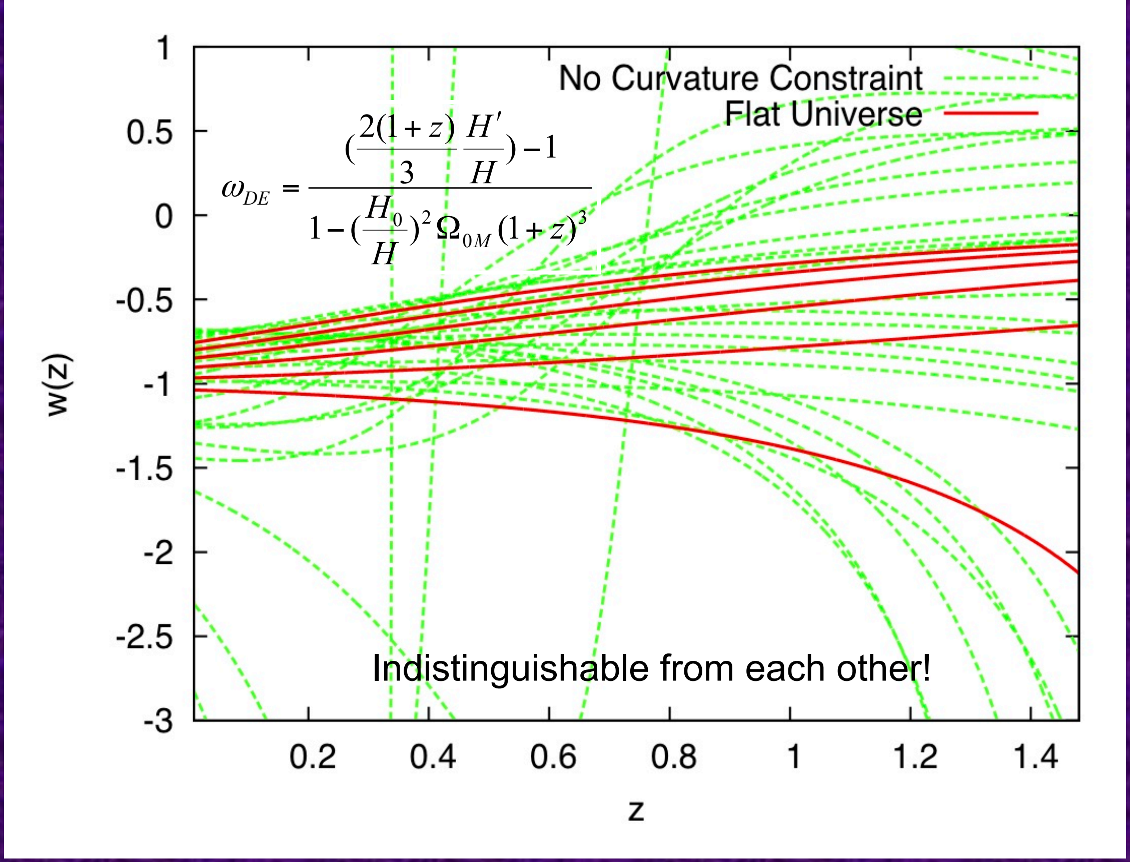
$$\begin{aligned} h(z)^2 &\equiv [H(z)/H_0]^2 \equiv (\dot{a}/a)^2 \\ &= \Omega_m(1+z)^3 + (1-\Omega_m-\Omega_{de})(1+z)^2 \\ &\quad + \Omega_{de} \exp\left[3\int_0^z \frac{dz'}{1+z'}[1+w(z')]\right], \end{aligned}$$

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.

