Consistency Tests of LCDM

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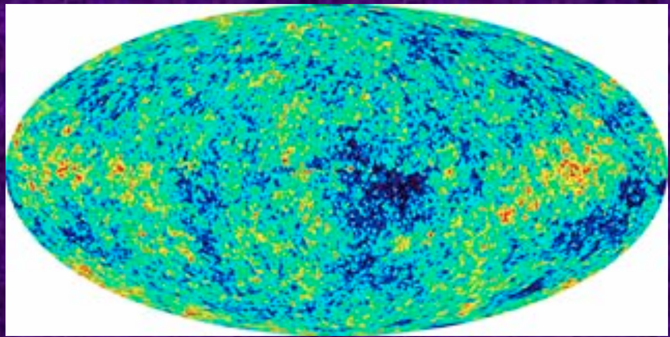
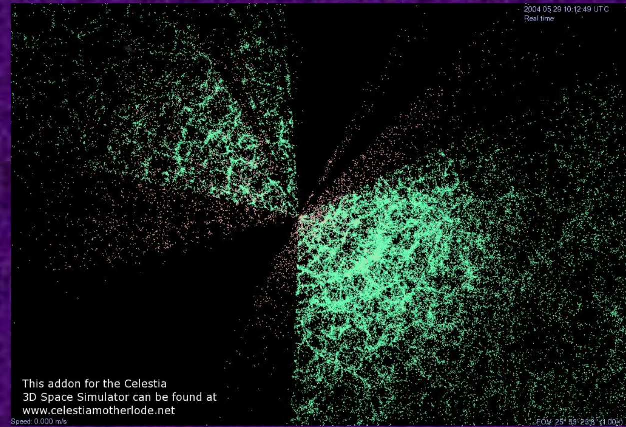
Cosmology, from ***fiction*** to being ***science*****…..**



Cosmic Microwave Background (CMB)

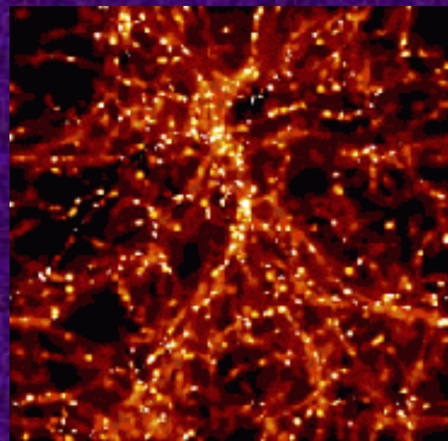


Large-scale structure

Cosmological Observations

Gravitational Lensing

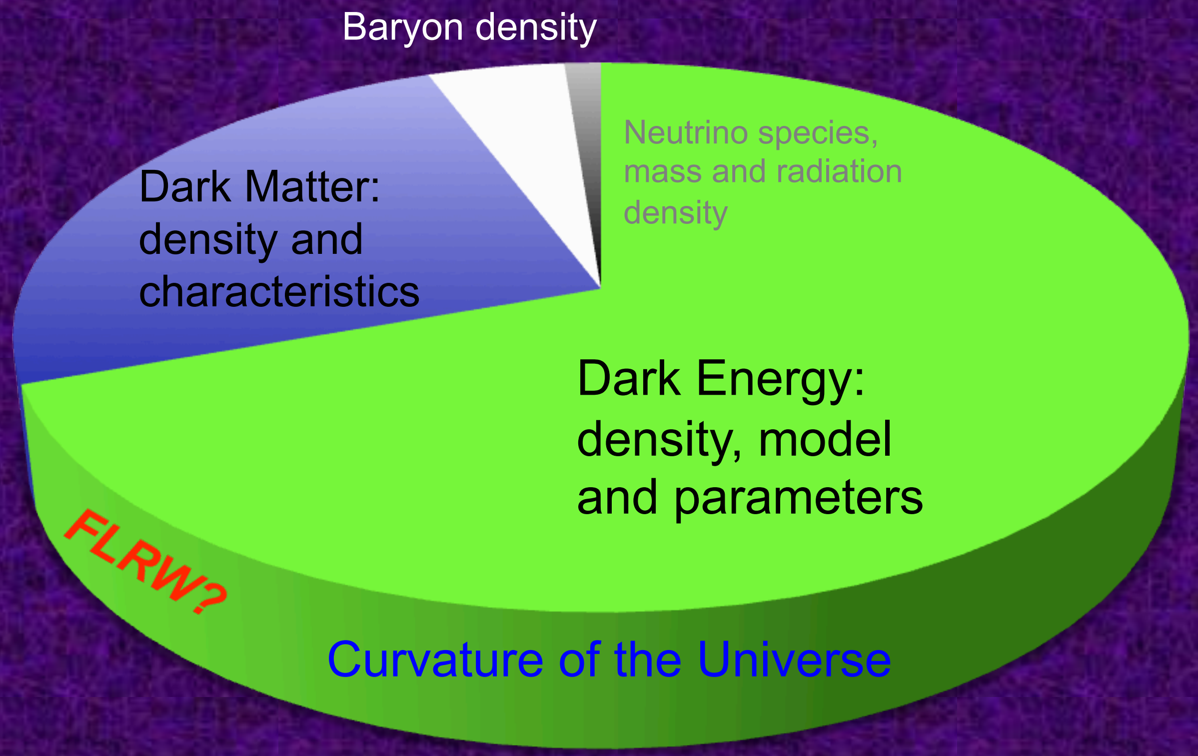
Type Ia supernovae



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.



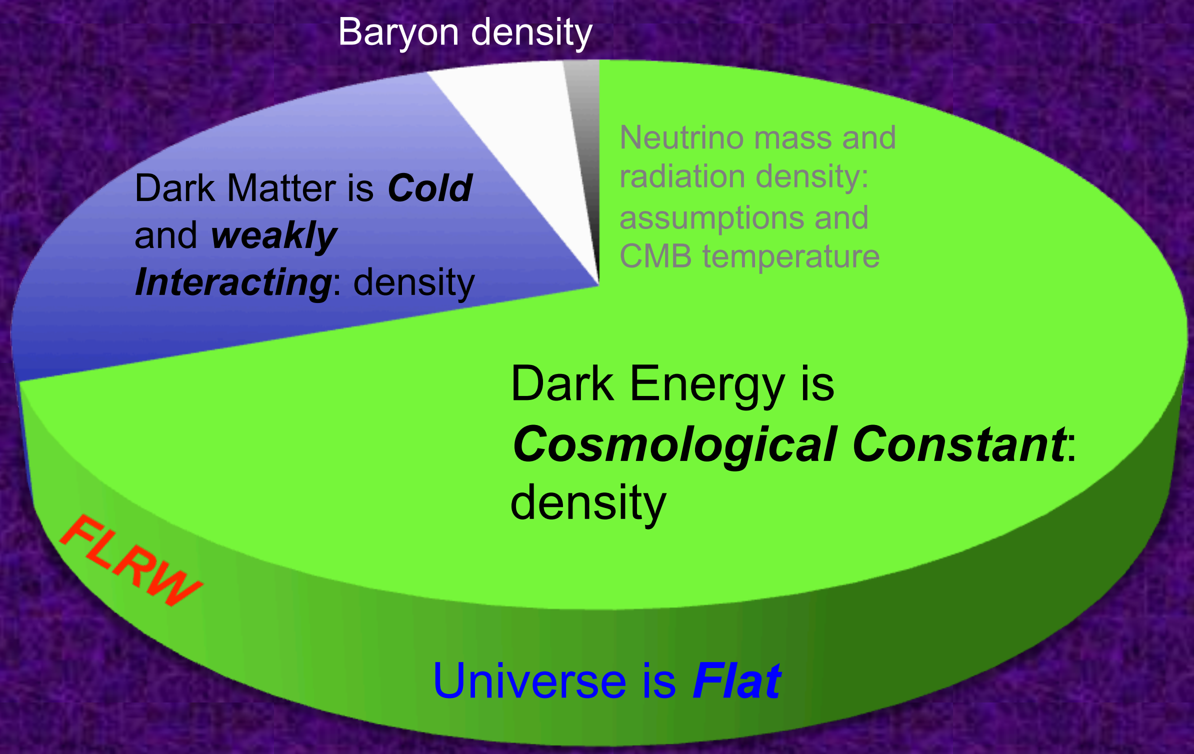
Initial Conditions:
Form of the Primordial Spectrum and Model of Inflation and its Parameters

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***

Epoch of reionization

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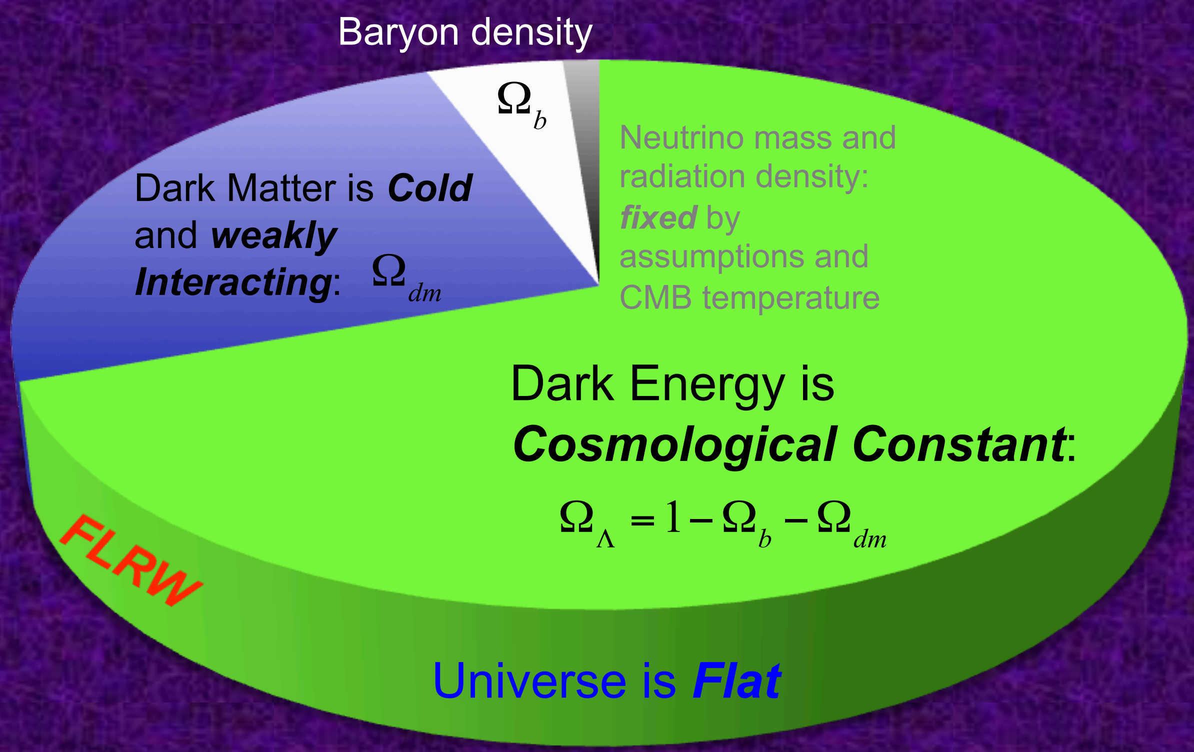


Initial Conditions:
Form of the Primordial Spectrum is ***Power-law***

n_s, A_s

Epoch of reionization

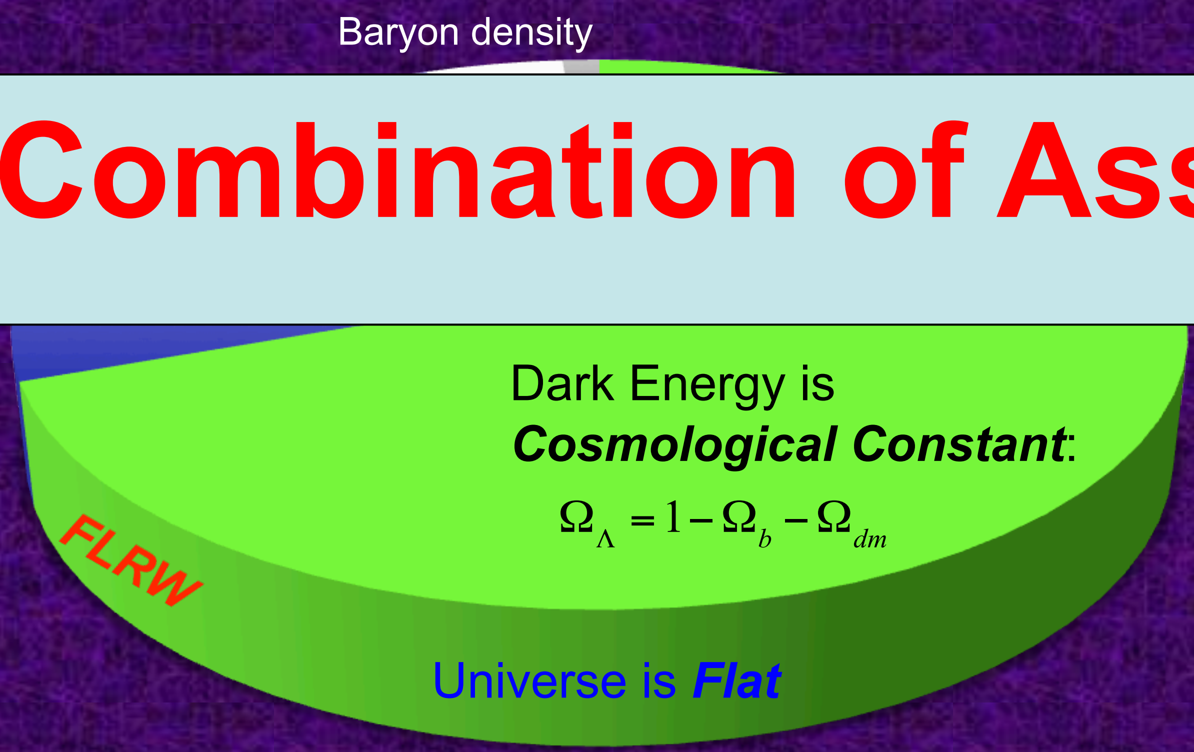
τ

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.



Combination of Assumptions

n_s, A_s

Epoch of reionization

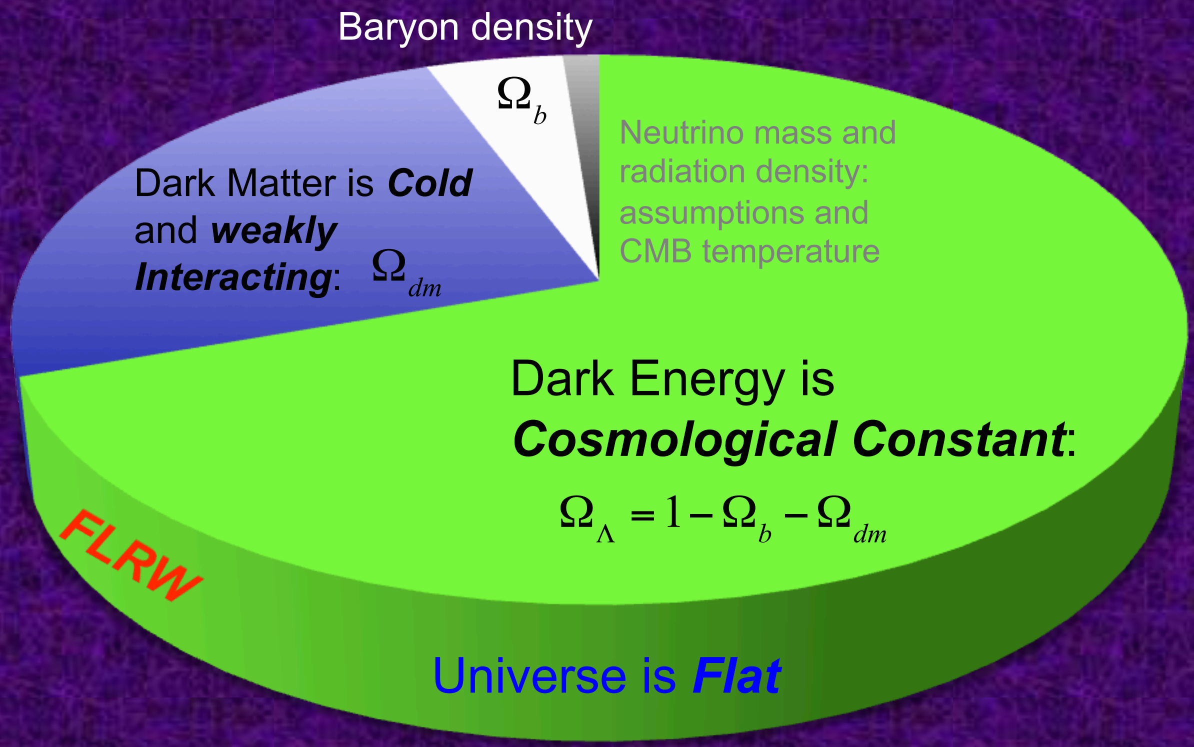
τ

Hubble Parameter and the Rate of Expansion

H_0

Standard Model of Cosmology

combination of *reasonable* assumptions, but…..



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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

Dark Energy is Lambda (w=-1)

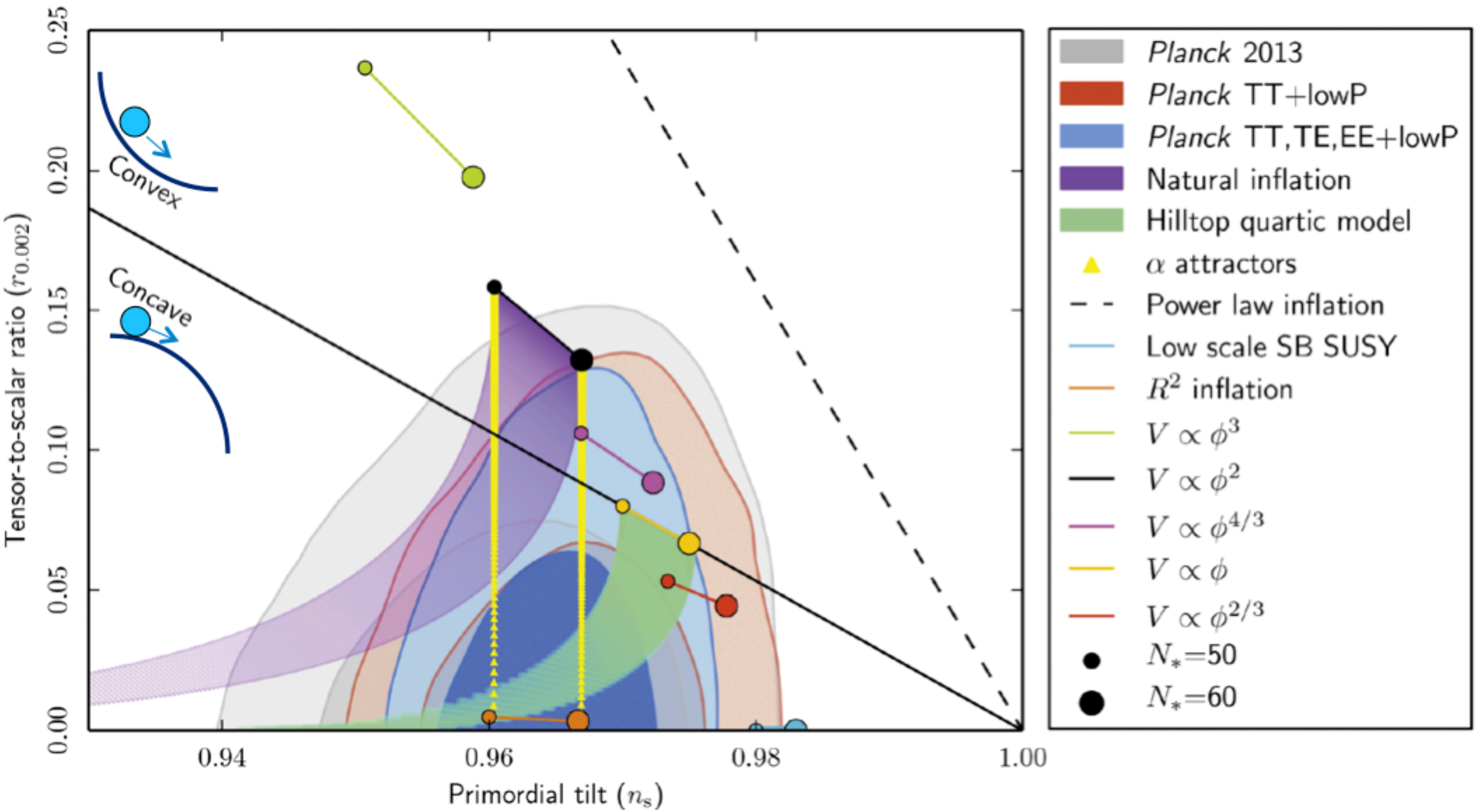
Power-Law primordial spectrum (n_s=const)

Dark Matter is cold

All within framework of FLRW

Planck 2015: No detectable primordial G-waves

Planck 2015: n_s vs r



Parameterization and Model Fitting

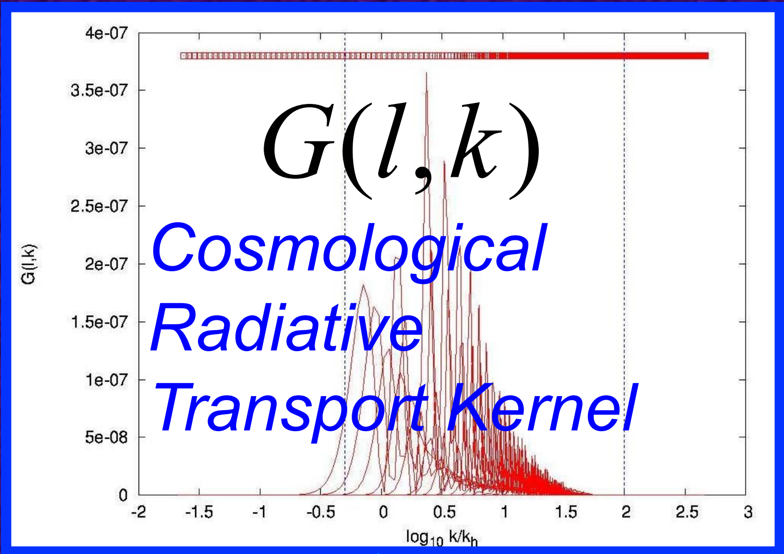
$P(k)$

Primordial Power Spectrum

?