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

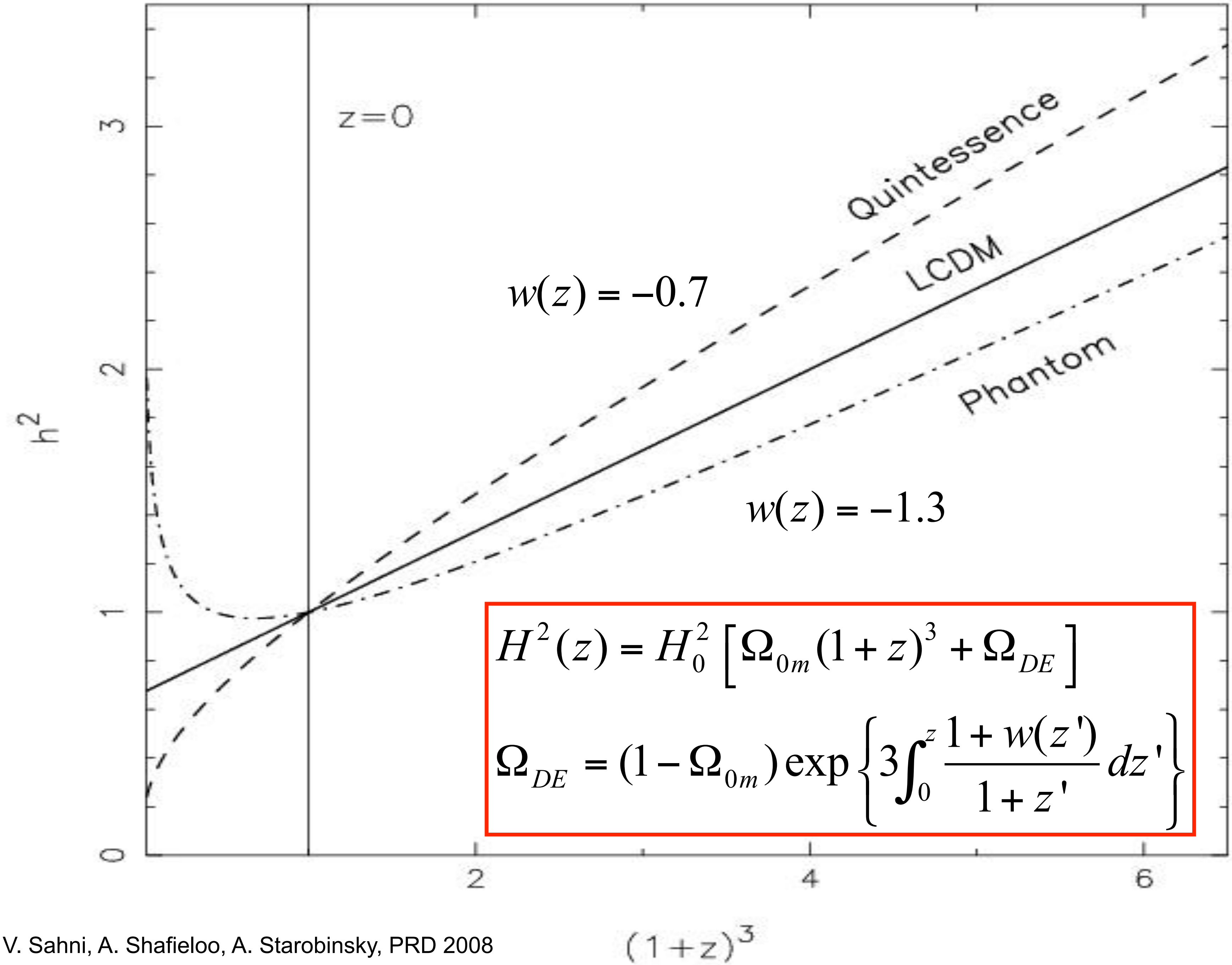
But, How?

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



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

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

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

Falsification: Null Test of Lambda

Om diagnostic

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

We Only Need h(z)

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

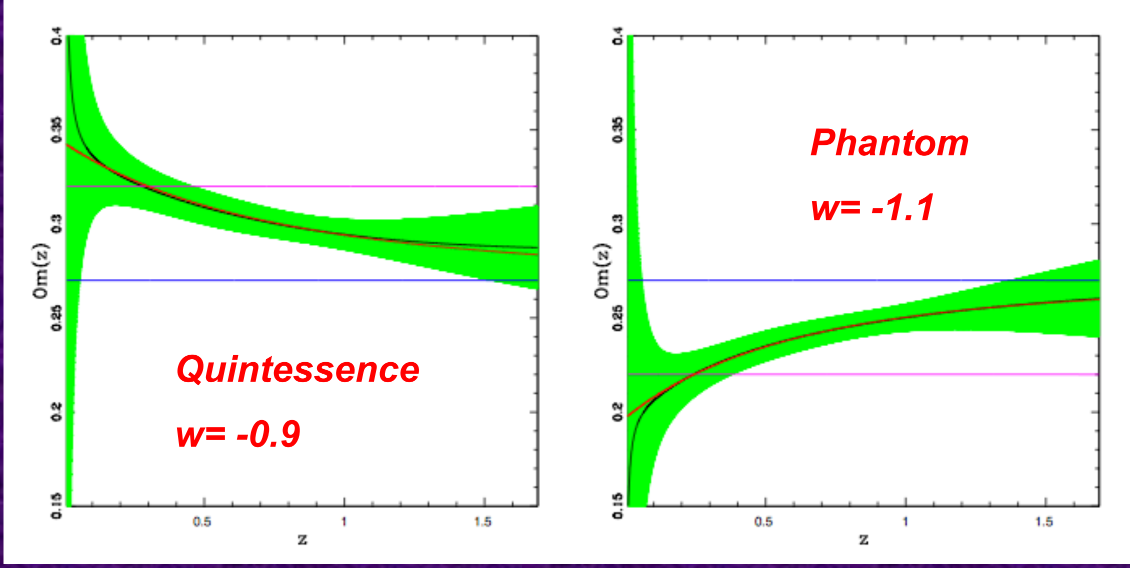
Om(z) is constant only for FLAT LCDM model