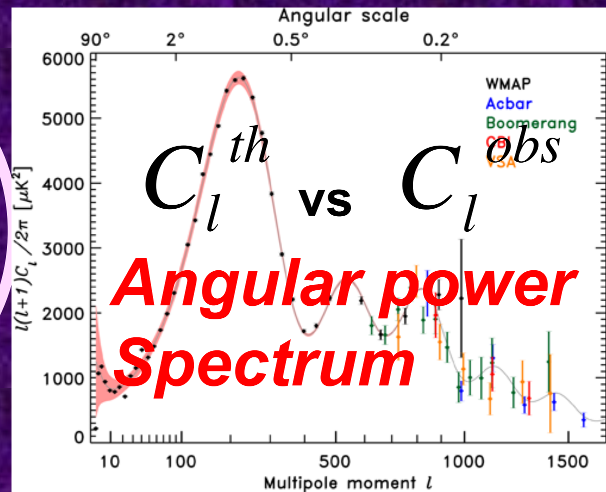
Suggested by Model of Inflation

$$C_l = \sum G(l,k)P(k)$$



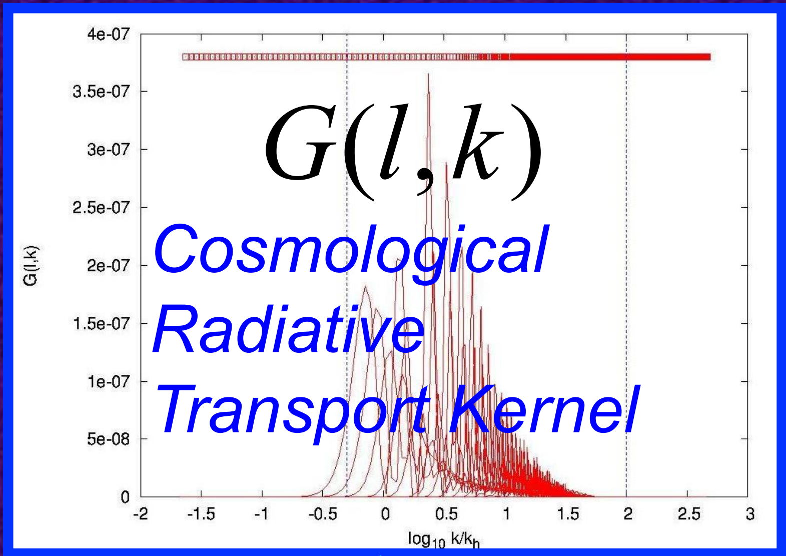
Determined by background model and cosmological parameters

Detected by observation

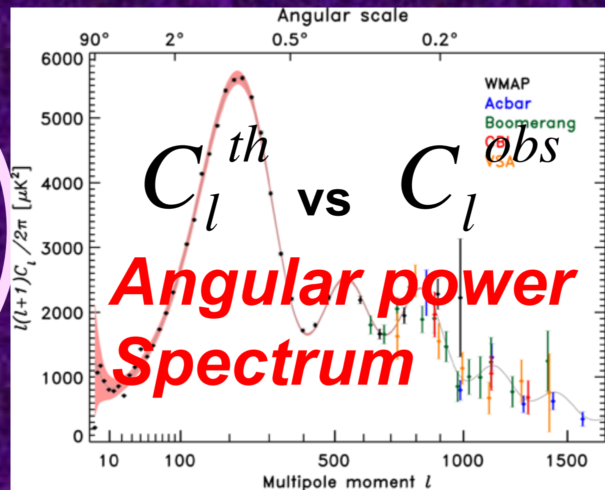


We cannot anticipate the unexpected !!

$$C_l = \sum G(l,k)P(k)$$



Determined by background model and cosmological parameters



Detected by observation

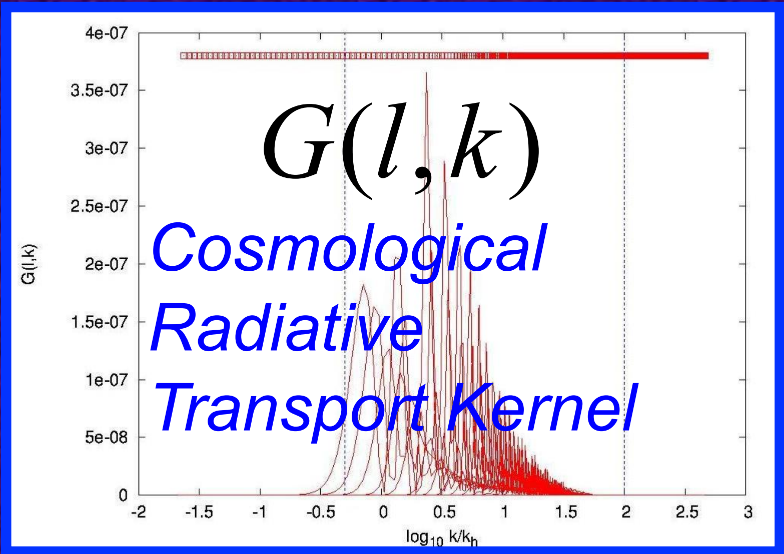
DIRECT TOP DOWN Reconstruction

$P(k)$
Primordial Power Spectrum

?

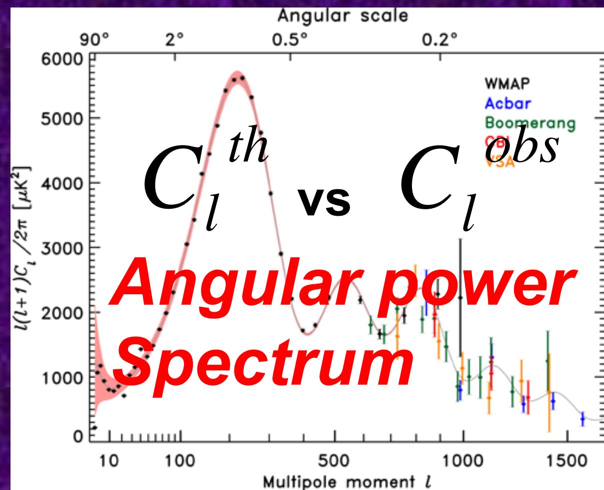
Reconstructed by Observations

$$C_l = \sum G(l,k)P(k)$$

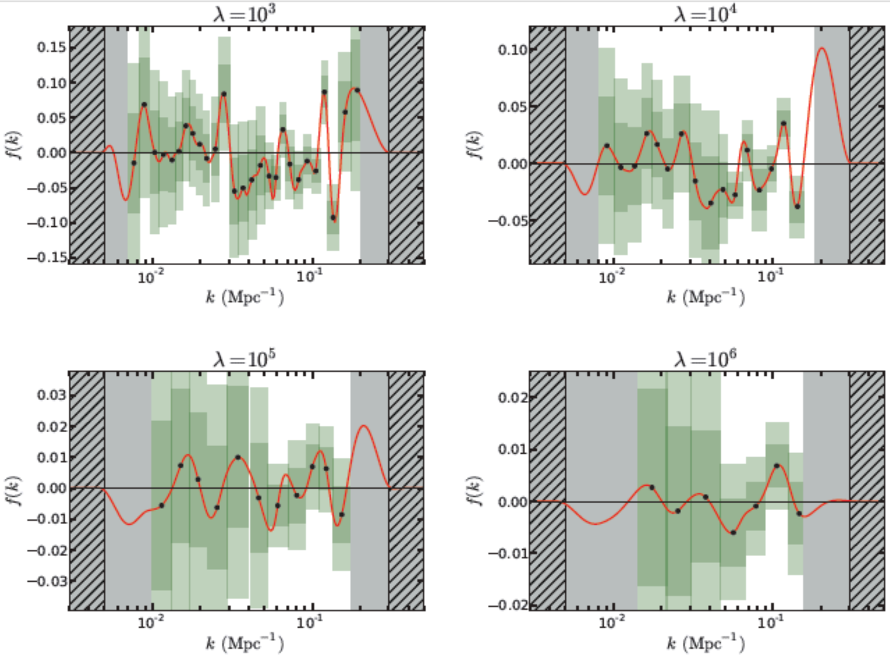


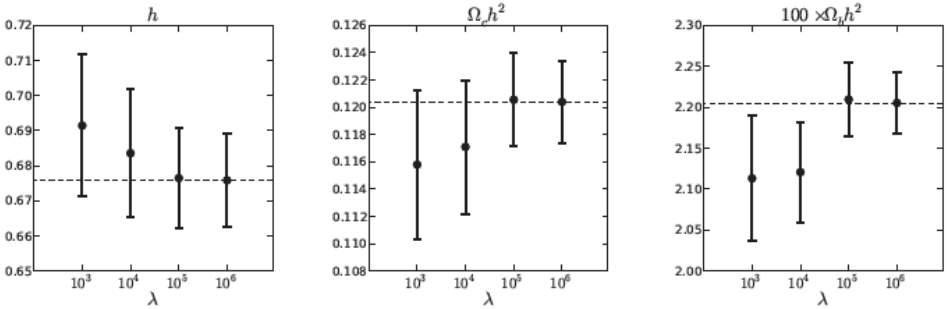
Determined by background model and cosmological parameters

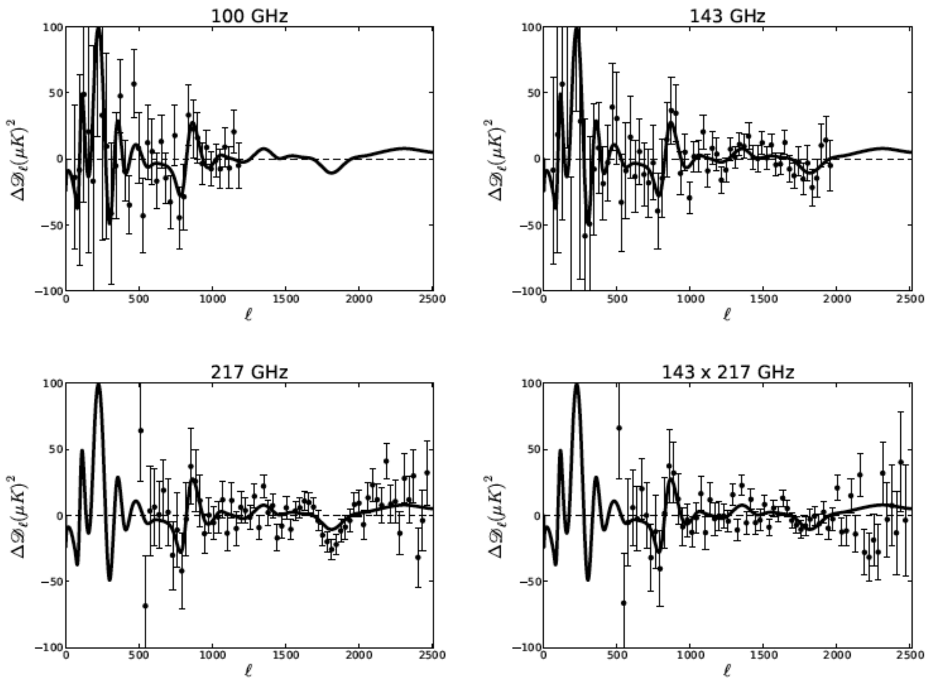
Detected by observation

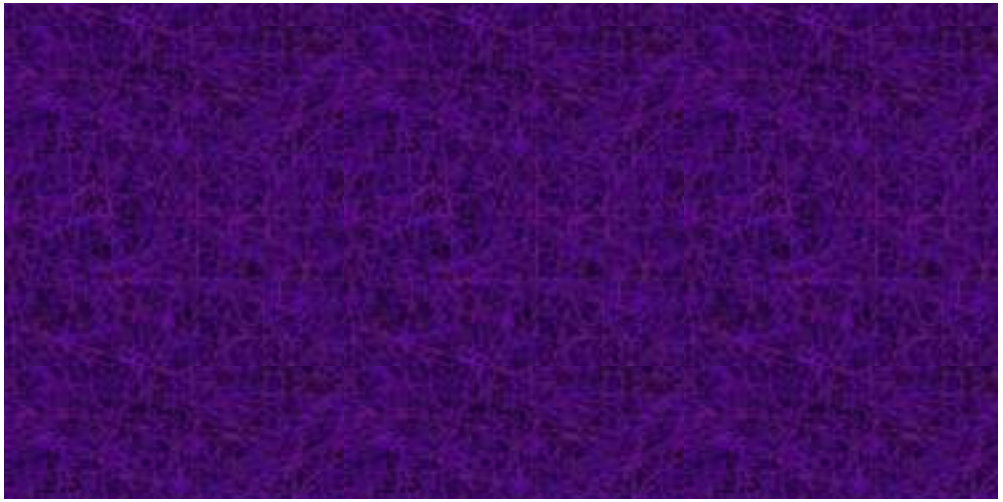


Planck 2013 reconstructed PPS
(Gauthier, Bucher 2012)





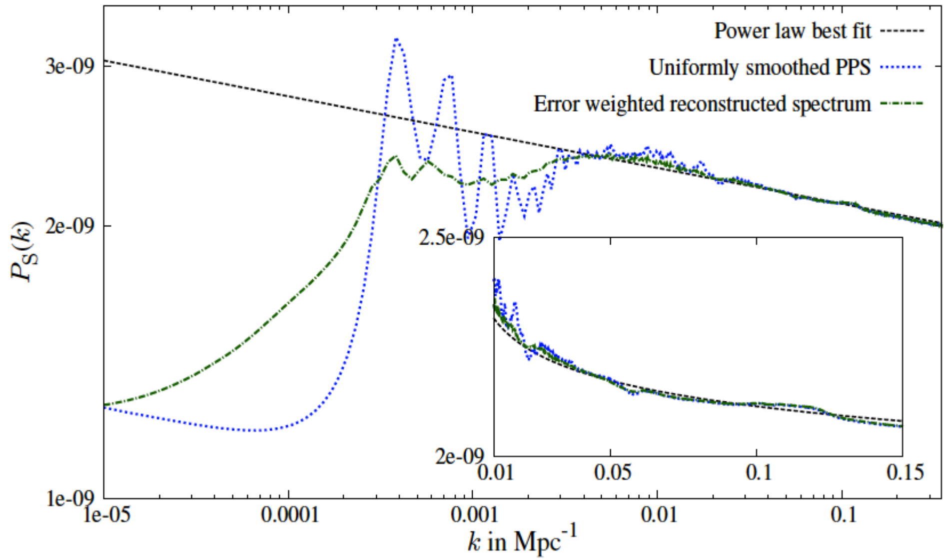


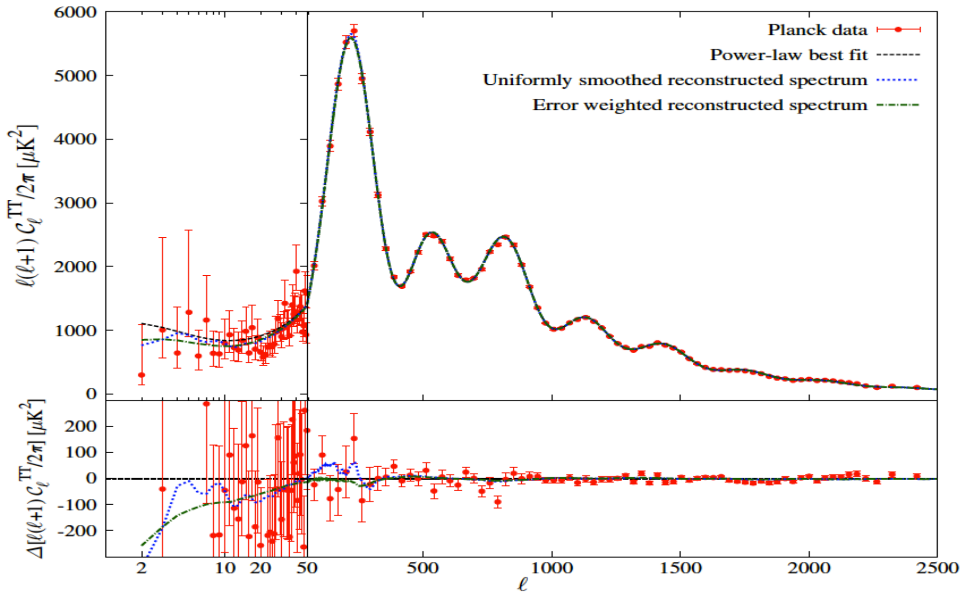


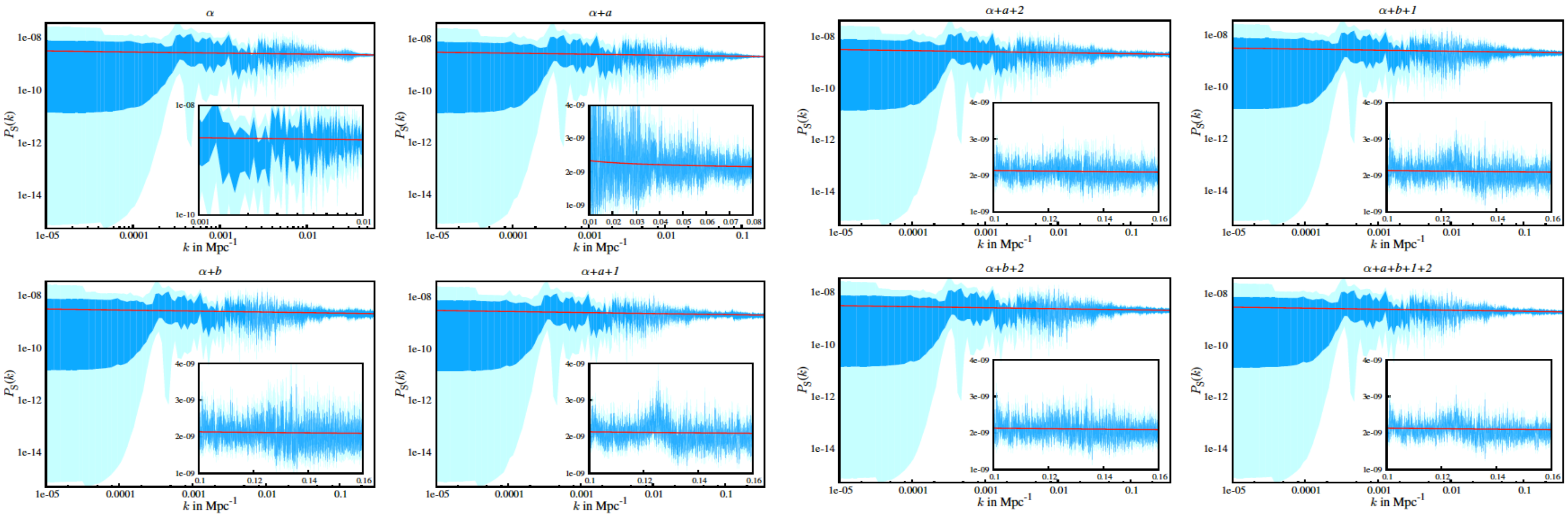
Our symbol	Spectra	Multipoles(ℓ)	Scales
α	low-ℓ	2-49	Largest scales
a	100 GHz $\times$ 100 GHz	50-1200	Intermediate scales
b	143 GHz $\times$ 143 GHz	50-2000	Intermediate scales
1	217 GHz $\times$ 217 GHz	500-2500	Small scales
2	143 GHz $\times$ 217 GHz	500-2500	Small scales

Primordial Power Spectrum from Planck

Hazra, Shafieloo & Souradeep, JCAP 2014

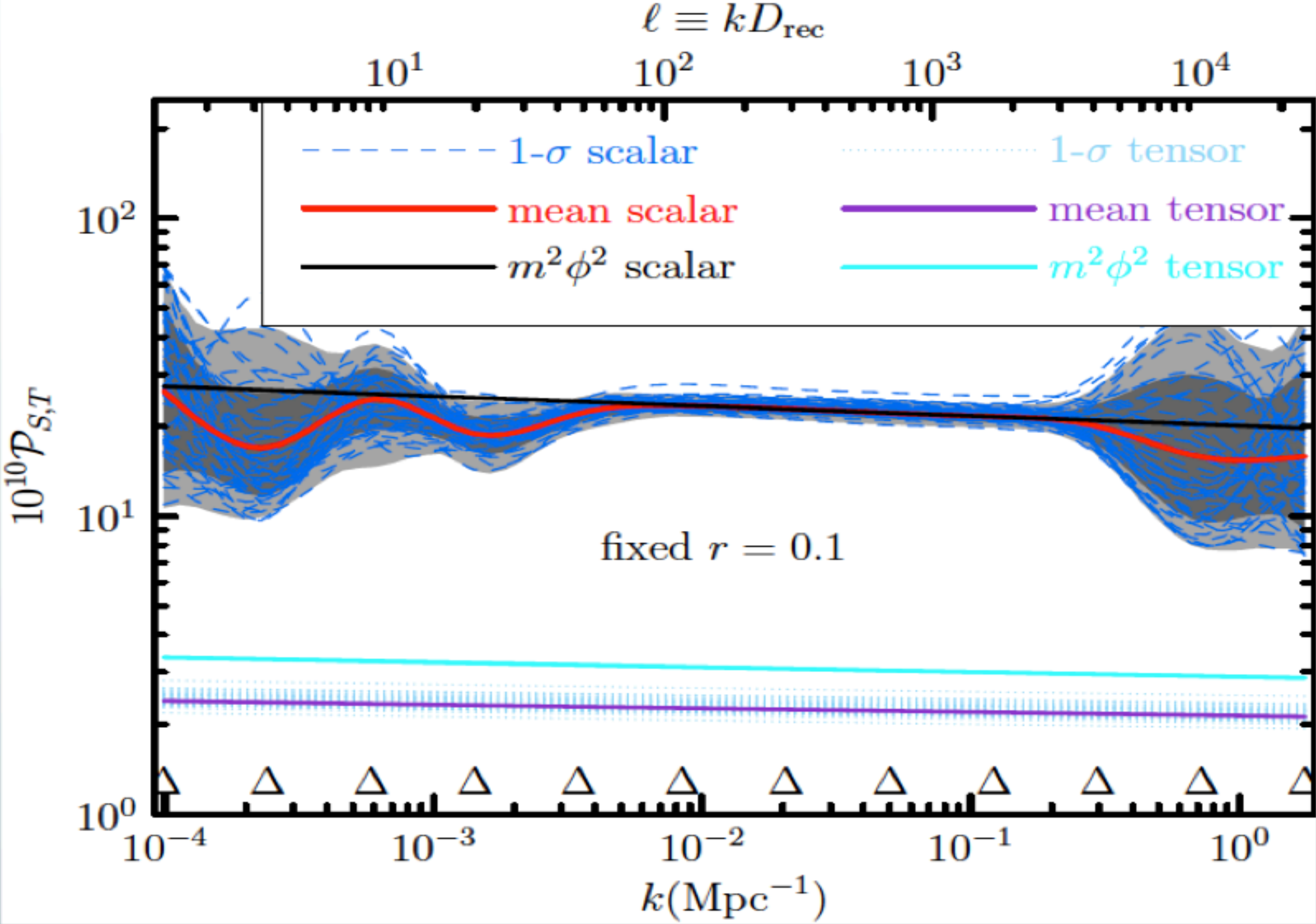






Planck 2015: No feature

Power spectra reconstruction



2015
TT+lowP
+BAO+JLA
+Hlow

12-knots power spectra

(actually used 3 different methods, all with similar results)

Cosmological Parameter Estimation with Power-Law Primordial Spectrum

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

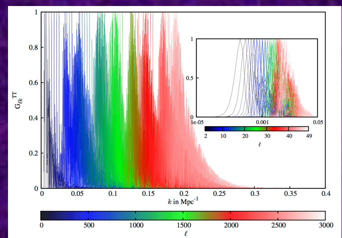
Ω_b, Ω_m, H_0, τ

A_s, n_s

1 → G(l,k)

2 →

$$C_l = \sum G(l,k)P(k)$$



2 ←

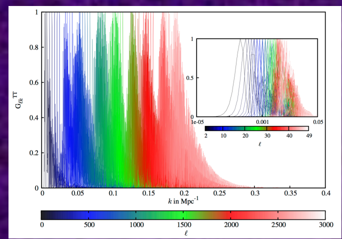
1 →

$$P(k) = A_s[\frac{k}{k_*}]^{n_s-1}$$

3 ↕

$$C_l^{obs}$$

Cosmological Parameter Estimation with Free form Primordial Spectrum



Ω_b

Ω_m

H_0

τ

~~A_s~~

~~n_s~~

1

G(l,k)

3

2

$$C_l = \sum G(l,k)P(k)$$

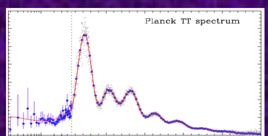
3

P(k)