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

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

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

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



Deviations from ΛCDM and GR 13

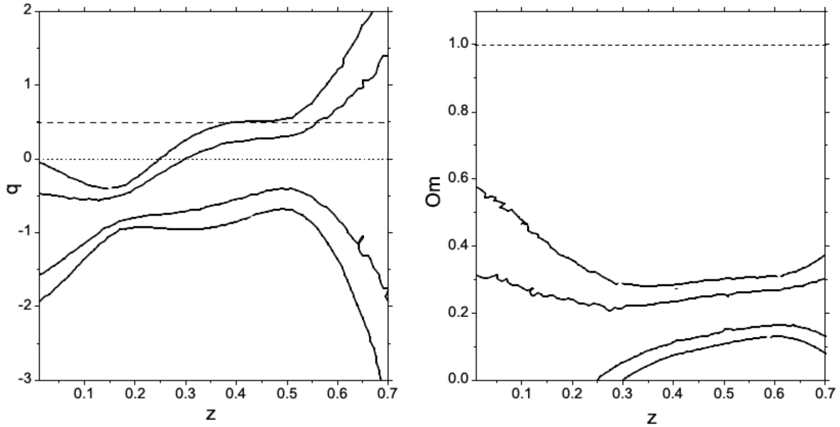


Figure 12. Confidence levels (1σ and 2σ) for the deceleration parameter as a function of redshift and Om(z) reconstructed from the compilation of geometric measurements in tables 2 and 3. H_0 is marginalised over with an HST prior. The dotted line in the left panel demarcates accelerating expansion (below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

Om diagnostic is very well established

SDSS III / BOSS collaboration
L. Samushia et al, MNRAS 2013

10 *Blake et al.*

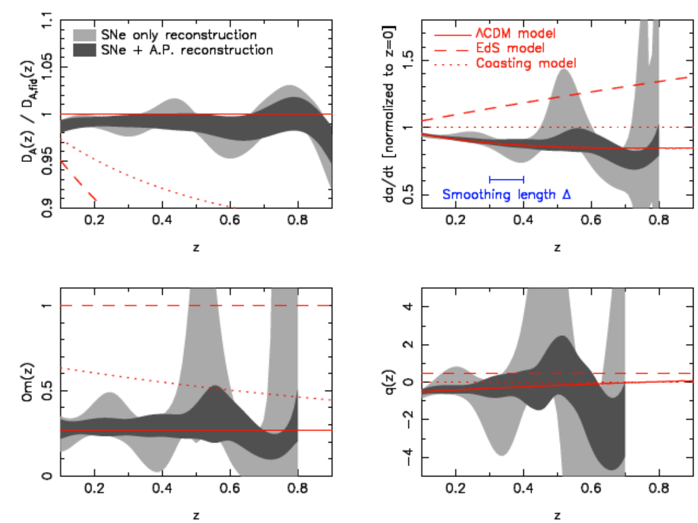


Figure 6. This Figure shows our non-parametric reconstruction of the cosmic expansion history using Alcock-Paczynski and supernovae data. The four panels of this figure display our reconstructions of the distance-redshift relation $D_A(z)$, the expansion rate $\dot{a}/H_0$, the Om(z) statistic and the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

WiggleZ collaboration
C. Blake et al, MNRAS 2011
(Alcock-Paczynski measurement)

Om3

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

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

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

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

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

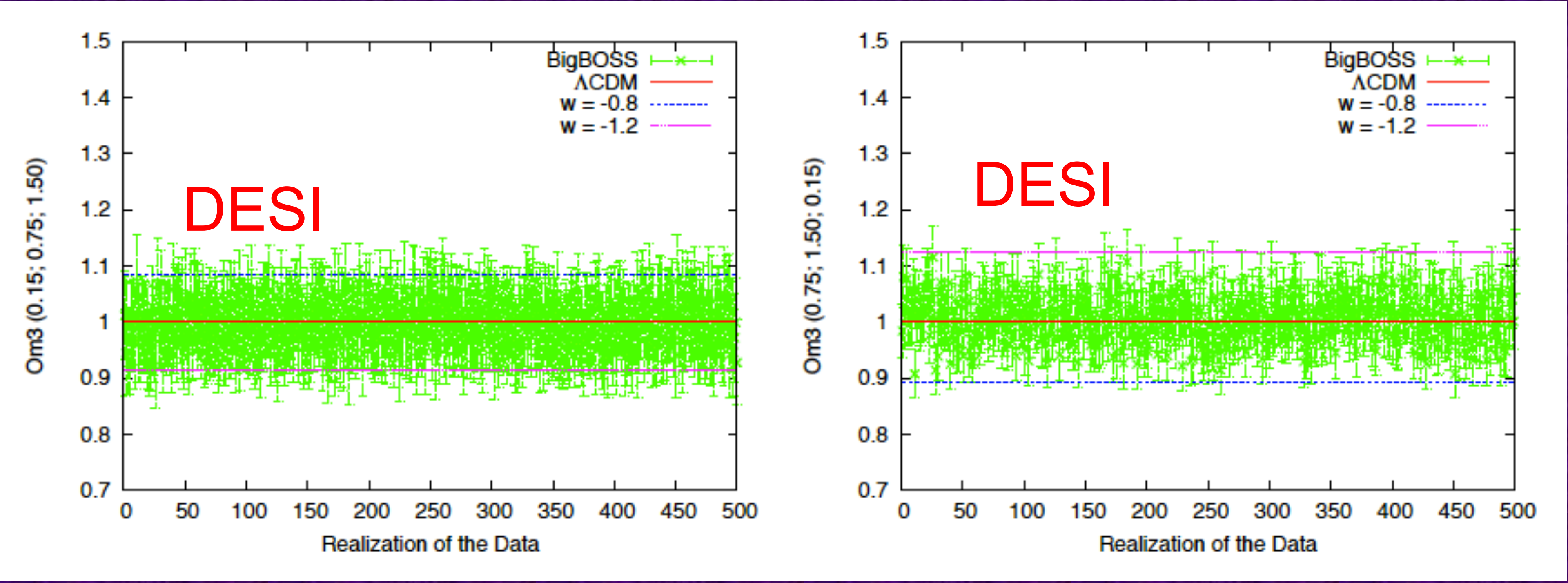
$$H(z_i; z_j) = \left(\frac{z_j}{z_i}\right)^2 \left[\frac{D(z_i)}{D(z_j)}\right]^2 \left[\frac{A(z_j)}{A(z_i)}\right]^3 = \frac{z_i}{z_j} \left[\frac{D(z_i)}{D(z_j)}\right]^2 \left[\frac{d(z_i)}{d(z_j)}\right]^3 ,$$

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

Shafieloo, Sahni, Starobinsky, PRD 2013

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

Omh2

A very recent result.

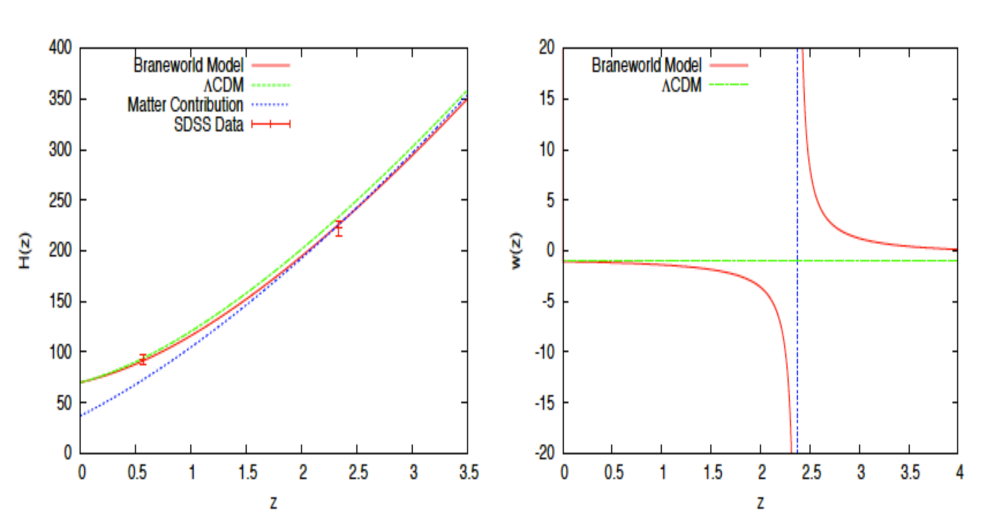
Important discovery if no systematic in the SDSS Quasar BAO data

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

$$Omh^2(z_1; z_2) = 0.124 \pm 0.045$$
$$Omh^2(z_1; z_3) = 0.122 \pm 0.010$$
$$Omh^2(z_2; z_3) = 0.122 \pm 0.012$$

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

Testing deviations from an assumed model
(without comparing different models)

Gaussian Processes:

Modeling of the data around a mean function searching for likely features by looking at the the likelihood space of the hyperparameters.

Bayesian Interpretation of Crossing Statistic:

Comparing a model with its own possible variations.

REACT:

Risk Estimation and Adaptation after Coordinate Transformation

Gaussian Process

- ➔Efficient in statistical modeling of stochastic variables
- ➔Derivatives of Gaussian Processes are Gaussian Processes
- ➔Provides us with all covariance matrices