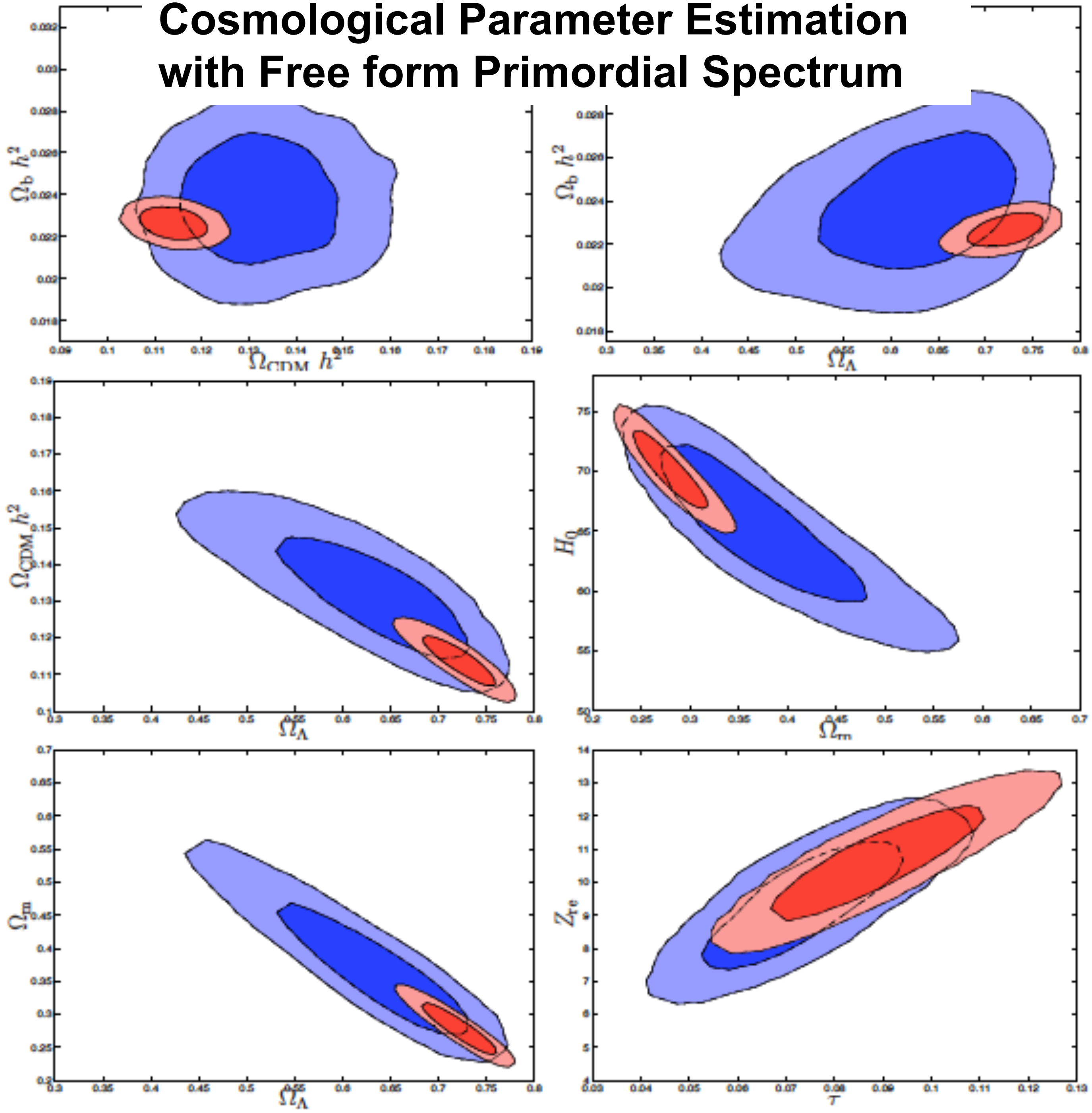
4

C_l^{obs}

2



Cosmological Parameter Estimation with Free form Primordial Spectrum



Red Contours: Power Law PPS

Blue Contours: Free Form PPS

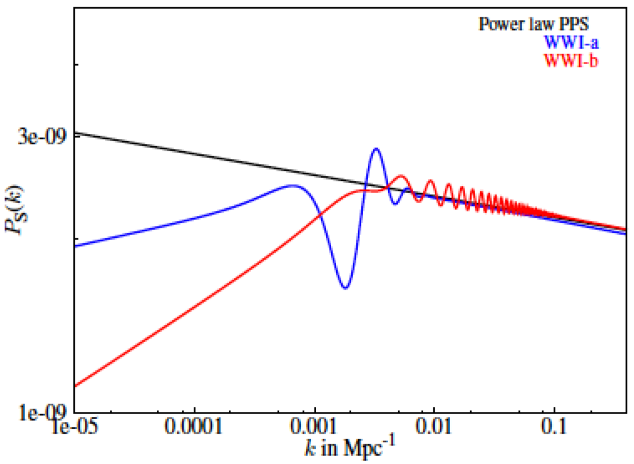
Hazra, Shafieloo & Souradeep, PRD 2013

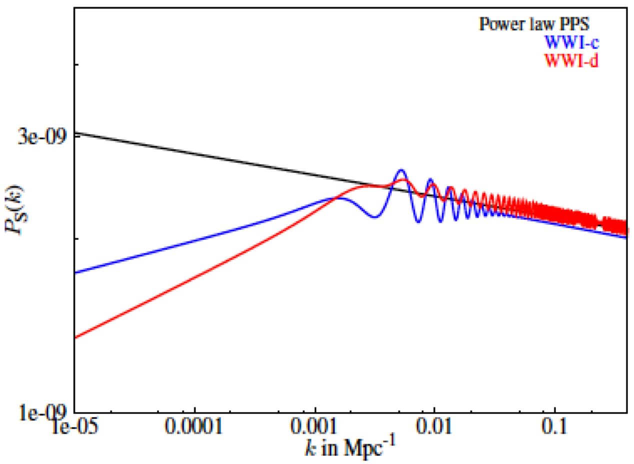
Discussed in Snowmass 2013

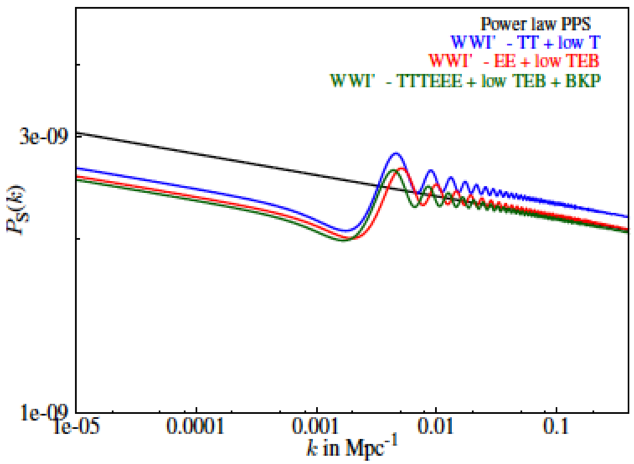
Individual likelihoods comparison						
Individual likelihood	Baseline	WWI-a $\Delta_{\rm DOF} = 4$	WWI-b $\Delta_{\rm DOF} = 4$	WWI-c $\Delta_{\rm DOF} = 4$	WWI-d $\Delta_{\rm DOF} = 4$	WWI′ $\Delta_{\rm DOF} = 2$
TT	761.1	762	761.9	762.8	762.8	762.4
lowT	15.4	8.2	13.4	12.1	13	10.2
Total	778.1	772.1 (-6)	777 (-1.1)	777 (-1.1)	778.4 (0.3)	775 (-3.1)
EE	751.2	748.8	747.2	748.6	750.2	746.8
lowTEB	10493.6	10490	10495.6	10492.4	10495.7	10492.2
Total	11248.8	11241.8 (-7)	11246.2 (-2.6)	11244.5 (-4.3)	11249.3 (0.5)	11242.3 (-6.5)
TTTEEE	2431.7	2432.7	2422.6	2427.8	2421.7	2426.5
lowTEB	10497	10490.8	10495.1	10493.4	10495.3	10492.7
Total	12935.6	12929.5 (-6.1)	12924.2 (-11.4)	12927.6 (-8)	12923.4 (-12.2)	12925.2 (-10.4)
TT	764.5	763.6	762.2	764.4	762.9	762.8
EE	753.9	754.8	750.5	750.8	750.8	751
TE	932	933.4	928.7	929.2	927	928.8
lowTEB	10498.4	10490.4	10495.8	10493.7	10495.6	10492.4
BKP	41.6	42	42	42.6	41.8	42.9
Total	12997	12991 (-6)	12985.9 (-11.1)	12987.2 (-9.8)	12985 (-12)	12985.1 (-11.9)
TTTEEE	2431.7	2432.8	2421.4	2426.7	2421	2425.7
lowTEB	10498.5	10490.5	10495.5	10493.6	10495.8	10492.6
BKP	41.6	42	42.7	42	41.9	42.5
Total	12978.3	12971.3 (-7)	12967.3 (-11)	12968.6 (-9.7)	12965 (-13.3)	12968.6 (-9.7)
TT (bin1)	8402.1	8404.1	8403.9	8405.2	8402.1	8401.9
lowT	15.4	8.3	13.3	11.9	13.2	10.3
Total	8419.6	8414.7 (-4.9)	8419.5 (-0.1)	8419.8 (0.2)	8418.1 (-1.5)	8414.4 (-5.2)
TTTEEE (bin1)	24158.2	24158.6	24149	24155	24148.4	24151.5
lowTEB	10497.6	10490.3	10493.4	10493.6	10495.3	10492.7
Total	34661.9	34655.3 (-6.6)	34650.5 (-11.4)	34654.4 (-7.5)	34649.5 (-12.4)	34650.6 (-11.3)

Beyond Power-Law: ***there are some other models consistent to the data.***

Hazra, Shafieloo, Smoot, JCAP 2013
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014A
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014B
Hazra, Shafieloo, Smoot, Starobinsky, Phys. Rev. Lett 2014
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2016







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Hazra, Shafieloo, Smoot, JCAP 2013
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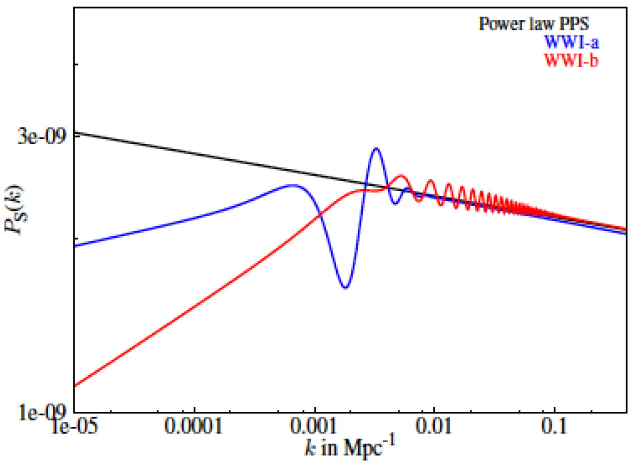
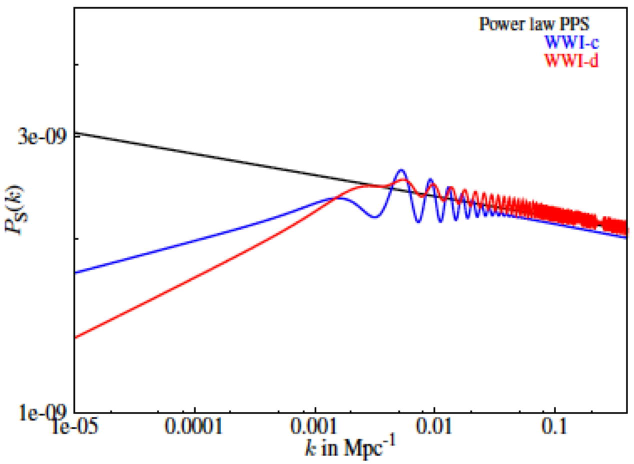
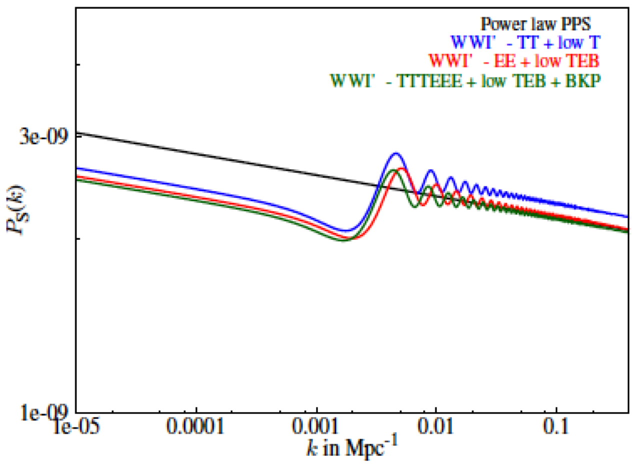
Hazra, Shafieloo, Smoot, Starobinsky, Phys. Rev. Lett 2014
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2016





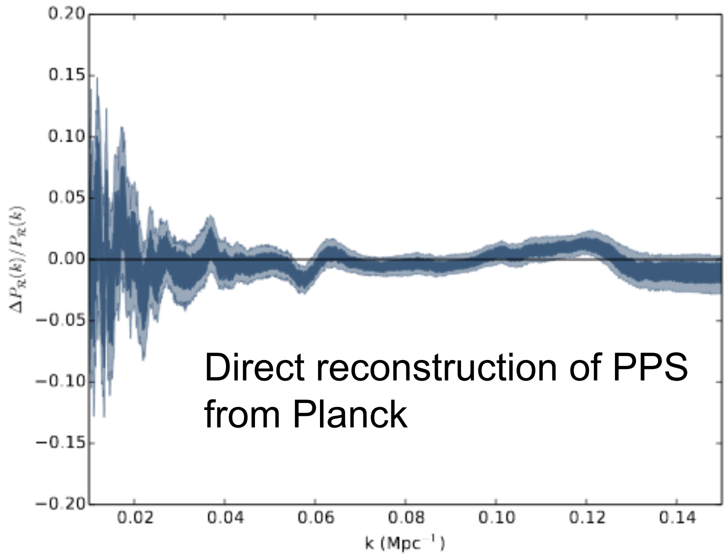


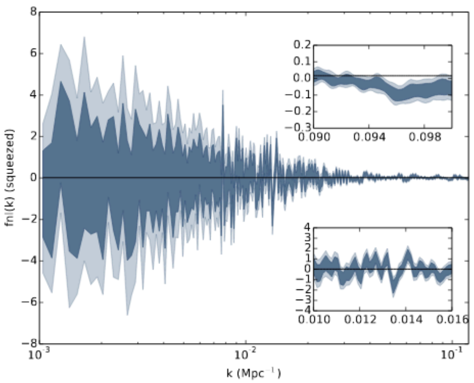
Understanding the Early Universe:

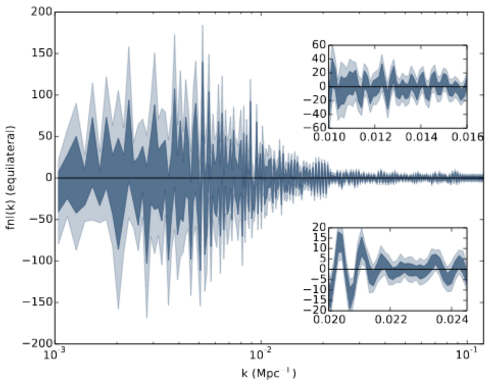
- Form of the primordial spectrum ***(degenerate with other cosmological quantities).***
- Tensor-to-scalar ratio of perturbation amplitudes
  (near future potential probe)
- Primordial non-Gaussianities
  (near future potential probe)

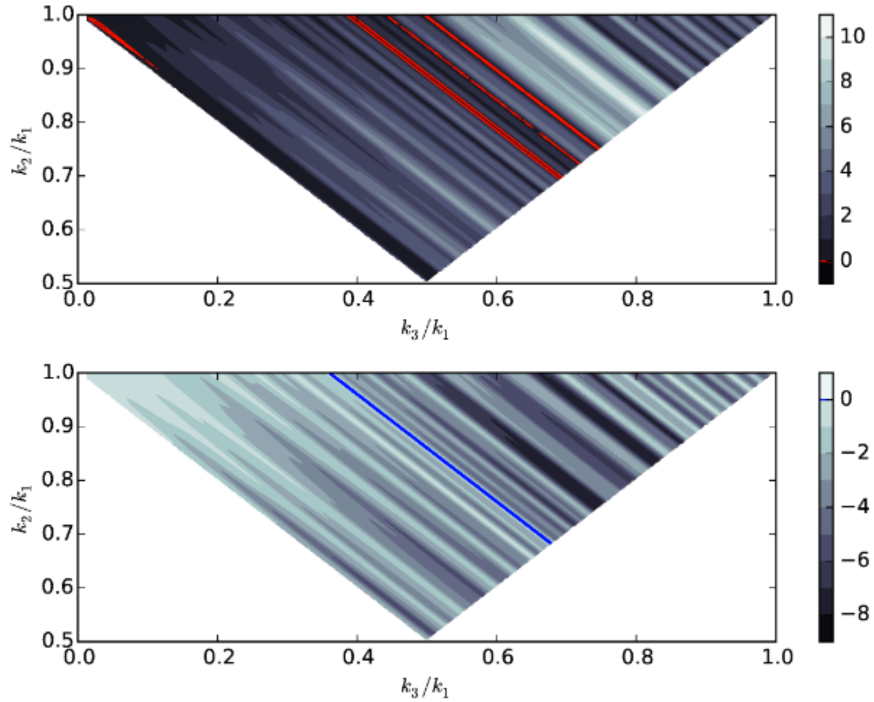
Plausible approach for the future:

Joint constraint on inflationary features using the two and three-point correlations of temperature and polarization anisotropies









Bispectrum in terms of the reconstructed power spectrum and its first two derivatives

Appleby, Gong, Hazra, Shafieloo, Sypsas, PLB 2016

From 2D to 3D

Using LSS data to test early universe scenarios

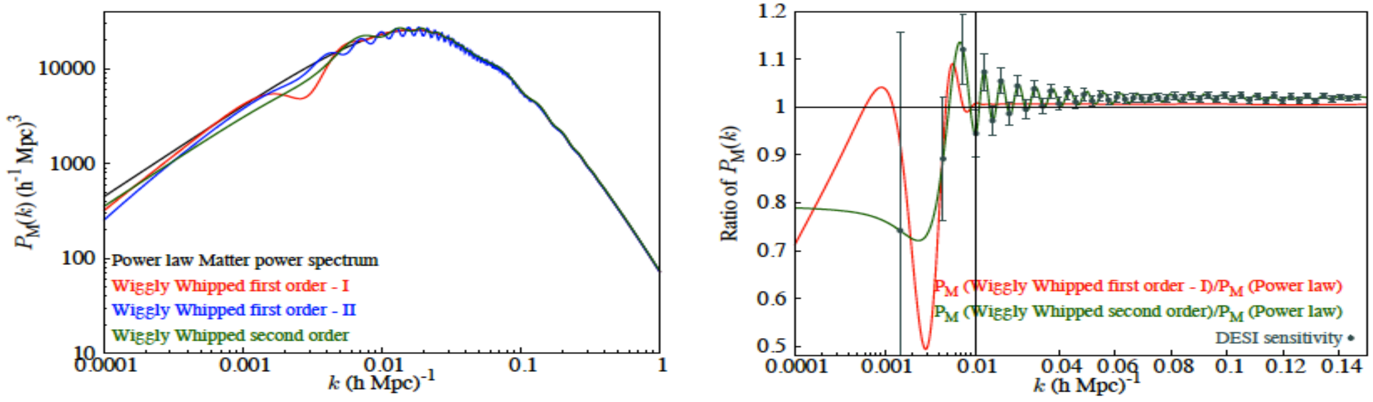


Figure 5. Wiggly Whipped Inflation : Matter power spectra (left) obtained from the best fit potential and background parameters (in Table 1) and the ratio (right) *w.r.t.* the matter power spectra obtained from power law best fit model. The DESI forecasted fractional errors are overlayed in the right panel as well. Note that from the future matter power spectrum data we shall be able to identify specific features in the primordial power spectrum.

Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014B

From 2D to 3D (first step)

-Generating many N-body simulations (similar to stage IV dark energy measurements such as DESI) based on various inflationary scenarios with features in PPS (but still degenerate to be distinguished by CMB data).

-Try to distinguish them by implementing/designing appropriate statistics.