Shafieloo, Kim & Linder, PRD 2012
Shafieloo, Kim & Linder, PRD 2013

Data

Mean Function

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f} \\ \mathbf{f}' \\ \mathbf{f}'' \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mathbf{m}(\mathbf{Z}) \\ \mathbf{m}(\mathbf{Z_1}) \\ \mathbf{m}'(\mathbf{Z_1}) \\ \mathbf{m}''(\mathbf{Z_1}) \end{bmatrix}, \begin{bmatrix} \Sigma_{00}(Z,Z) & \Sigma_{00}(Z,Z_1) & \Sigma_{01}(Z,Z_1) & \Sigma_{02}(Z,Z_1) \\ \Sigma_{00}(Z_1,Z) & \Sigma_{00}(Z_1,Z_1) & \Sigma_{01}(Z_1,Z_1) & \Sigma_{02}(Z_1,Z_1) \\ \Sigma_{10}(Z_1,Z) & \Sigma_{10}(Z_1,Z_1) & \Sigma_{11}(Z_1,Z_1) & \Sigma_{12}(Z_1,Z_1) \\ \Sigma_{20}(Z_1,Z) & \Sigma_{20}(Z_1,Z_1) & \Sigma_{21}(Z_1,Z_1) & \Sigma_{22}(Z_1,Z_1) \end{bmatrix} \right),$$

$$\Sigma_{\alpha\beta} = \frac{d^{(\alpha+\beta)}K}{dz_i^\alpha dz_j^\beta},$$

$$\begin{bmatrix} \overline{\mathbf{f}} \\ \overline{\mathbf{f}'} \\ \overline{\mathbf{f}''} \end{bmatrix} = \begin{bmatrix} \mathbf{m}(\mathbf{Z_1}) \\ \mathbf{m}'(\mathbf{Z_1}) \\ \mathbf{m}''(\mathbf{Z_1}) \end{bmatrix} + \begin{bmatrix} \Sigma_{00}(Z_1,Z) \\ \Sigma_{10}(Z_1,Z) \\ \Sigma_{20}(Z_1,Z) \end{bmatrix} \Sigma_{00}^{-1}(Z,Z)\,\mathbf{y}$$