(power spectrum, bi-spectrum etc may not work)

(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

Dark Energy in 2016

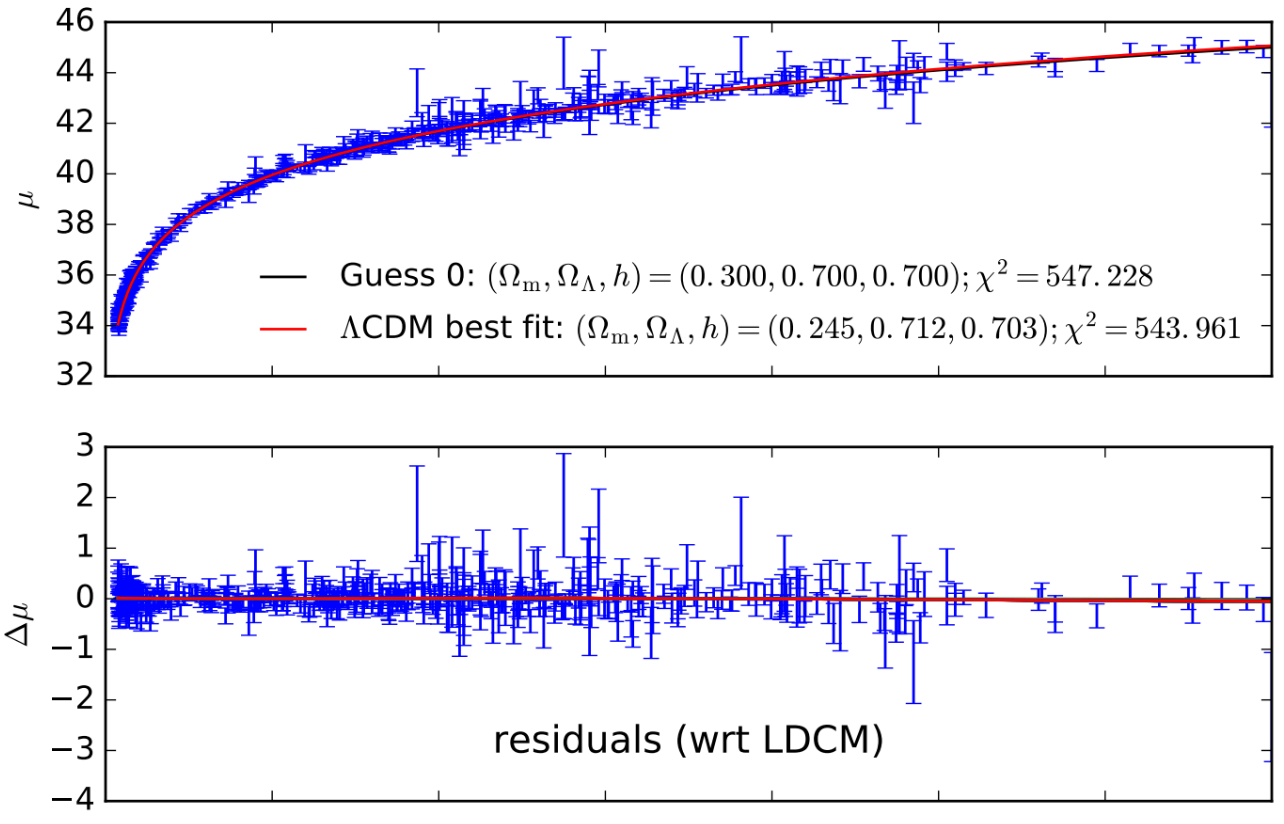
SN

18 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 2016

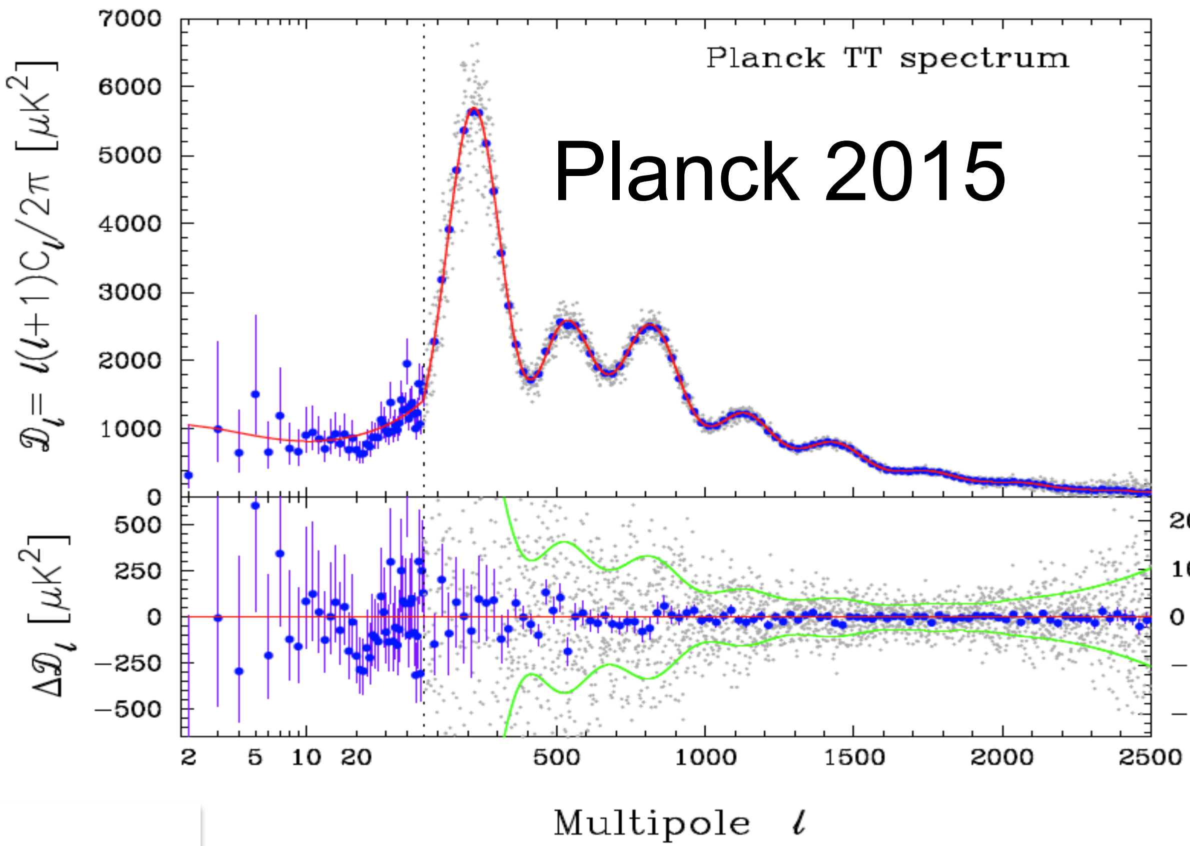


Dark Energy in 2016

CMB

18 years after discovery of the acceleration of the universe:

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

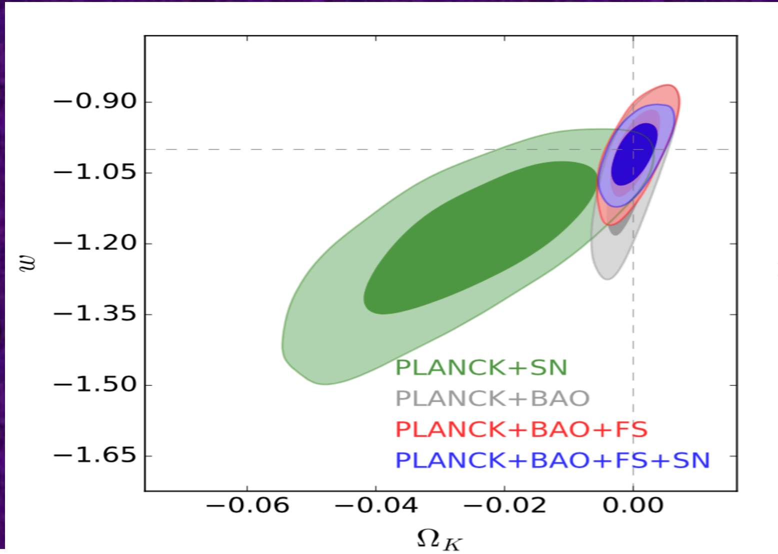


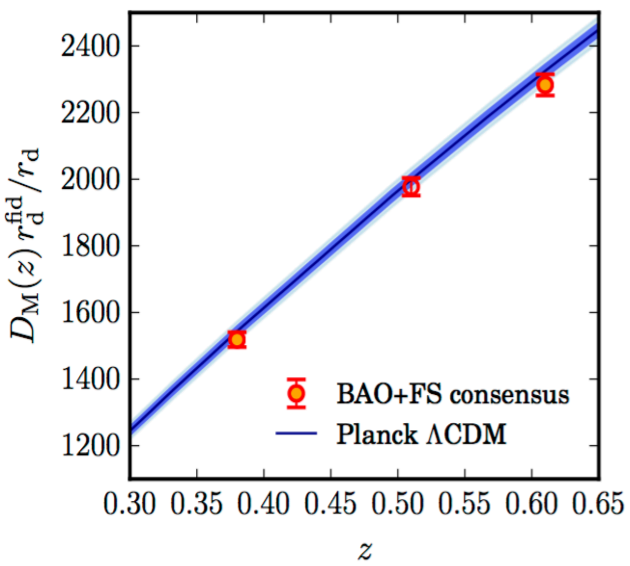
Dark Energy in 2016

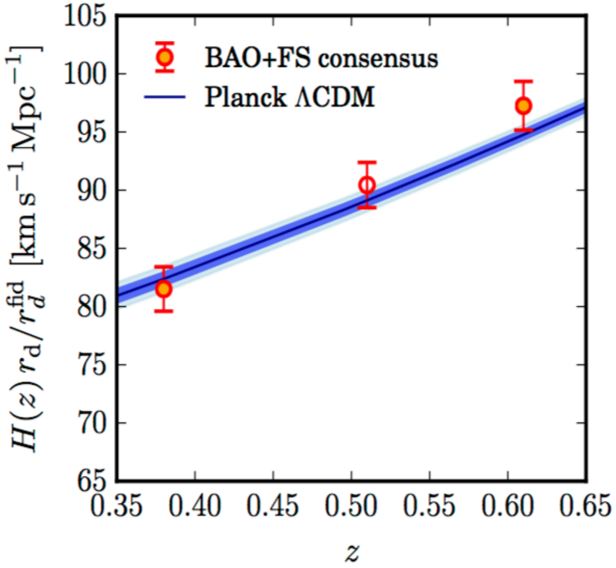
LSS

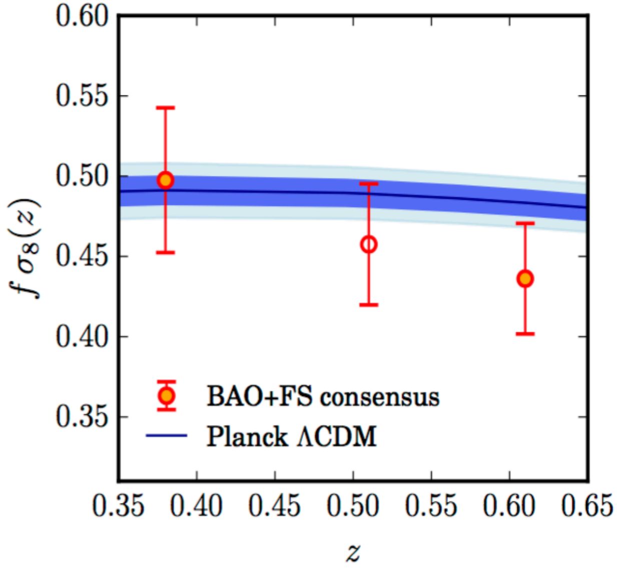
18 years after discovery of the acceleration of the universe:

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

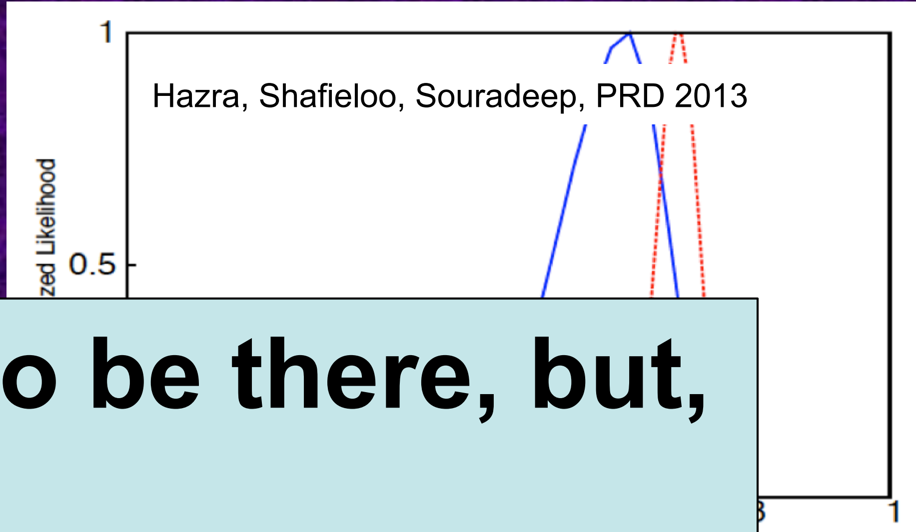






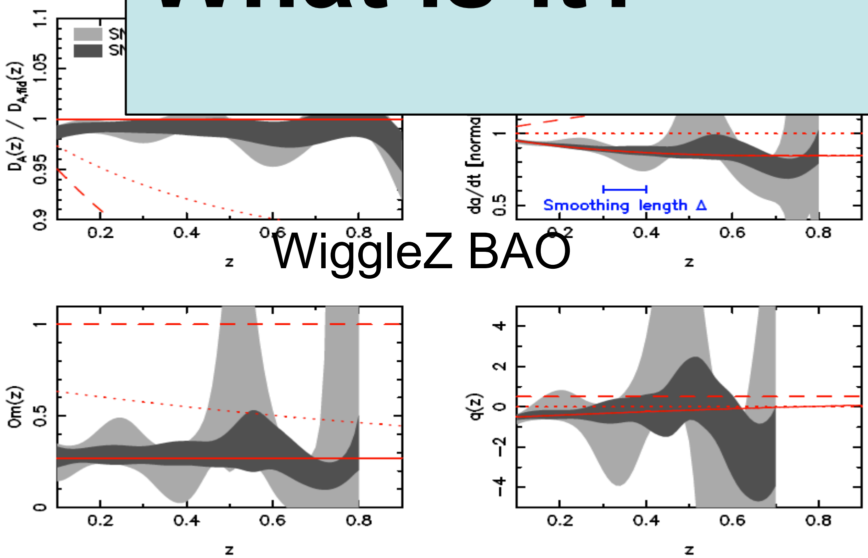


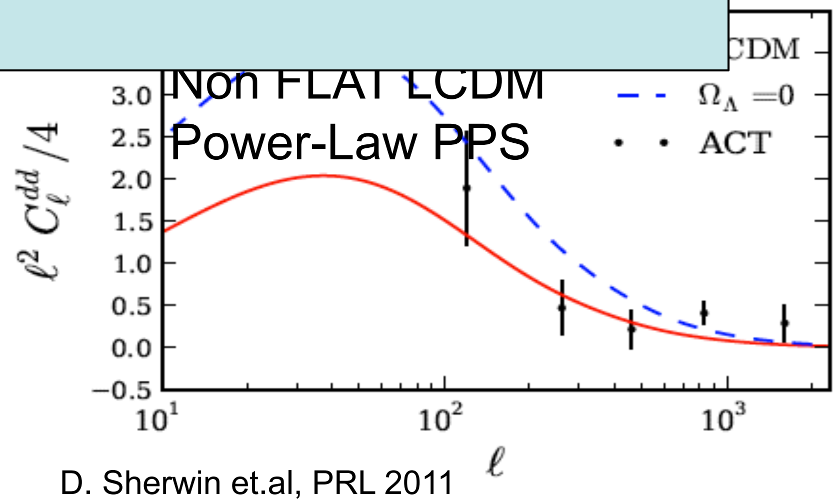
Accelerating Universe, Now



Something seems to be there, but,

What is it?





D. Sherwin et.al, PRL 2011

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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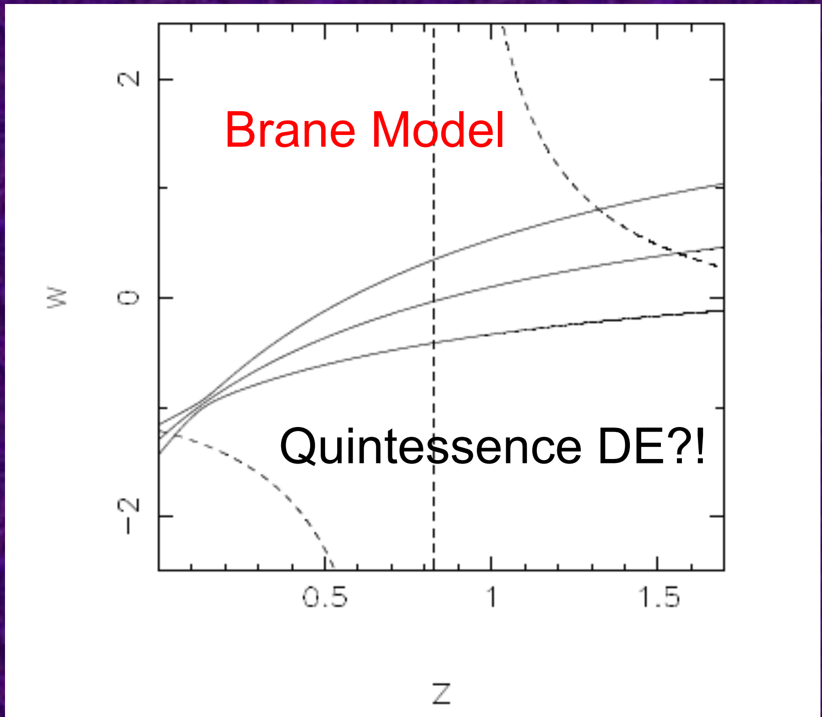
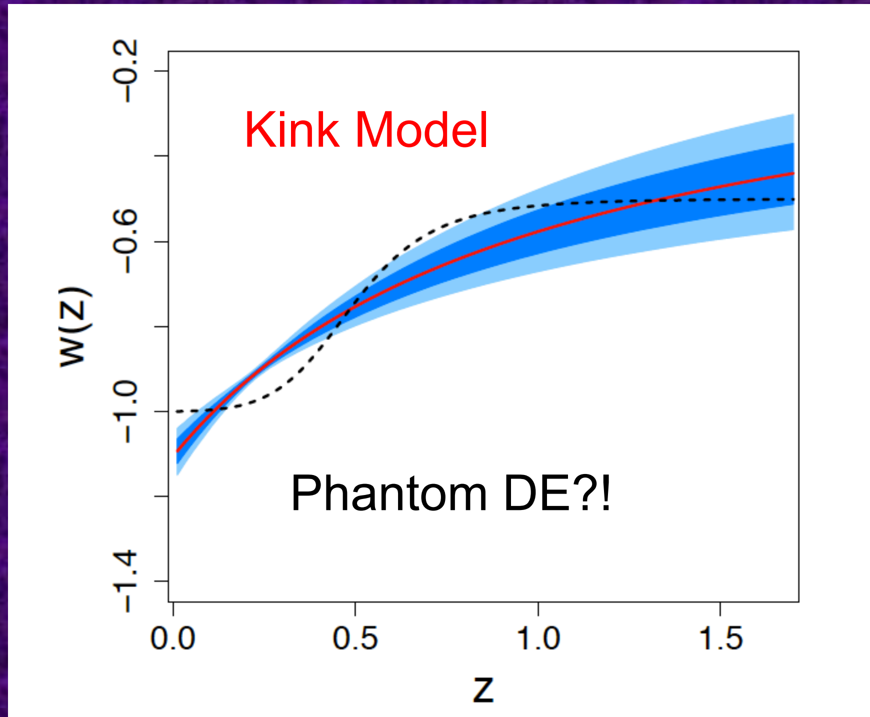
Problems of Dark Energy Parameterizations (model fitting)





Shafieloo, Alam, Sahni & Starobinsky, MNRAS 2006

Holsclaw et al, PRD 2011

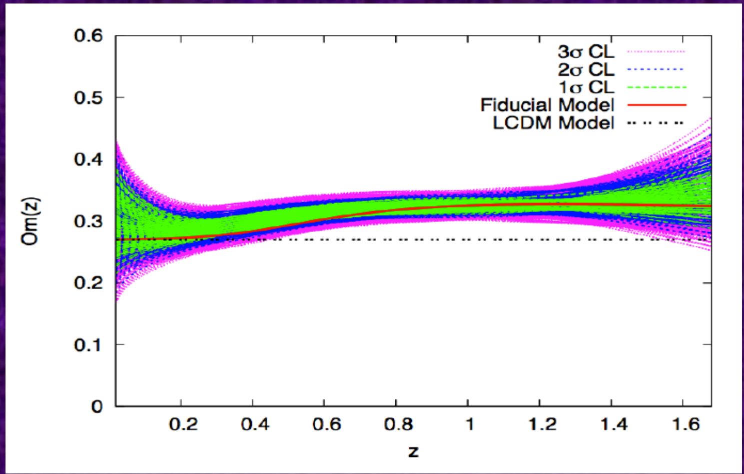
$$w(z) = w_0 + w_a \frac{z}{1+z}.$$

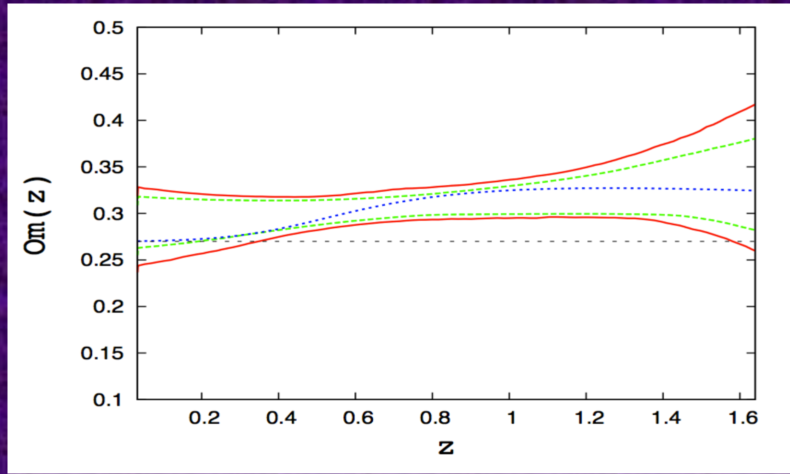
Chevallier-Polarski-Linder ansatz (CPL).

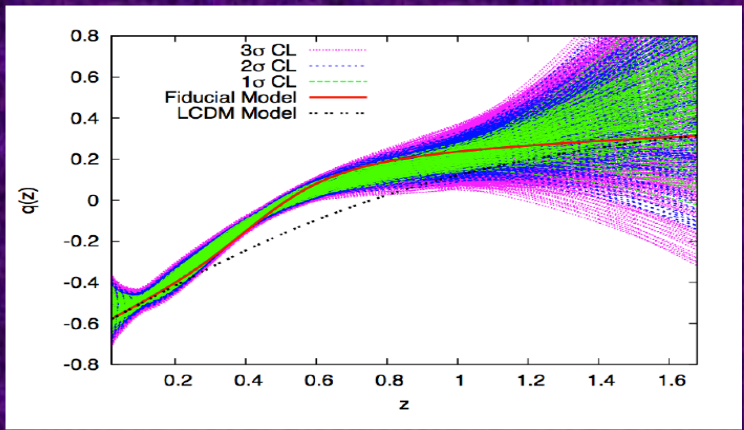
Model independent reconstruction of the expansion history

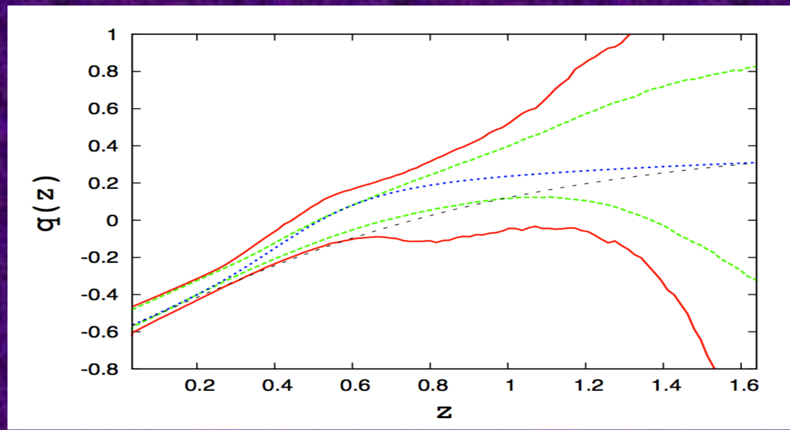
Crossing Statistic + Smoothing

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).