Kernel ➔

$$k(z,z') = \sigma_f^2 \exp\left(-\frac{|z-z'|^2}{2l^2}\right),$$

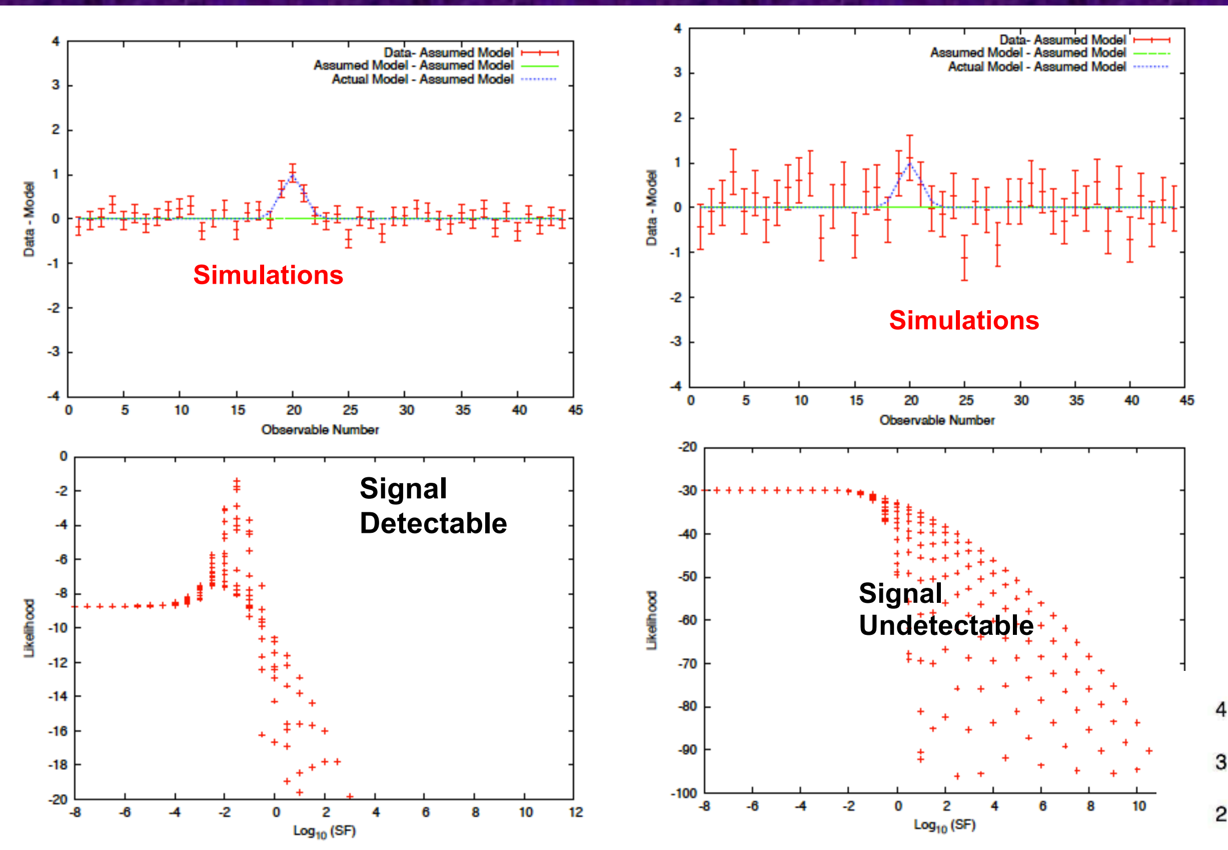
GP Hyper-parameters

$$\mathrm{Cov}\left(\begin{bmatrix} \mathbf{f} \\ \mathbf{f}' \\ \mathbf{f}'' \end{bmatrix}\right) = \begin{bmatrix} \Sigma_{00}(Z_1,Z_1) & \Sigma_{01}(Z_1,Z_1) & \Sigma_{02}(Z_1,Z_1) \\ \Sigma_{10}(Z_1,Z_1) & \Sigma_{11}(Z_1,Z_1) & \Sigma_{12}(Z_1,Z_1) \\ \Sigma_{20}(Z_1,Z_1) & \Sigma_{21}(Z_1,Z_1) & \Sigma_{22}(Z_1,Z_1) \end{bmatrix} - \begin{bmatrix} \Sigma_{00}(Z_1,Z) \\ \Sigma_{10}(Z_1,Z) \\ \Sigma_{20}(Z_1,Z) \end{bmatrix} \Sigma_{00}^{-1}(Z,Z)\,[\Sigma_{00}(Z,Z_1), \Sigma_{01}(Z,Z_1), \Sigma_{02}(Z,Z_1)].$$

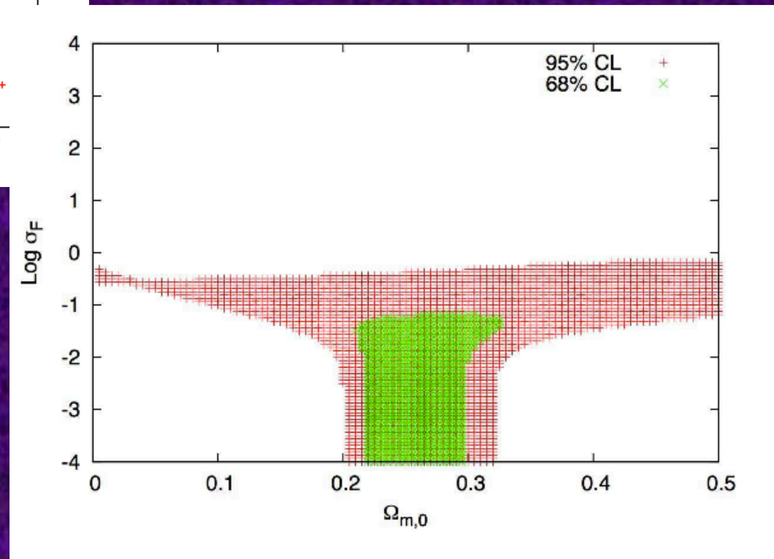
$$2\ln p(y|f) = -y^T\Sigma_{00}(Z,Z)^{-1}y - \ln\det\Sigma_{00}(Z,Z) - n\ln(2\pi),$$

GP Likelihood

Detection of the features in the residuals



GP to test GR
Shafieloo, Kim, Linder, PRD 2013

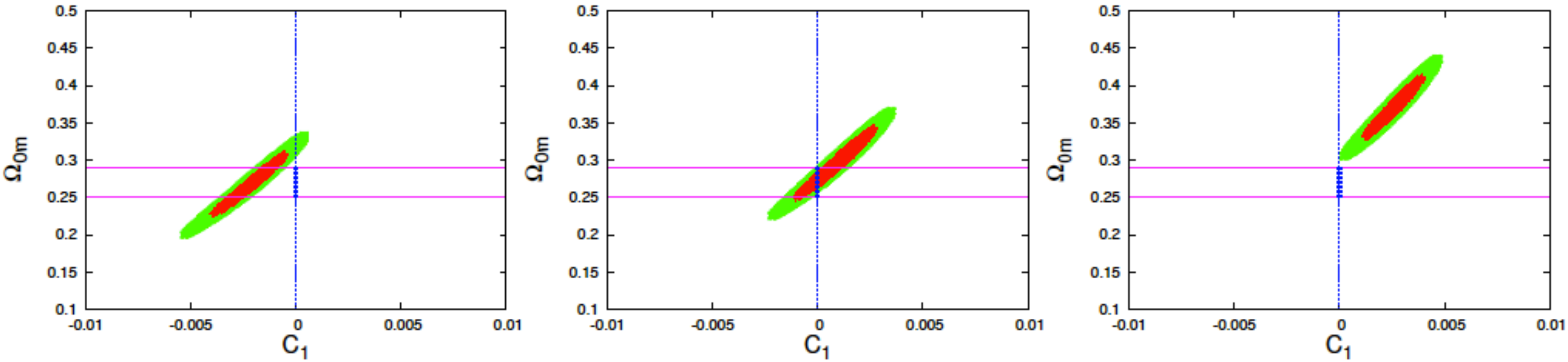


Crossing Statistic (Bayesian Interpretation)

Theoretical model　　Crossing function

$$\mu_M^{T_N}(z) = \mu_M(p_i, z) \times T_N(C_1, \ldots, C_N, z)$$

Comparing a model with its own variations



$$T_I(C_1, z) = 1 + C_1\left(\frac{z}{z_{max}}\right)$$

Chebishev Polynomials as Crossing Functions

$$T_{II}(C_1, C_2, z) = 1 + C_1\left(\frac{z}{z_{max}}\right) + C_2\left[2\left(\frac{z}{z_{max}}\right)^2 - 1\right],$$

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

Crossing Statistic (Bayesian Interpretation)

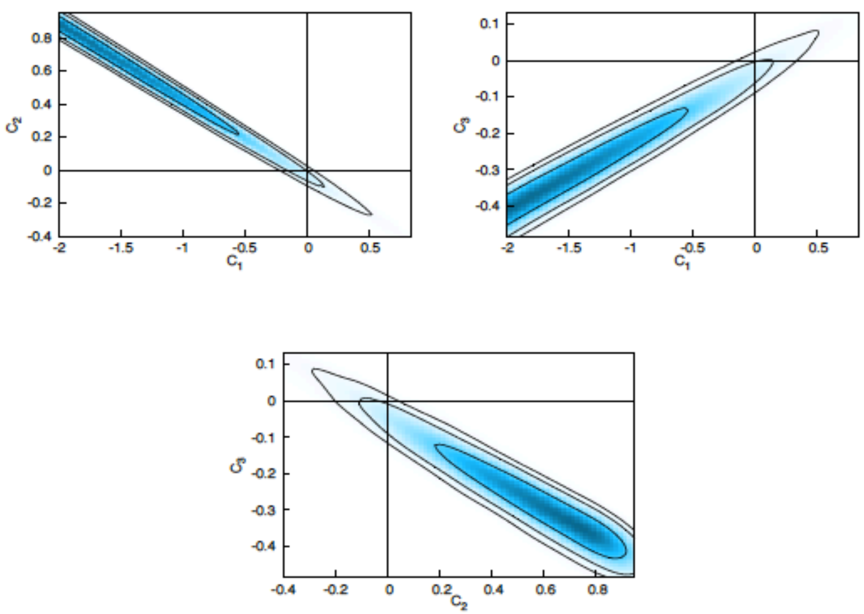
Theoretical model Crossing function

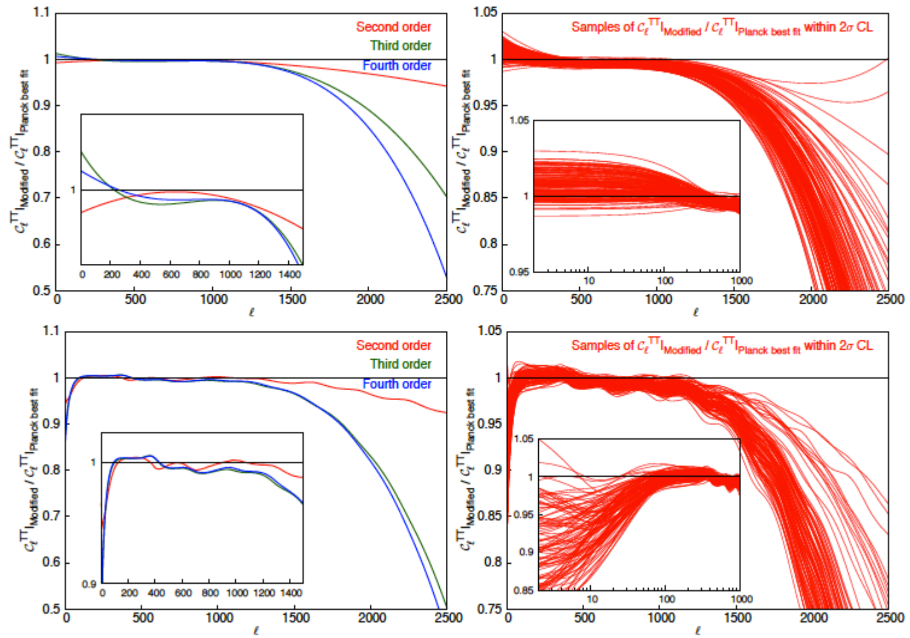
$$\mathcal{C}_\ell^{\rm TT}\,\Big|^{N}_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\,\Big|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H}_0,\tau,{\rm A}_{\rm S},{\rm n}_{\rm S},\ell} \times\; T_i(C_0, C_1, C_2, ..., C_N, \ell).$$