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

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

Full theoretical picture:

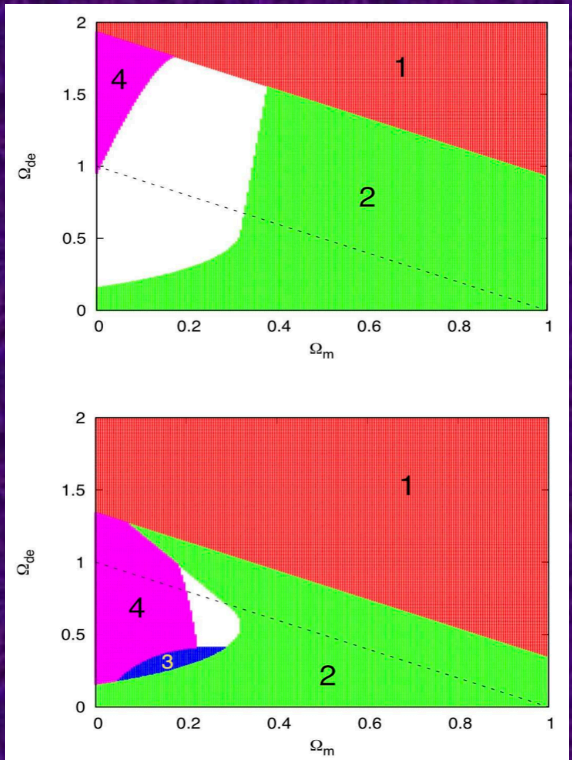
Cosmographic Degeneracy

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

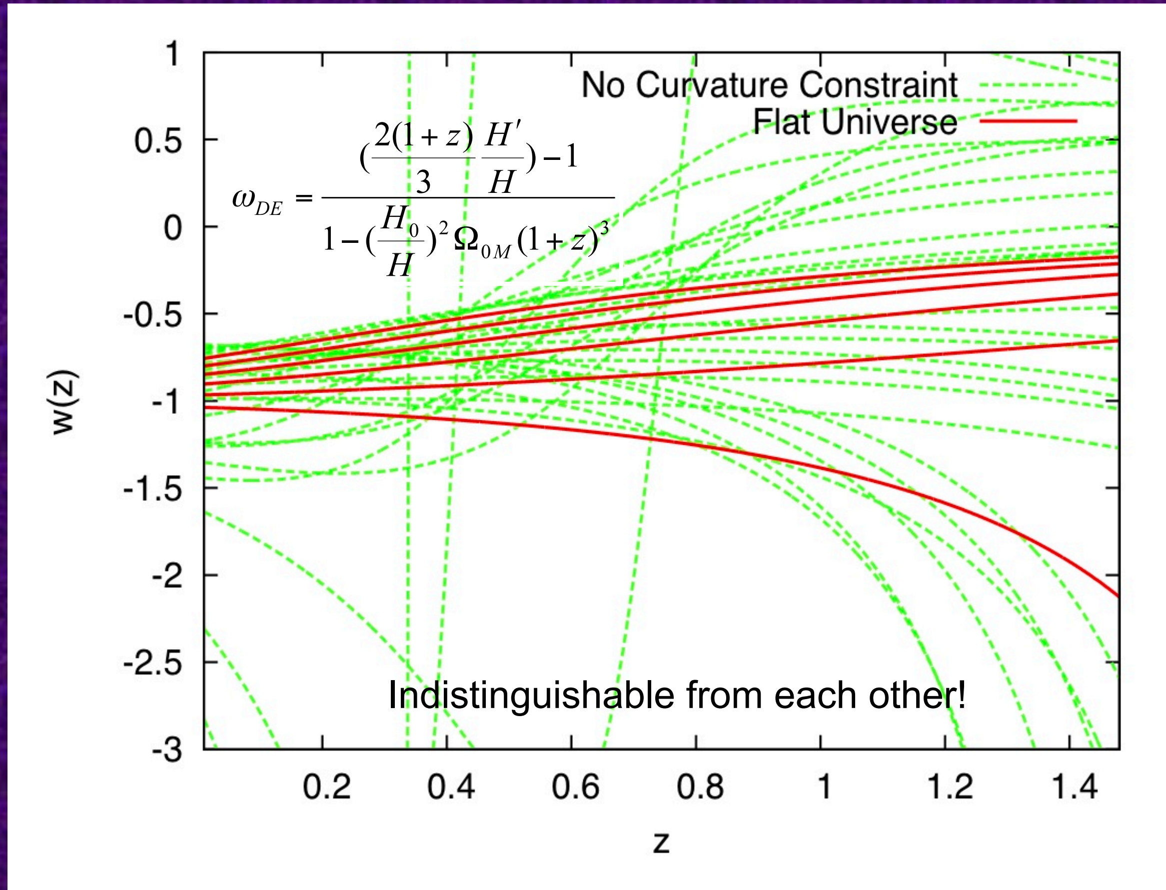
$$\begin{aligned} h(z)^2 &\equiv [H(z)/H_0]^2 \equiv (\dot{a}/a)^2 \\ &= \Omega_m(1+z)^3 + (1-\Omega_m-\Omega_{de})(1+z)^2 \\ &\quad + \Omega_{de} \exp\left[3\int_0^z \frac{dz'}{1+z'}[1+w(z')]\right], \end{aligned}$$

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.

But, How?

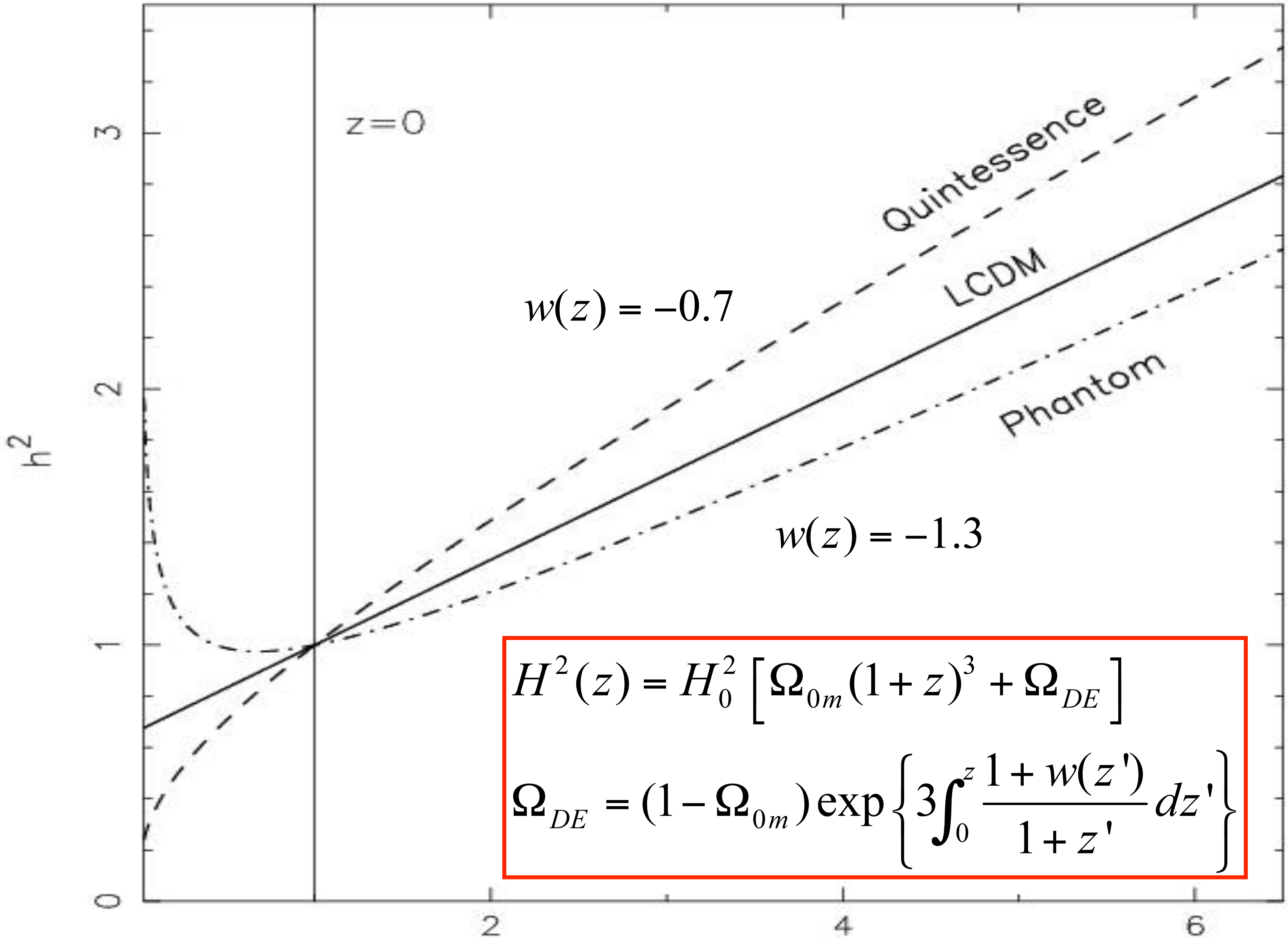
We should look for special characteristics of the standard model and relate them to observables.

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



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

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

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

Falsification: Null Test of Lambda

Om diagnostic

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

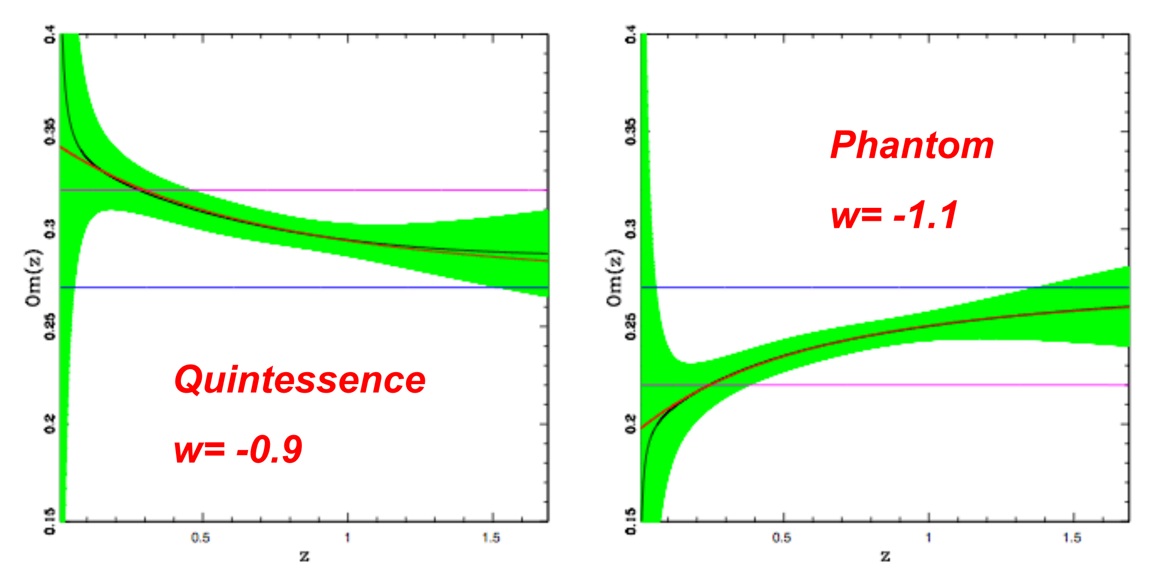
We Only Need h(z)

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

Om(z) is constant only for FLAT LCDM model

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

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



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

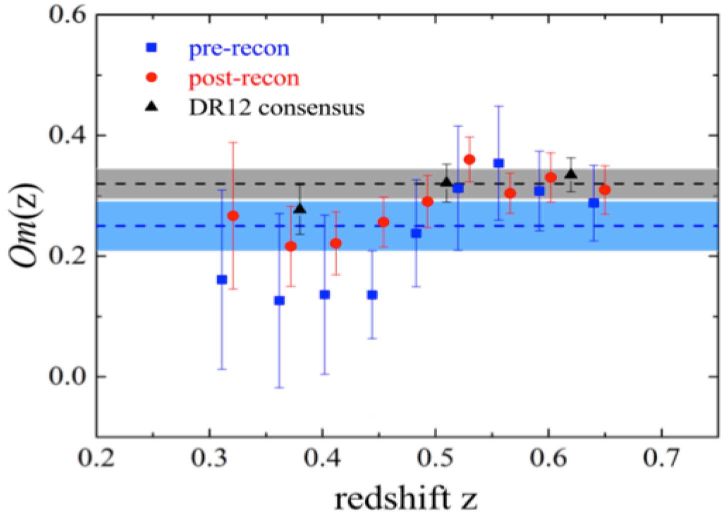


Figure 17. The $Om(z)$ values converted by our measurements on Hubble parameter in 9 redshift bins.

Om diagnostic is very well established

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

Deviations from ΛCDM and GR 13

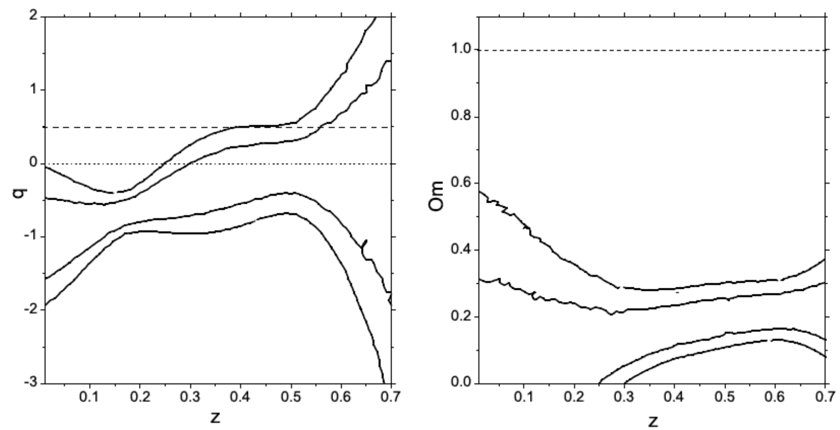


Figure 12. Confidence levels (1σ and 2σ) for the deceleration parameter as a function of redshift and Om(z) reconstructed from the compilation of geometric measurements in tables 2 and 3. H_0 is marginalised over with an HST prior. The dotted line in the left panel demarcates accelerating expansion (below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

WiggleZ collaboration
C. Blake et al, MNRAS 2011

10 *Blake et al.*

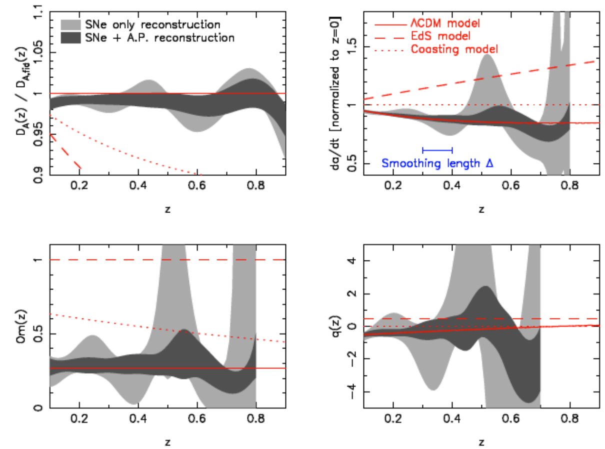


Figure 6. This Figure shows our non-parametric reconstruction of the cosmic expansion history using Alcock-Paczynski and supernovae data. The four panels of this figure display our reconstructions of the distance-redshift relation $D_A(z)$, the expansion rate $\dot{a}/H_0$, the Om(z) statistic and the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

A very recent result.

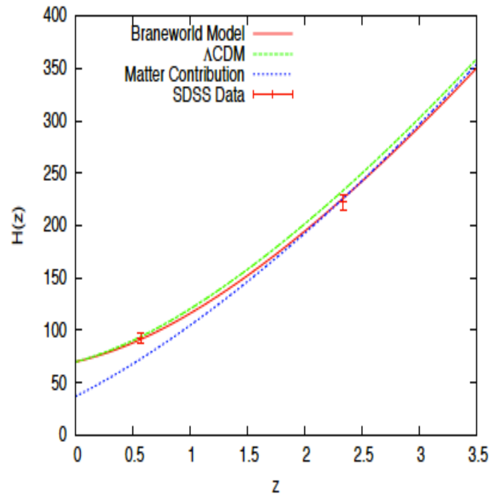
Important discovery if no systematic in the SDSS Quasar BAO data

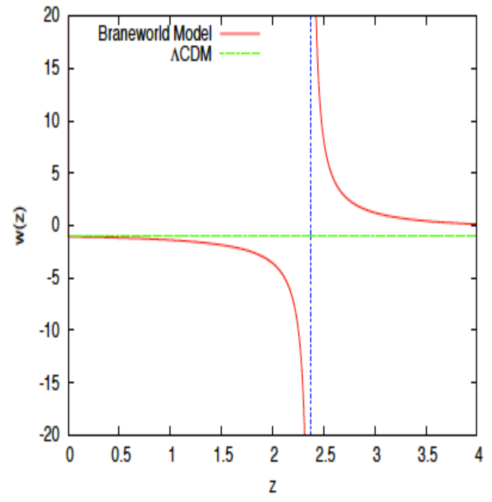
Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

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

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

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

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

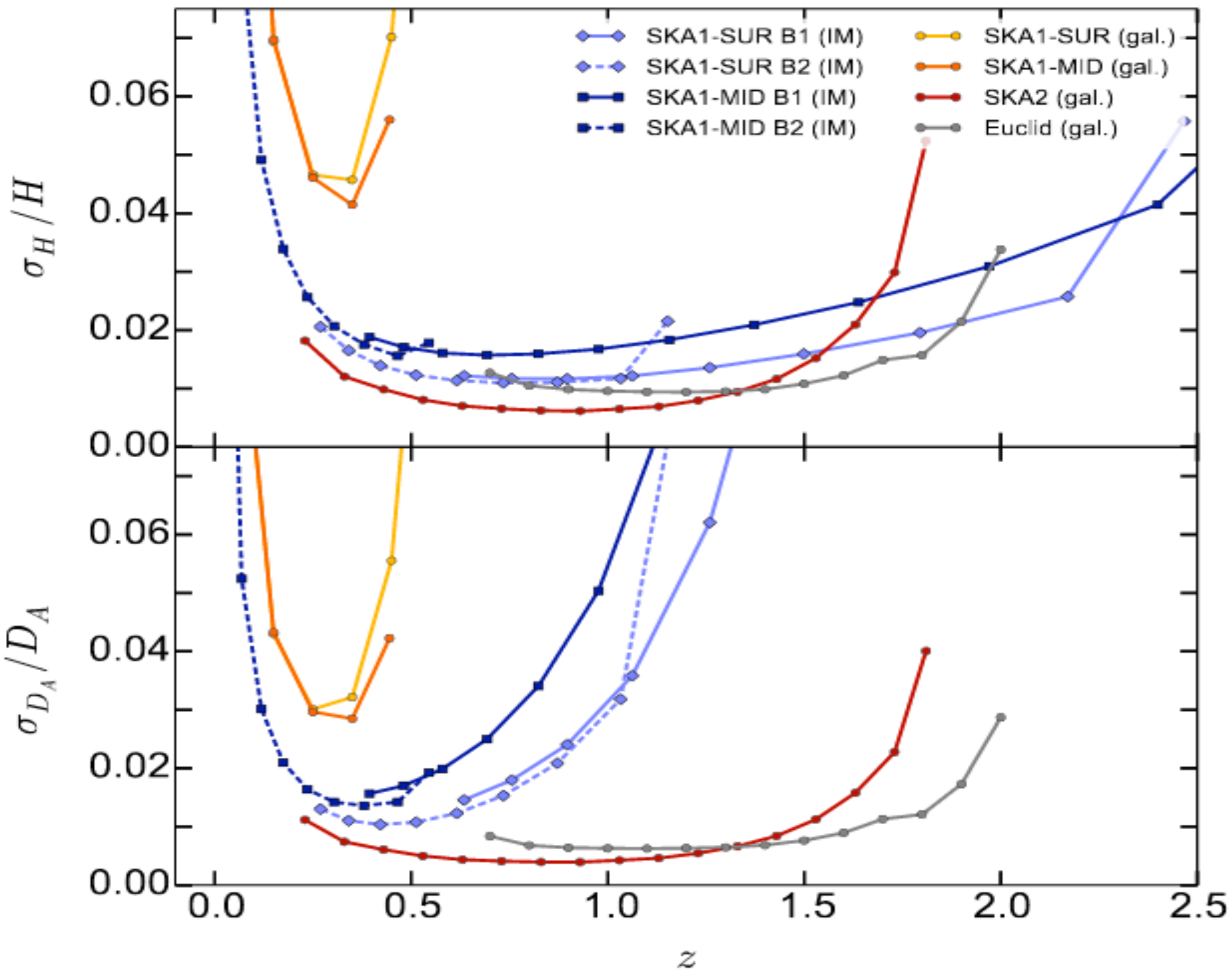
$$H(z_i; z_j) = \left(\frac{z_j}{z_i}\right)^2 \left[\frac{D(z_i)}{D(z_j)}\right]^2 \left[\frac{A(z_j)}{A(z_i)}\right]^3 = \frac{z_i}{z_j} \left[\frac{D(z_i)}{D(z_j)}\right]^2 \left[\frac{d(z_i)}{d(z_j)}\right]^3 ,$$

Om3 is independent of H0 and the 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.

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

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

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

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

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

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

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

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

(Present)t

Standard Model of Cosmology

Universe is Flat

Universe is Isotropic

Universe is Homogeneous (large scales)

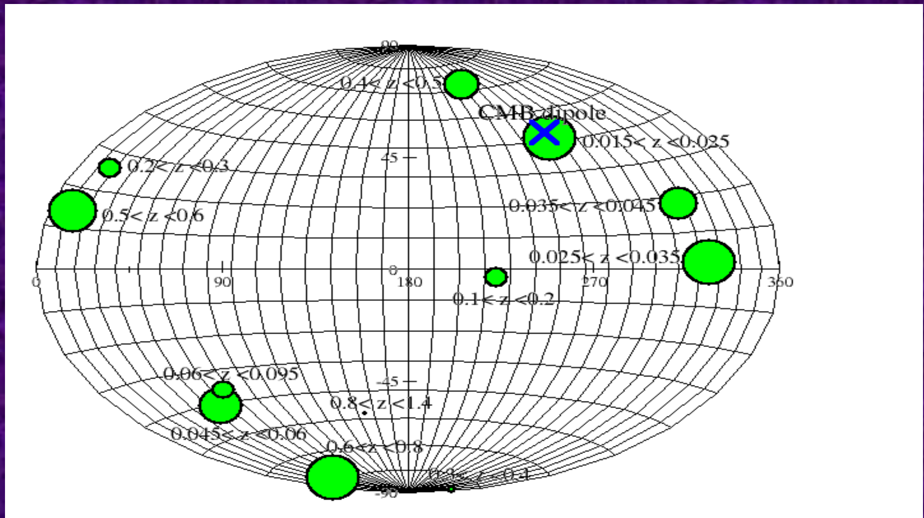
Dark Energy is Lambda (w=-1)

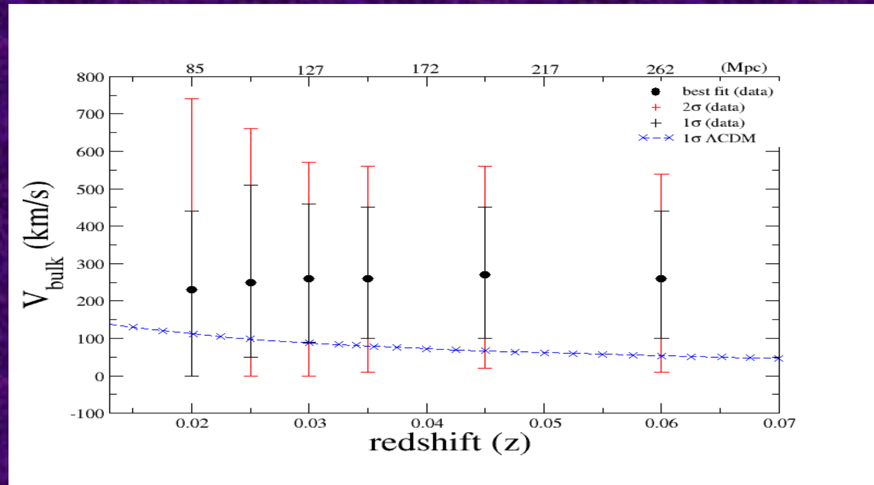
Power-Law primordial spectrum (n_s=const)

Dark Matter is cold

All within framework of FLRW

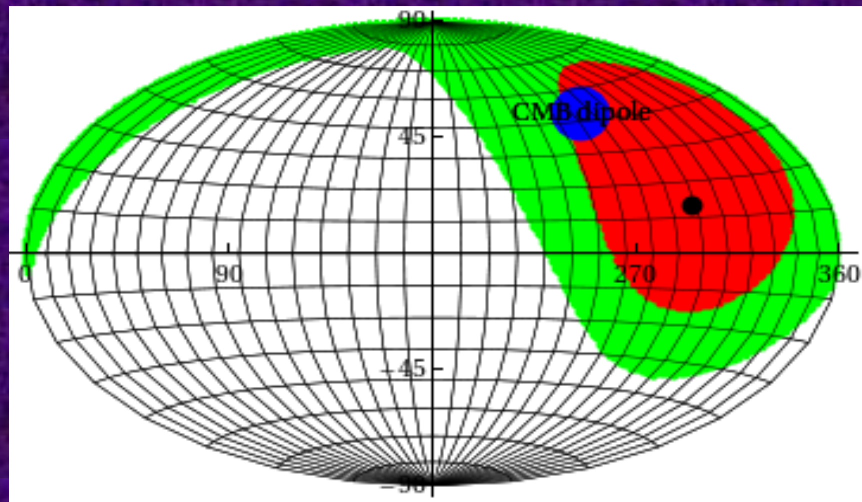
Falsification:
Is Universe Isotropic?





Method of Smoothed Residuals

➔*Residual Analysis,*
➔*Tomographic Analysis,*
➔*2D Gaussian Smoothing,*
➔*Frequentist Approach*
➔*Insensitive to non-uniform distribution of the data*



Colin, Mohayaee, Sarkar & Shafieloo MNRAS 2011

Measuring cosmic bulk flows with Type Ia Supernovae from the Nearby Supernova Factory

U. Feindt[1*], M. Kerschhaggl[1*], M. Kowalski[1], G. Aldering[2], P. Antilogus[3], C. Aragon[2], S. Bailey[2], C. Baltay[4], S. Bongard[3], C. Buton[1], A. Canto[3], F. Cellier-Holzem[3], M. Childress[5], N. Chotard[6], Y. Copin[6], H. K. Fakhouri[2,7], E. Gangler[6], J. Guy[3], A. Kim[2], P. Nugent[8,9], J. Nordin[2,10], K. Paech[1], R. Pain[3], E. Pecontal[11], R. Pereira[6], S. Perlmutter[2,7], D. Rabinowitz[4], M. Rigault[6], K. Runge[2], C. Saunders[2], R. Scalzo[5], G. Smadja[6], C. Tao[12,13], R. C. Thomas[8], B. A. Weaver[14], C. Wu[3,15]

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ABSTRACT

Context. Our Local Group of galaxies appears to be moving relative to the cosmic microwave background with the source of the peculiar motion still uncertain. While in the past this has been studied mostly using galaxies as distance indicators, the weight of type Ia supernovae (SNe Ia) has increased recently with the continuously improving statistics of available low-redshift supernovae.
Aims. We measured the bulk flow in the nearby universe ($0.015 < z < 0.1$) using 117 SNe Ia observed by the Nearby Supernova Factory, as well as the Union2 compilation of SN Ia data already in the literature.
Methods. The bulk flow velocity was determined from SN data binned in redshift shells by including a coherent motion (dipole) in a cosmological fit. Additionally, a method of spatially smoothing the Hubble residuals was used to verify the results of the dipole fit. To constrain the location and mass of a potential mass concentration (e.g., the Shapley supercluster) responsible for the peculiar motion, we fit a Hubble law modified by adding an additional mass concentration.
Results. The analysis shows a bulk flow that is consistent with the direction of the CMB dipole up to $z \sim 0.06$, thereby doubting the volume over which conventional distance measures are sensitive to a bulk flow. We see no significant turnover behind the center of the Shapley supercluster. A simple attractor model in the proximity of the Shapley supercluster is only marginally consistent with our

Method of Smoothed Residuals is well received and was used recently by Supernovae Factory collaboration

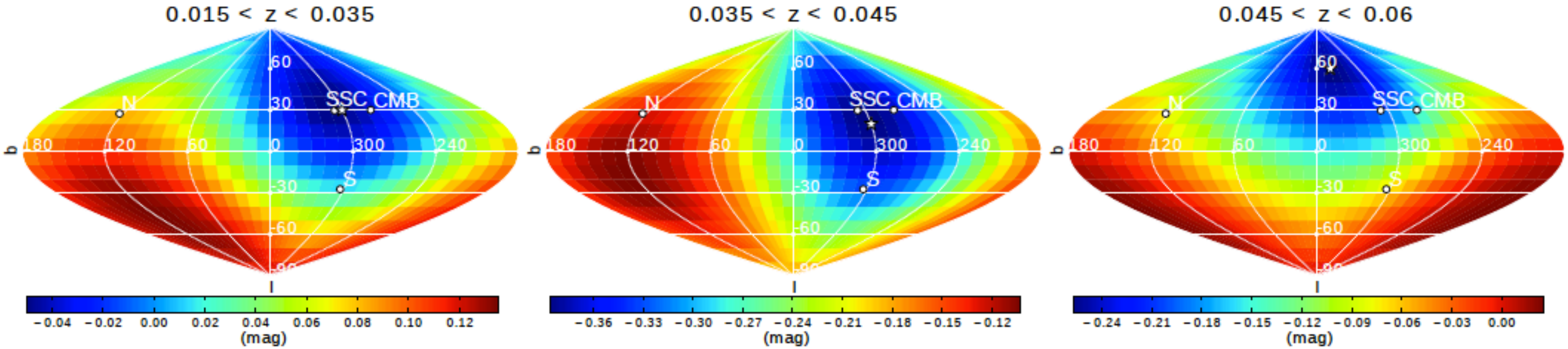


Fig. 3. Magnitude residuals of SNe Ia from the combined Union2 and SNFACTORY dataset as a function of galactic coordinates (l, b) after smoothing with a Gaussian window function of width $\delta = \frac{\pi}{2}$ in the redshift range $0.015 < z < 0.035$ (left), $0.035 < z < 0.045$ (middle) and $0.045 < z < 0.06$ (right). The bulk flow direction is marked by a star.

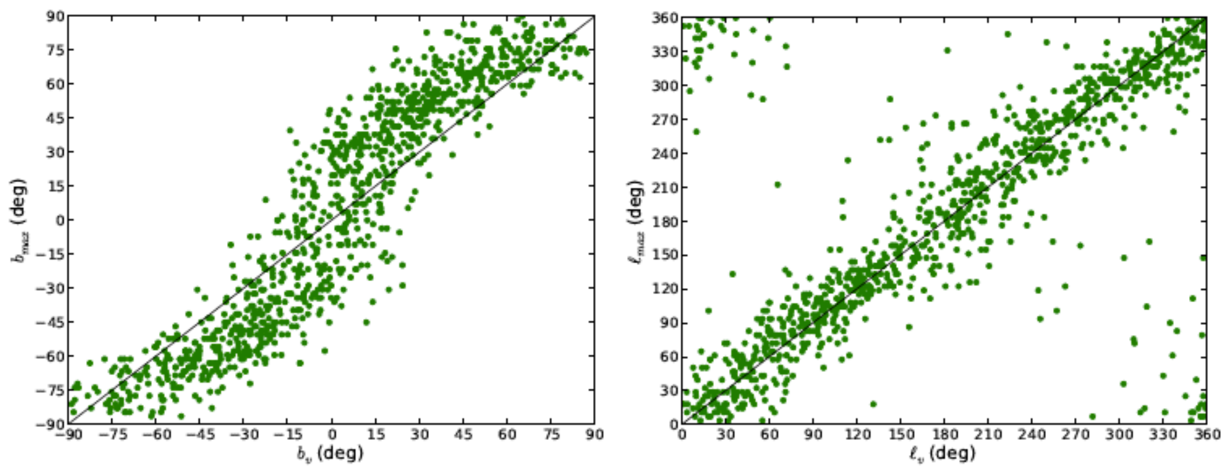
Catalog	$0.015 \le z < 0.025$	$0.025 \le z < 0.035$	$0.035 \le z < 0.045$	$0.045 \le z < 0.06$	$0.06 \le z < 0.1$
Union 2.1	61	51	15	17	19
Constitution	53	40	11	12	8
LOSS	76	64	23	17	19
Combined	98	67	22	27	12

Method of Smoothed Residuals

New Results and Bias Control

Δz	Catalog	$b_{\max}$	$\ell_{\max}$	p	Δz	Catalog	$b_{\max}$	$\ell_{\max}$	p
	Union 2.1	49°	259°	0.084		Union 2.1	49°	259°	0.084
	Const (SALT II)	20°	284°	0.624		Const (SALT II)	20°	284°	0.624
$0.015 \le z < 0.025$	Const (MLCS 17)	67°	241°	0.692	$0.015 < z \le 0.025$	Const (MLCS 17)	67°	241°	0.692
	LOSS	4°	247°	0.412		LOSS	4°	247°	0.412
	Combined	27°	241°	0.179		Combined	27°	241°	0.179
	Union 2.1	−29°	289°	0.665		Union 2.1	29°	274°	0.166
	Const (SALT II)	36°	320°	0.271		Const (SALT II)	27°	322°	0.201
$0.025 \le z < 0.035$	Const (MLCS 17)	40°	313°	0.202	$0.015 < z \le 0.035$	Const (MLCS 17)	52°	288°	0.201
	LOSS	38°	320°	0.156		LOSS	39°	283°	0.177
	Combined	56°	328°	0.339		Combined	41°	266°	0.119
	Union 2.1	27°	320°	0.172		Union 2.1	31°	284°	0.063
	Const (SALT II)	25°	306°	0.672		Const (SALT II)	27°	301°	0.123
$0.035 \le z < 0.045$	Const (MLCS 17)	36°	316°	0.192	$0.015 < z \le 0.045$	Const (MLCS 17)	49°	299°	0.083
	LOSS	−27°	292°	0.534		LOSS	20°	284°	0.149
	Combined	11°	313°	0.381		Combined	38°	276°	0.070
	Union 2.1	−49°	58°	0.412		Union 2.1	25°	295°	0.198
	Const (SALT II)	−54°	55°	0.572		Const (SALT II)	22°	310°	0.216
$0.045 \le z < 0.06$	Const (MLCS 17)	−59°	68°	0.074	$0.015 < z \le 0.06$	Const (MLCS 17)	38°	315°	0.372
	LOSS	54°	3°	0.457		LOSS	22°	288°	0.159
	Combined	−12°	94°	0.495		Combined	39°	281°	0.176
	Union 2.1	−5°	43°	0.426		Union 2.1	25°	306°	0.295
	Const (SALT II)	54°	32°	0.574		Const (SALT II)	27°	317°	0.197
$0.06 \le z < 0.1$	Const (MLCS 17)	−4°	65°	0.352	$0.015 < z \le 0.1$	Const (MLCS 17)	41°	342°	0.431
	LOSS	52°	349°	0.532		LOSS	27°	295°	0.114
	Combined	−54°	65°	0.788		Combined	36°	280°	0.270

Δz	p_A	p_B
$0.015 \le z < 0.025$	0.179	0.371
$0.015 \le z < 0.035$	0.119	0.355
$0.015 \le z < 0.045$	0.070	0.290
$0.015 \le z < 0.060$	0.176	0.412
$0.015 \le z < 0.100$	0.270	0.531

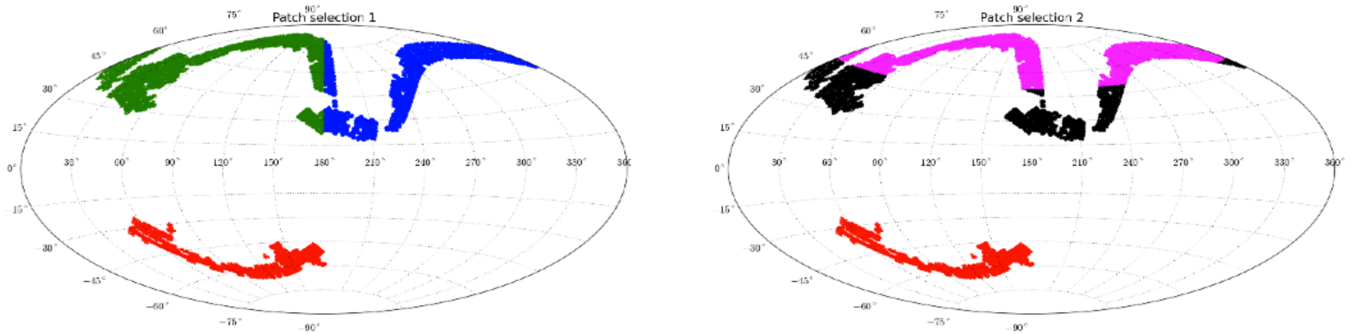


Bias in the Sky

	North ($b_v > 20°$)		South ($b_v < -20°$)	
$V_{\rm bulk}({\rm kms}^{-1})$	$(\Delta b, \Delta\ell)$	$(\delta b, \delta\ell)$	$(\Delta b, \Delta\ell)$	$(\delta b, \delta\ell)$
400	$(13°, -3°)$	$(14°, 28°)$	$(-12°, 2°)$	$(14°, 29°)$
800	$(15°, -4°)$	$(9°, 22°)$	$(-13°, 2°)$	$(9°, 21°)$

Appleby, Shafieloo, JCAP 2014
Appleby, Shafieloo, Johnson, ApJ 2015

Falsification:
Testing Isotropy of the Universe in Matter Dominated Era through Lyman Alpha forest



Redshift range(z)	SNR	$\bar{F} \pm \Delta F$
$2.15 - 2.45$ ($\bar{z} = 2.3$)	$6 - 8$	$0.826^{+0.154}_{-0.375}$
	$8 - 10$	$0.822^{+0.138}_{-0.405}$
	> 10	$0.819^{+0.129}_{-0.487}$
$2.45 - 2.75$ ($\bar{z} = 2.6$)	$6 - 8$	$0.762^{+0.172}_{-0.39}$
	$8 - 10$	$0.758^{+0.159}_{-0.427}$
	> 10	$0.756^{+0.152}_{-0.454}$
$2.75 - 3.05$ ($\bar{z} = 2.9$)	$6 - 8$	$0.69^{+0.191}_{-0.377}$
	$8 - 10$	$0.687^{+0.181}_{-0.396}$
	> 10	$0.686^{+0.176}_{-0.413}$

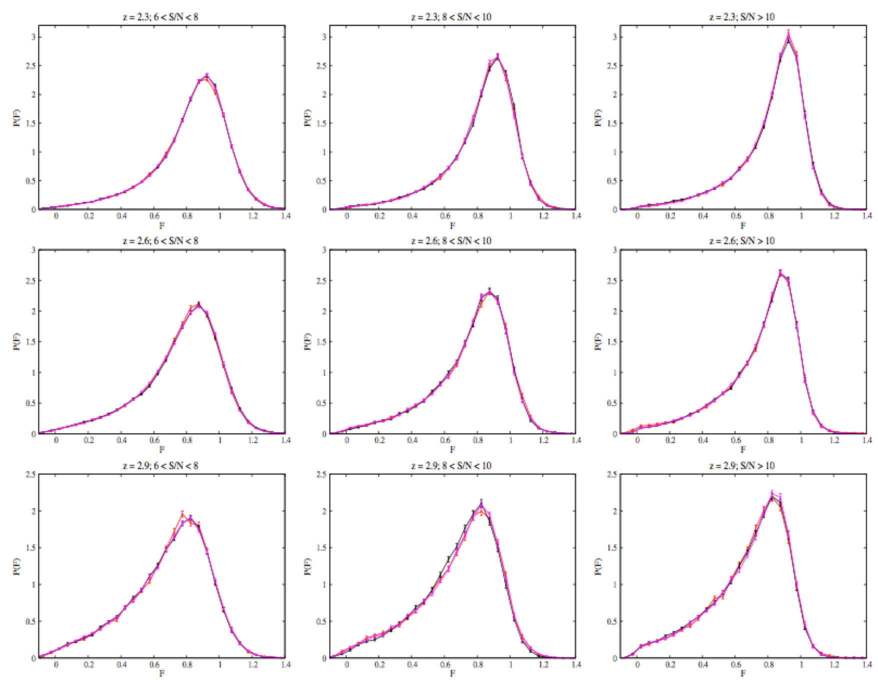
➔*Comparing statistical properties of the PDF of the Lyman-alpha transmitted flux in different patches*

➔*Different redshift bins and different signal to noise*

➔*Results for BOSS DR9 quasar sample*

Results consistent to Isotropy

Hazra and Shafieloo, JCAP 2015



Falsification: Test of Statistical Isotropy in CMB

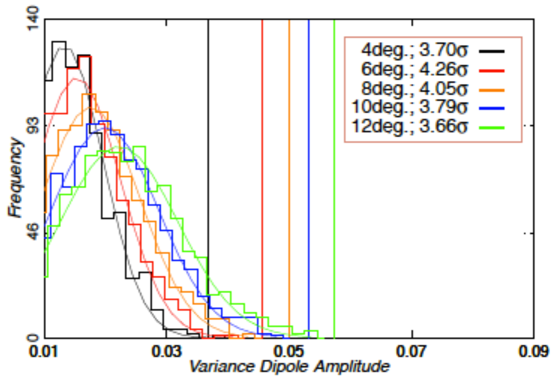


FIG. 3.— Histograms of the local-variance dipole amplitudes from the 1000 FFP6 simulations for disk radii 4°, 6°, 8°, 10° and 12°, together with the best-fit Gaussian distributions in all cases. Vertical lines indicate the corresponding amplitudes measured from the Planck data. The legend shows the rough estimates of detection significances derived from the Gaussian fits.

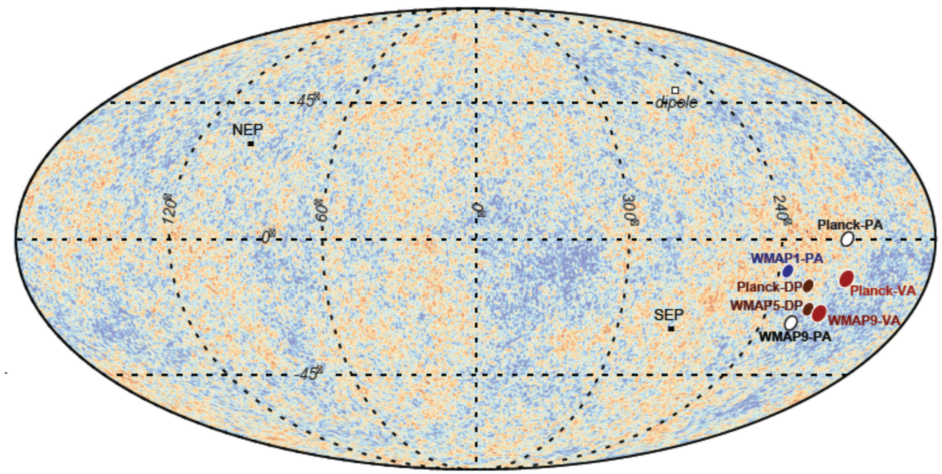


FIG. 6.— Asymmetry directions found in this work by analyzing the local variance of the WMAP 9-year and Planck 2013 data [denoted by *WMAP9-VA* and *Planck-VA*], as well as the directions found previously from the latest likelihood analyses of the dipole modulation model [denoted by *WMAP5-DP* (Hoftuft *et al.* 2009) and *Planck-DP* (Ade *et al.* 2013a)] and the local-power spectrum analyses [denoted by *WMAP1-PA* (Eriksen *et al.* 2004), *WMAP9-PA* (Axelsson *et al.* 2013) and *Planck-PA* (Ade *et al.* 2013a)] for the WMAP and Planck data.

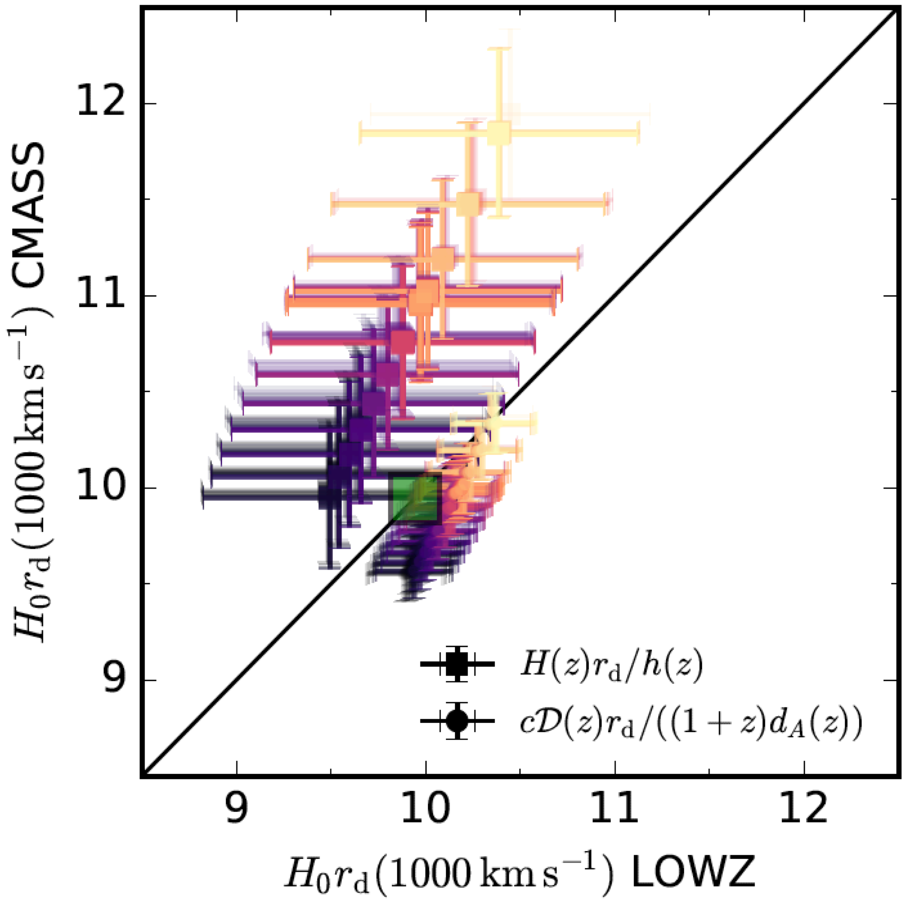
Using Local Variance to Test Statistical Isotropy in CMB maps

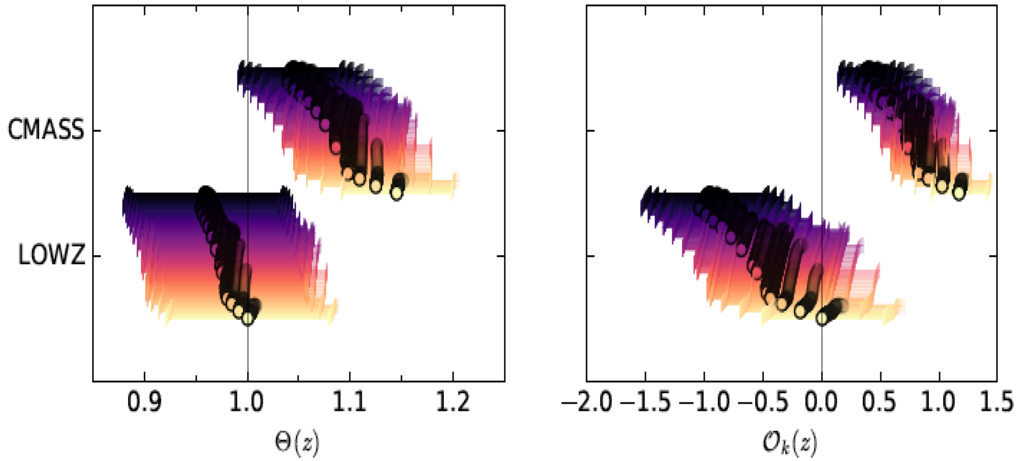
- ➔*Based on Crossing Statistic*
- ➔*Residual Analysis,*
- ➔*Real Space Analysis*
- ➔ *Low Sensitivity to Systematics*
- ➔*2D Adaptive Gaussian Smoothing*
- ➔*Frequentist Approach*