Confronting the concordance model of cosmology with Planck data

Hazra and Shafieloo, JCAP 2014

Consistent only at 2~3 sigma CL





Dates

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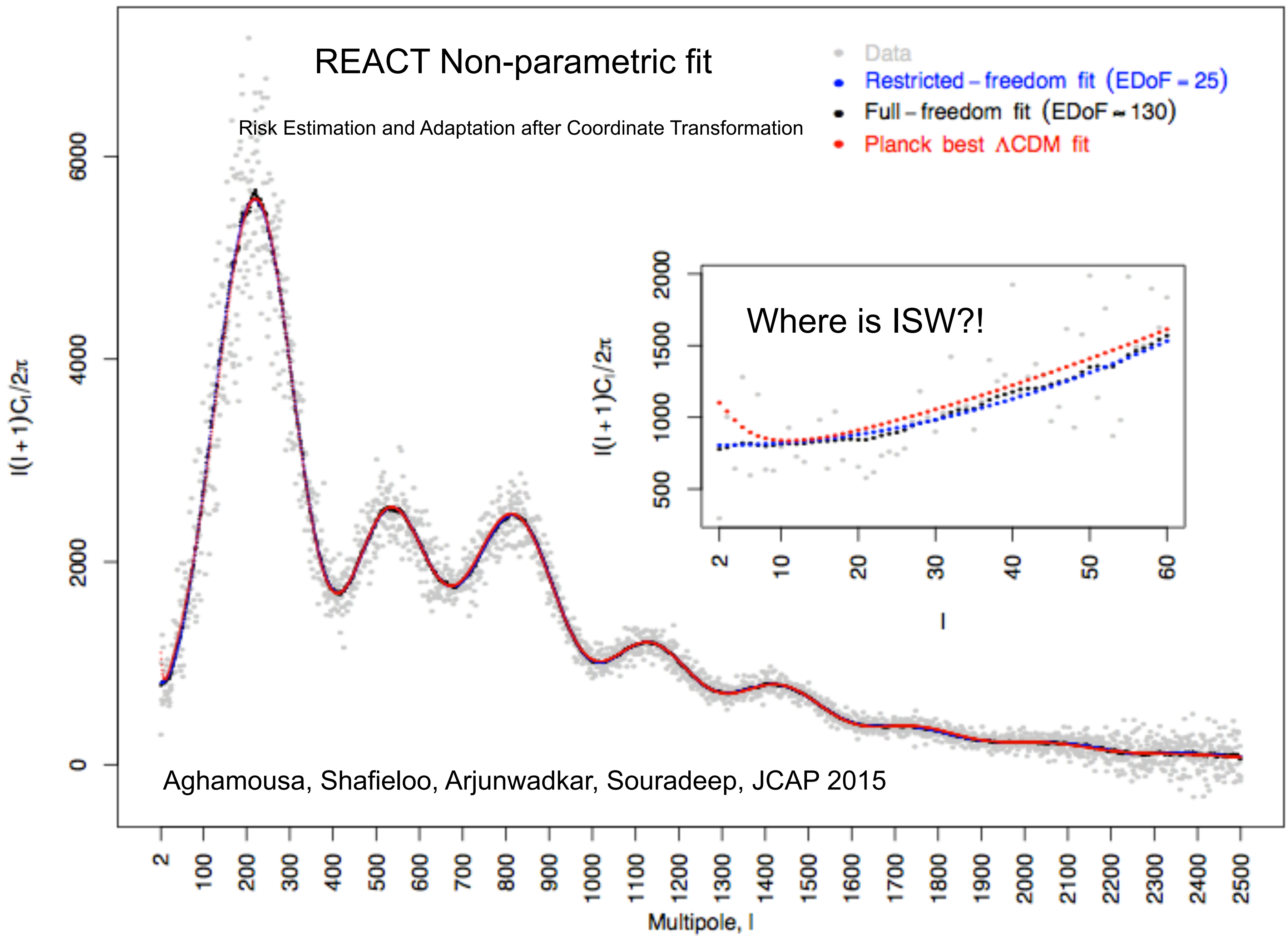
REACT Non-parametric fit
Risk Estimation and Adaptation after Coordinate Transformation
Data
Restricted – freedom fit (EDoF = 25)
Full – freedom fit (EDoF = 130)
Planck best ΛCDM fit
Where is ISW?!
l(l + 1)C_l/2π
l
Multipole, l
Aghamousa, Shafieloo, Arjunwadkar, Souradeep, JCAP 2015

Summary:

- The nature of dark energy is unknown. We just know it exist (?!), long way to understand what it is.

- To study the behavior of dark energy we need to undesrtand the expansion history of the universe and growth of fluctuations.

- Parametric and Non-Parametric approaches are both useful and each has some advantages and some disadvantages over the other one. Best is to combine them.

- First target can be testing the standard 'Vanilla' model. If it is not '*Lambda*' then we can look further. Falsifying DE models and in particular ***Cosmological Constant*** is more realistic and affordable than reconstructing dark energy and it can have a huge theoretical implications. This explains the importance of null tests like Om, Omh2 and Om3 and falsification methods.

Conclusion (Large Scales)

- Still something like 96% of the universe is missing. Something might be fundamentally wrong.
- 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 new generation of experiments.
- We should be happy that there are lots of problems unsolved. Problems that we might be able to solve some of them (to some extend) with our limited intelligence.