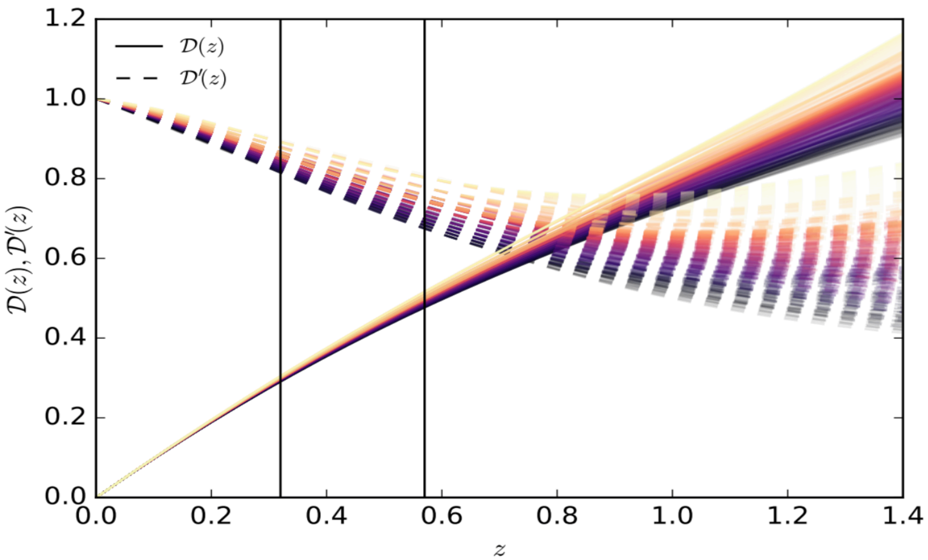
TABLE 1
ASYMMETRY DIRECTIONS

Map	(l,b) [°]	Significance or p-value	Reference
Planck-VA	(212, -13)	0/1000	present work
WMAP9-VA	(219, -24)	10/1000	present work
Planck-DP	(227, -15)	3.5σ	Ade *et al.* (2013a)
WMAP5-DP	(224, -22)	3.3σ	Hoftuft *et al.* (2009)
Planck-PA	(224, 0)	0/500	Ade *et al.* (2013a)
WMAP9-PA	(227, -27)	7/10000	Axelsson *et al.* (2013)

Akrami, Fantaye, Shafieloo, Eriksen, Hansen, Banday, Gorski, ApJ L 2014







Curvature and Metric Test by combining observables of SN and BAO data

L'Huillier and Shafieloo, arXiv:1606.06832

Shafieloo & Clarkson, PRD 2010
Wiltshire, PRD 2009
Clarkson, Bassett, Lu, PRL 2008

$$\Theta(z) = \frac{1+z}{c}\left(H(z)r_\mathrm{d}\frac{d_\mathrm{A}(z)}{r_\mathrm{d}}\right)\left(\frac{\mathcal{D}'(z)}{\mathcal{D}(z)}\right),$$

$$\mathcal{O}_k(z) = \frac{\Theta^2(z)-1}{\mathcal{D}^2(z)},$$

$$\Theta(z) \equiv h(z)\mathcal{D}'(z) = \frac{H(z)}{H_0}\mathcal{D}'(z) = 1.$$

Testing deviations from an assumed model

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

Holsclaw et al, PRD 2011
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 →

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

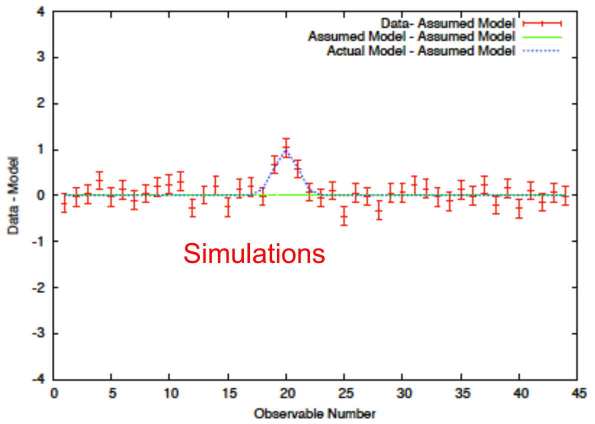
GP Hyper-parameters

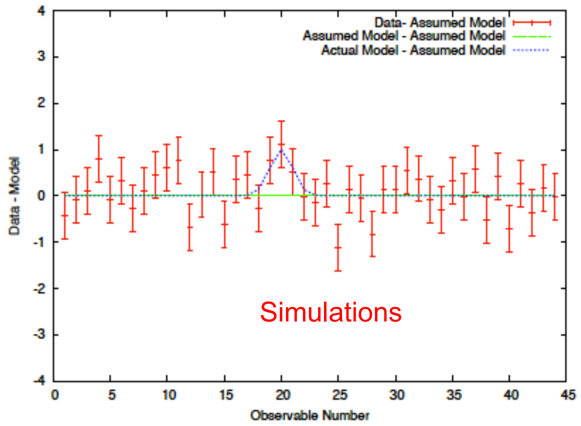
$$\mathrm{Cov}\left(\begin{bmatrix} \mathbf{f} \\ \mathbf{f}' \\ \mathbf{f}'' \end{bmatrix}\right) = \begin{bmatrix} \Sigma_{00}(Z_1,Z_1) & \Sigma_{01}(Z_1,Z_1) & \Sigma_{02}(Z_1,Z_1) \\ \Sigma_{10}(Z_1,Z_1) & \Sigma_{11}(Z_1,Z_1) & \Sigma_{12}(Z_1,Z_1) \\ \Sigma_{20}(Z_1,Z_1) & \Sigma_{21}(Z_1,Z_1)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

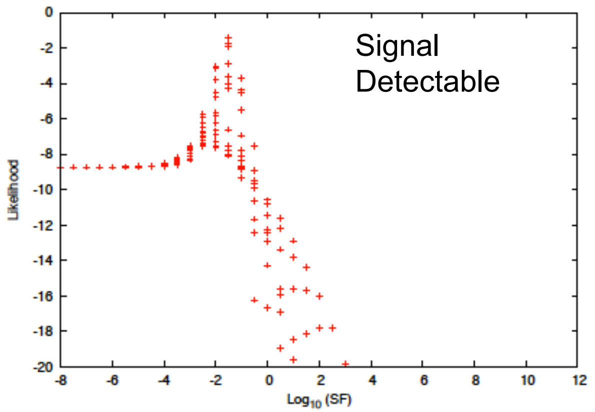
$$2\ln p(y|f) = -y^T \Sigma_{00}(Z,Z)^{-1} y - \ln\det \Sigma_{00}(Z,Z) - n\ln(2\pi),$$

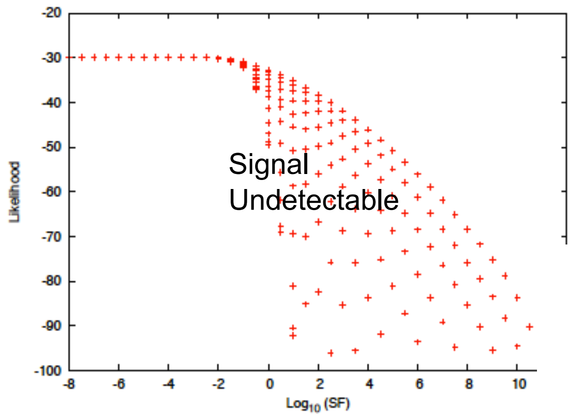
GP Likelihood

Detection of the features in the residuals

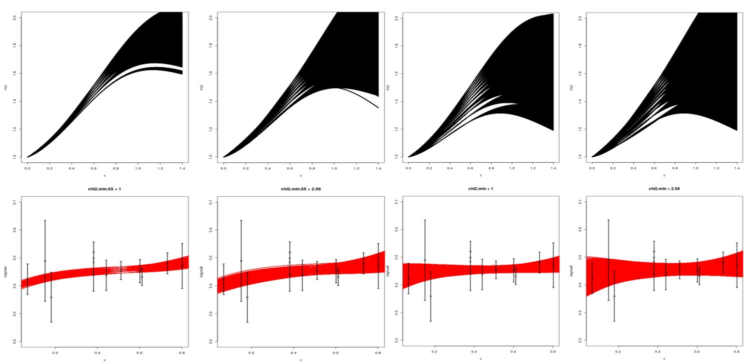






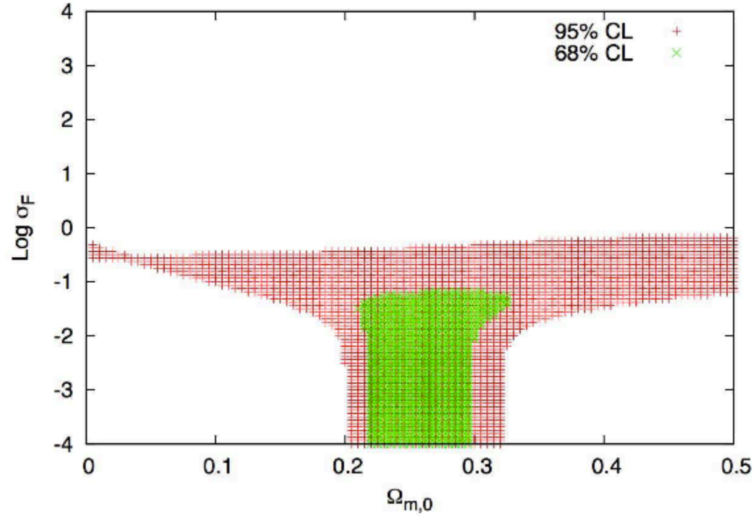


GP to test GR
Shafieloo, Kim, Linder, PRD 2013



Cosmic Growth vs Expansion

Aghamousa, L'Huillier & Shafieloo (in preo)



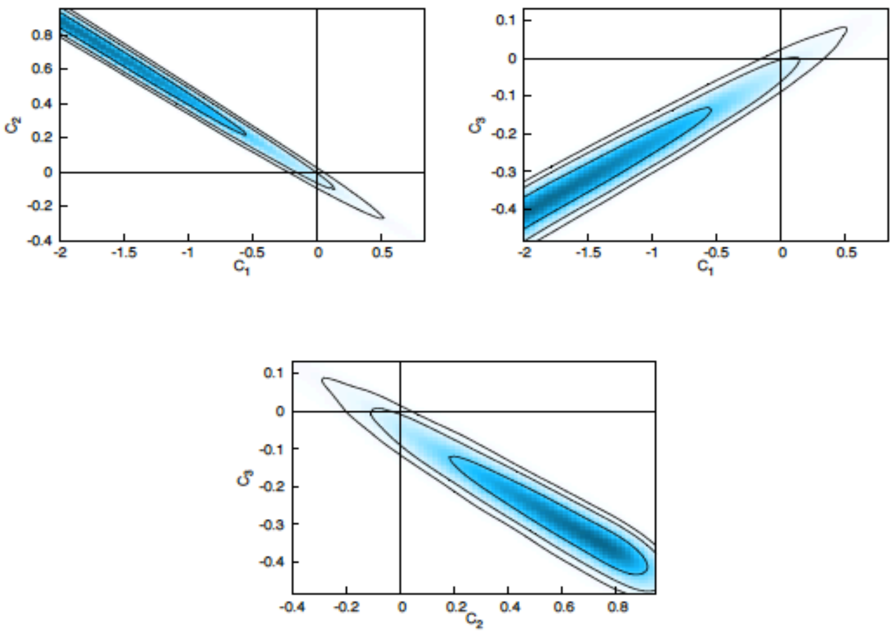
Crossing Statistic (Bayesian Interpretation)

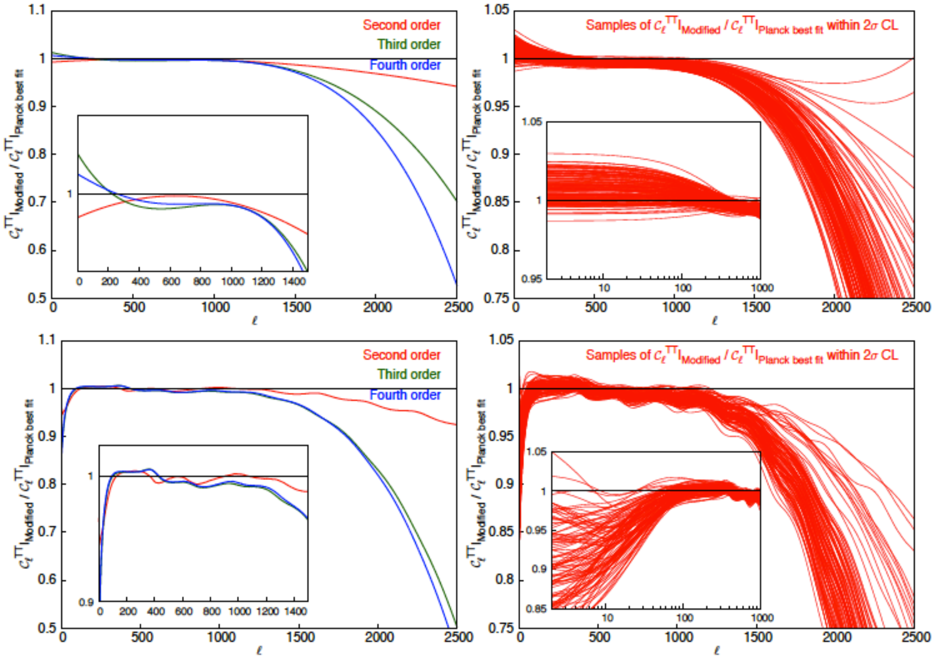
Theoretical model Crossing function

$$C_\ell^{\rm TT}\ |_{\rm modified}^{N} = C_\ell^{\rm TT}\ |_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H_0},\tau,{\rm A_S},{\rm n_S},\ell} \times T_i(C_0, C_1, C_2, ..., C_N, \ell).$$

Confronting the concordance model of cosmology with Planck 2013 data

Hazra and Shafieloo, JCAP 2014 ***Consistent only at 2~3 sigma CL***





Dates

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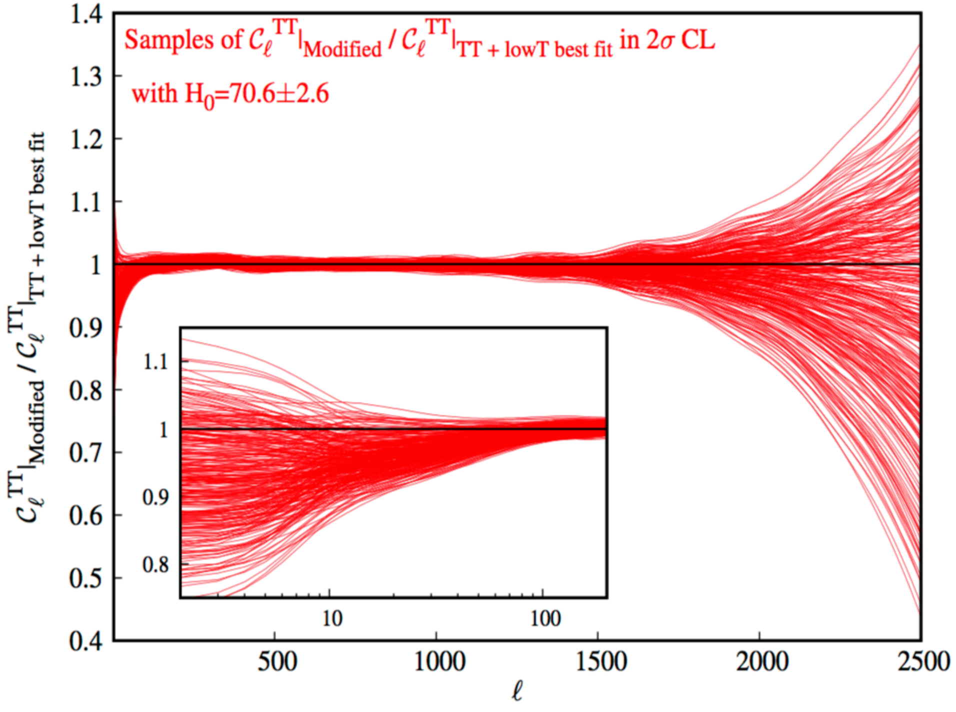
Crossing Statistic (Bayesian Interpretation)

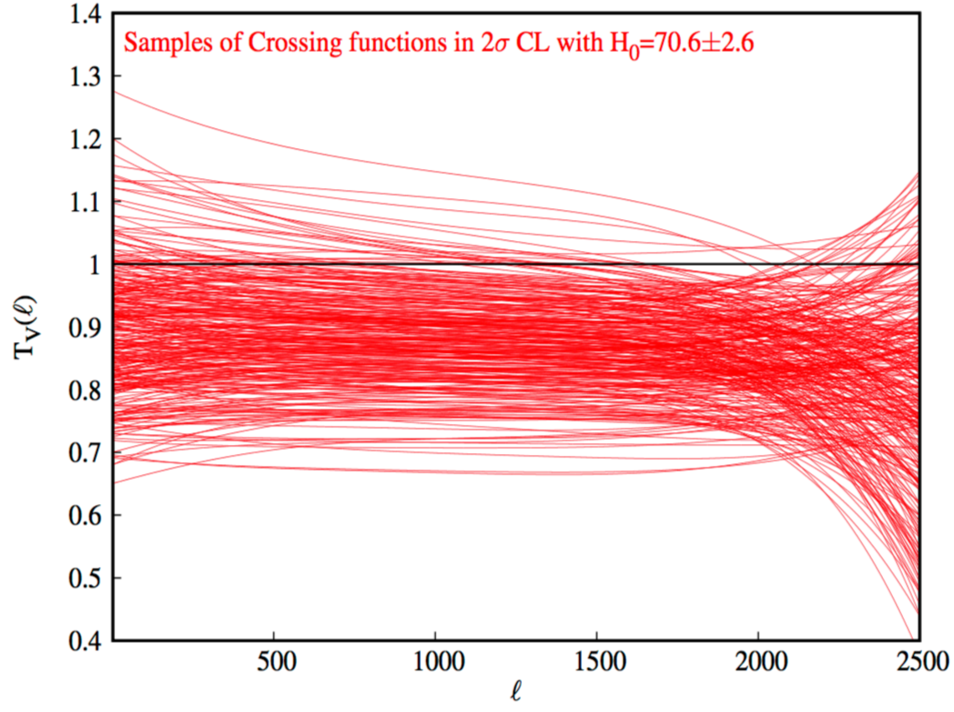
Theoretical model Crossing function

$$\mathcal{C}_\ell^{\rm TT}\,|^{N}_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\,|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H_0},\tau,{\rm A_S},{\rm n_S},\ell} \times T_i(C_0, C_1, C_2, ..., C_N, \ell).$$

Confronting the concordance model of cosmology with Planck 2015 data

Hazra and Shafieloo, arXiv:1610.07402 ***Completely Consistent***





Crossing Statistic (Bayesian Interpretation)

Theoretical model Crossing function

$$\mathcal{C}_\ell^{\rm TT}\ |^N_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\ |_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H}_0,\tau,{\rm A_S},{\rm n_S},\ell} \times T_i(C_0, C_1, C_2, ..., C_N, \ell).$$

Confronting the concordance model of cosmology with Planck 2015 data

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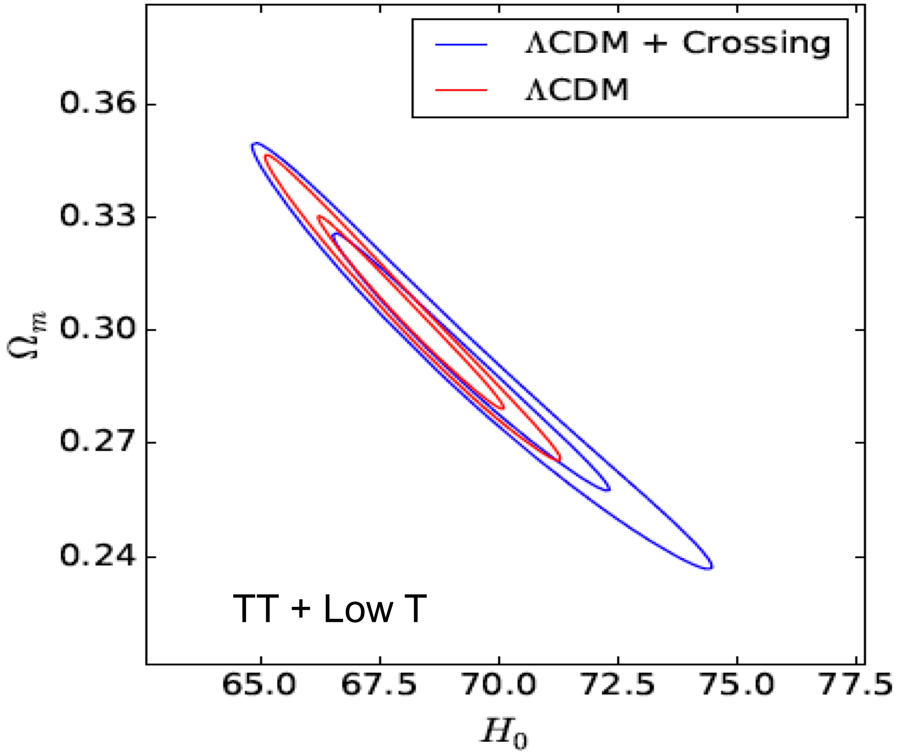


Crossing Statistic (Bayesian Interpretation)

Theoretical model — Crossing function

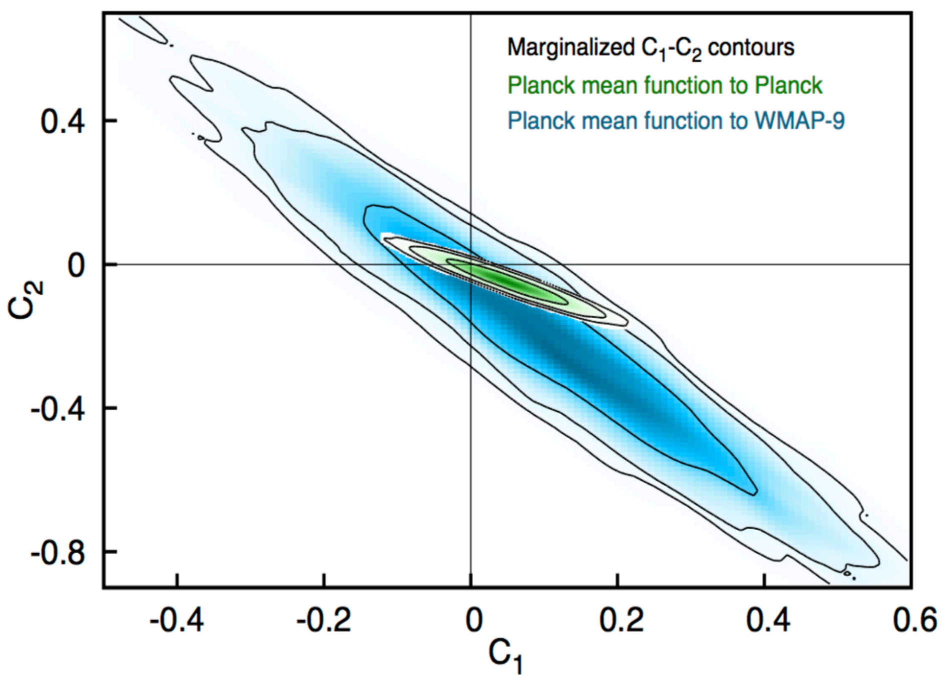
$$\mathcal{C}_\ell^{\rm TT}\Big|^N_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\Big|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H_0},\tau,{\rm A_S},{\rm n_S},\ell} \times T_i(C_0, C_1, C_2, ..., C_N, \ell).$$

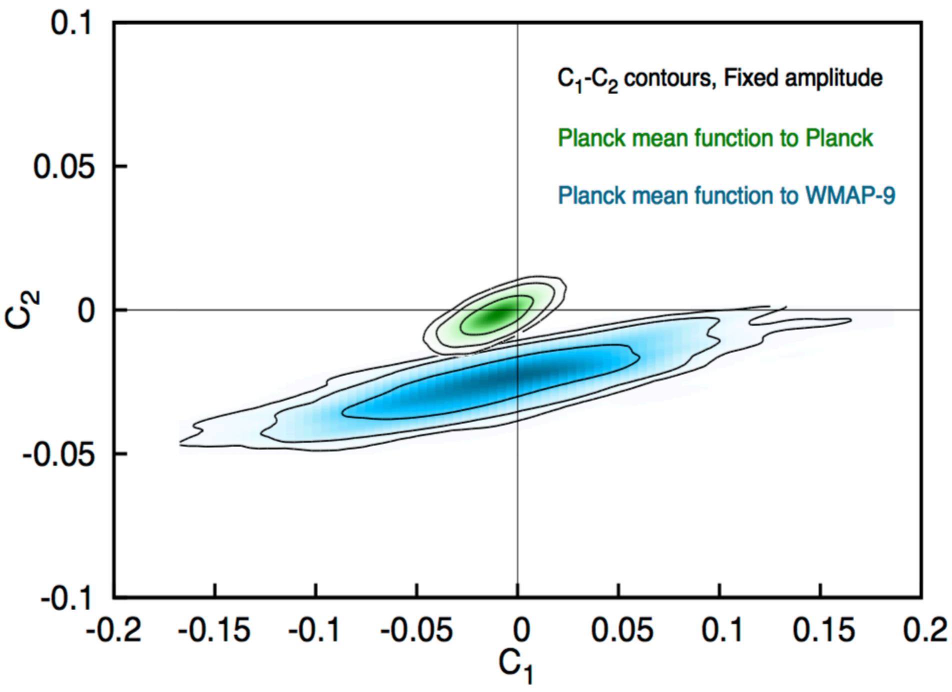
Test of consistency between Planck and WMAP

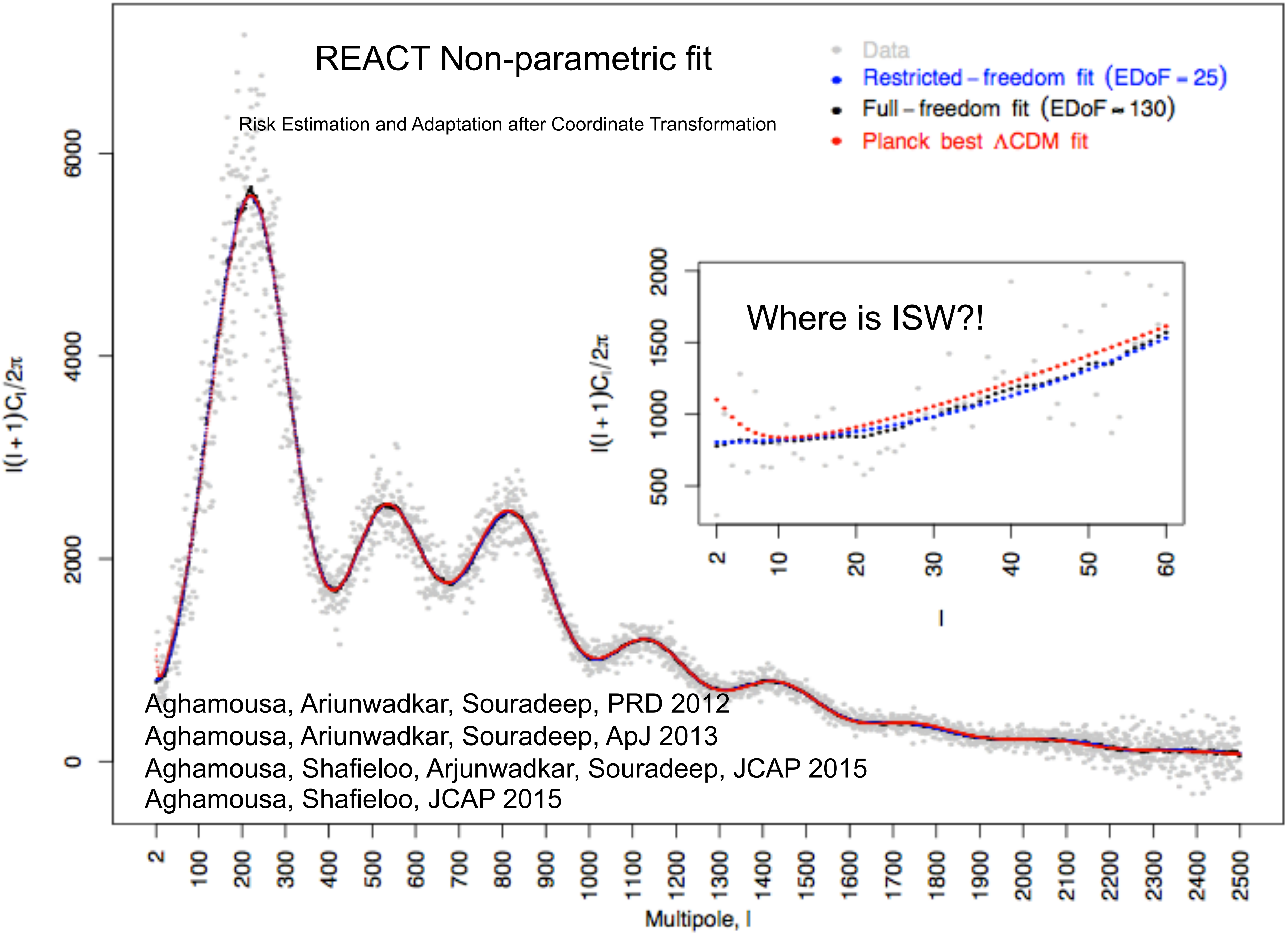
Hazra and Shafieloo, PRD 2014

Amplitude discrepancy!

(issue was later on resolved)







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
Multipole, l
l
Aghamousa, Ariunwadkar, Souradeep, PRD 2012
Aghamousa, Ariunwadkar, Souradeep, ApJ 2013
Aghamousa, Shafieloo, Arjunwadkar, Souradeep, JCAP 2015
Aghamousa, Shafieloo, JCAP 2015

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.

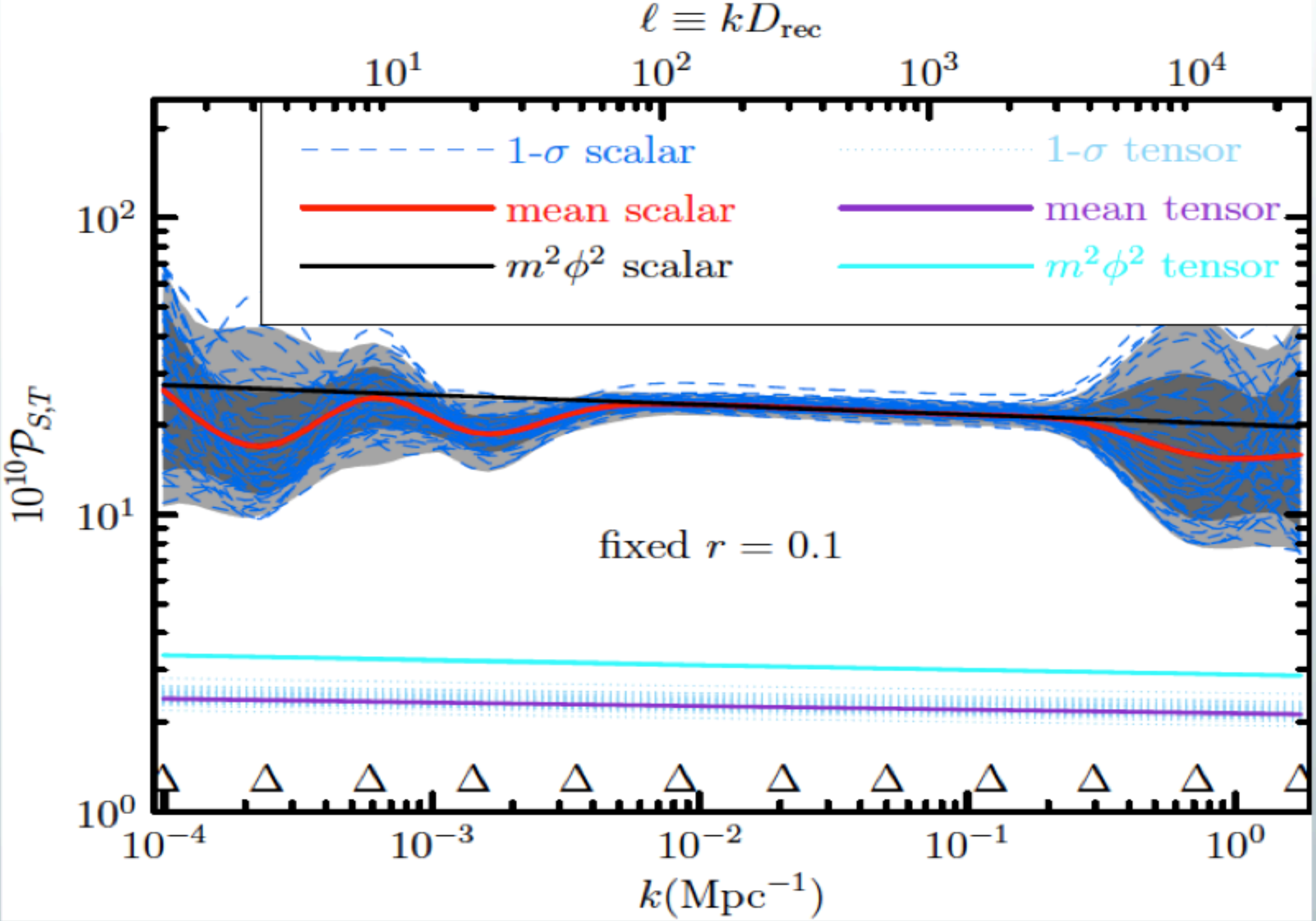
Conclusion (Large Scales)

- 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.

Planck 2015: No feature

Power spectra reconstruction

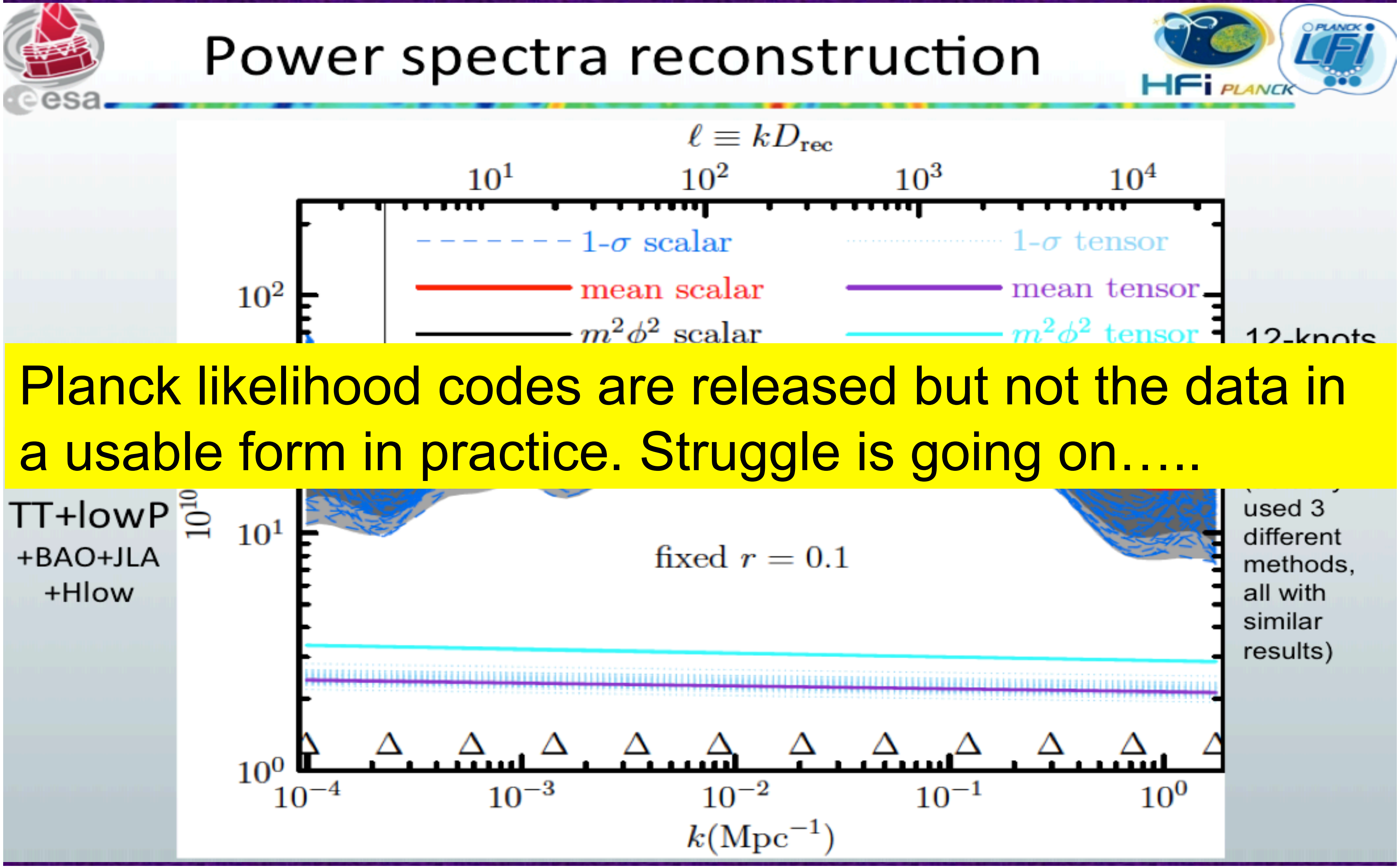


2015
TT+lowP
+BAO+JLA
+Hlow

12-knots power spectra

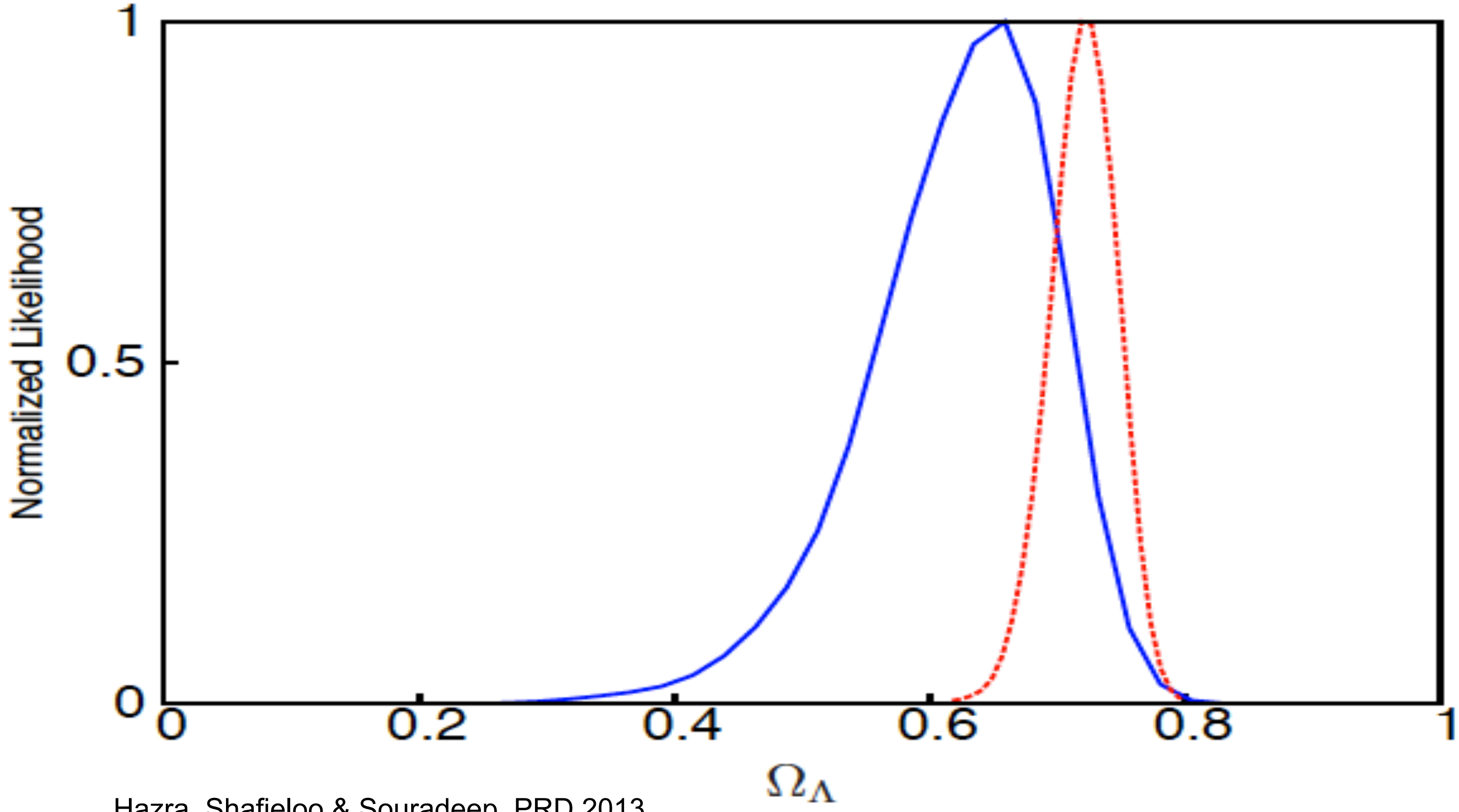
(actually used 3 different methods, all with similar results)

Planck 2015: No feature



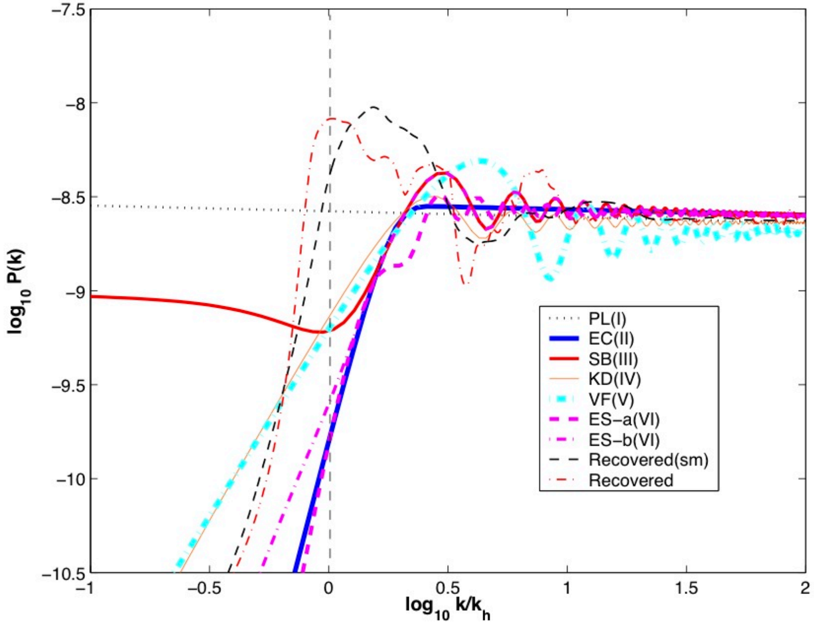
Planck likelihood codes are released but not the data in a usable form in practice. Struggle is going on…..

First strong Indication towards Dark Energy using CMB data alone with no prior on Hubble parameter or form of the primordial spectrum.



Hazra, Shafieloo & Souradeep, PRD 2013

The one dimensional marginalized likelihood of dark energy density Ω_Λ obtained using free form of primordial spectrum (in solid blue line) and using power law (in dashed red line). $\Omega_\Lambda = 0$ is clearly not favored by the data even if we allow a power spectra free of forms. Quantitatively, in 4σ the data rules out $\Omega_\Lambda < 0.25$. This is probably the first indication towards presence of dark energy with a very high confidence using CMB data alone.



Starobinsky (1992)
Kink in the potential
Vilenkin and Ford (1982)
Pre-inflationary radiation dominated era
Contaldi et al, (2003)
Pre-inflationary kinetic dominated era
Cline et al, (2003)
Exponential cut off

Shafieloo & Souradeep (PRD 2004)
Direct Reconstruction

Theoretical Implication:
Importance of the Features in the primordial spectrum

TABLE II: Best fit values of parameters specifying the initial power spectrum (k_*, α, R_*, n_s) and other relevant cosmological parameters for a class of model power spectra with a infrared cutoff (dataset used: WMAP TT data).

Parameter	Expo-cutoff EC(II)	Starobinsky SB(III)	Kin. Dom. KD(IV)	VF VF(V)	**Expo-staro(a)**† ES-a(VI)	Expo-staro(b)‡ ES-b(VI)	Power Law PL(I)
$k_*(\times 10^{-4})\mathrm{Mpc}^{-1}$	$3.0^{+4.8}_{-2.9}$	$3.1^{+5.8}_{-2.8}$	$3.5^{+3.0}_{-3.3}$	$0.4^{+0.7}_{-0.3}$	$\mathbf{3.0^{+0.5}_{-2.0}}$	$3.1^{+5.8}_{-2.1}$	–
α	$9.6^{+0.3}_{-8.6}$	–	–	–	$\mathbf{0.58^{+4.6}_{-0.43}}$	$0.72^{+9.1}_{-0.55}$	–
R_*	–	$0.73^{+0.25}_{-0.14}$	–	–	$\mathbf{0.17^{+0.80}_{-0.15}}$	$0.35^{+0.63}_{-0.20}$	–
n_s	$0.95^{+0.16}_{-0.03}$	$0.98^{+0.14}_{-0.07}$	$1.4^{+0.09}_{-0.90}$	$1.0^{+0.04}_{-0.15}$	$\mathbf{0.96^{+0.15}_{-0.08}}$	$0.99^{+0.08}_{-0.12}$	$0.96^{+0.30}_{-0.05}$
τ	$0.014^{+0.37}_{-0.004}$	$0.15^{+0.25}_{-0.14}$	$0.17^{+0.09}_{-0.15}$	$0.01^{+0.35}_{-0.001}$	$\mathbf{0.26^{+0.15}_{-0.08}}$	$0.28^{+0.12}_{-0.27}$	$0.014^{+0.500}_{-0.004}$
$z_{re}{}^a$	$3.2^{+21.7}_{-0.7}$	$16.3^{+11.5}_{-13.9}$	$17.8^{+4.9}_{-15.2}$	$2.7^{+23.5}_{-0.22}$	$\mathbf{23.8^{+5.9}_{-5.0}}$	$23.5^{+3.9}_{-21.0}$	$3.2^{+26.6}_{-0.83}$
Ω_Λ	$0.70^{+0.16}_{-0.18}$	$0.71^{+0.17}_{+0.24}$	$0.70^{+0.13}_{-0.21}$	$0.71^{+0.12}_{-0.20}$	$\mathbf{0.74^{+0.13}_{-0.10}}$	$0.75^{+0.12}_{-0.23}$	$0.65^{+0.24}_{-0.23}$
$\Omega_b h^2$	$0.022^{+0.006}_{-0.001}$	$0.023^{+0.005}_{-0.004}$	$0.024^{+0.001}_{-0.002}$	$0.023^{+0.005}_{-0.002}$	$\mathbf{0.023^{+0.004}_{-0.003}}$	$0.025^{+0.002}_{-0.005}$	$0.023^{+0.009}_{-0.002}$
$-\ln\mathcal{L}$	484.89	484.89	485.18	486.46	**483.44**	484.45	486.28
$\chi^2_{\rm eff} \equiv -2\ln\mathcal{L}$	969.78	969.78	970.36	972.92	**966.88**	968.90	972.56
d.o.f.	891	891	892	892	**890**	890	893

Inflationary scenarios

Is the recovered spectrum unusual for inflationary scenarios?

- Starobinsky (1992): sharp changes in the slope in the inflation potential.
- Vilenkin and Ford (1982): pre-inflationary radiation dominated epoch.

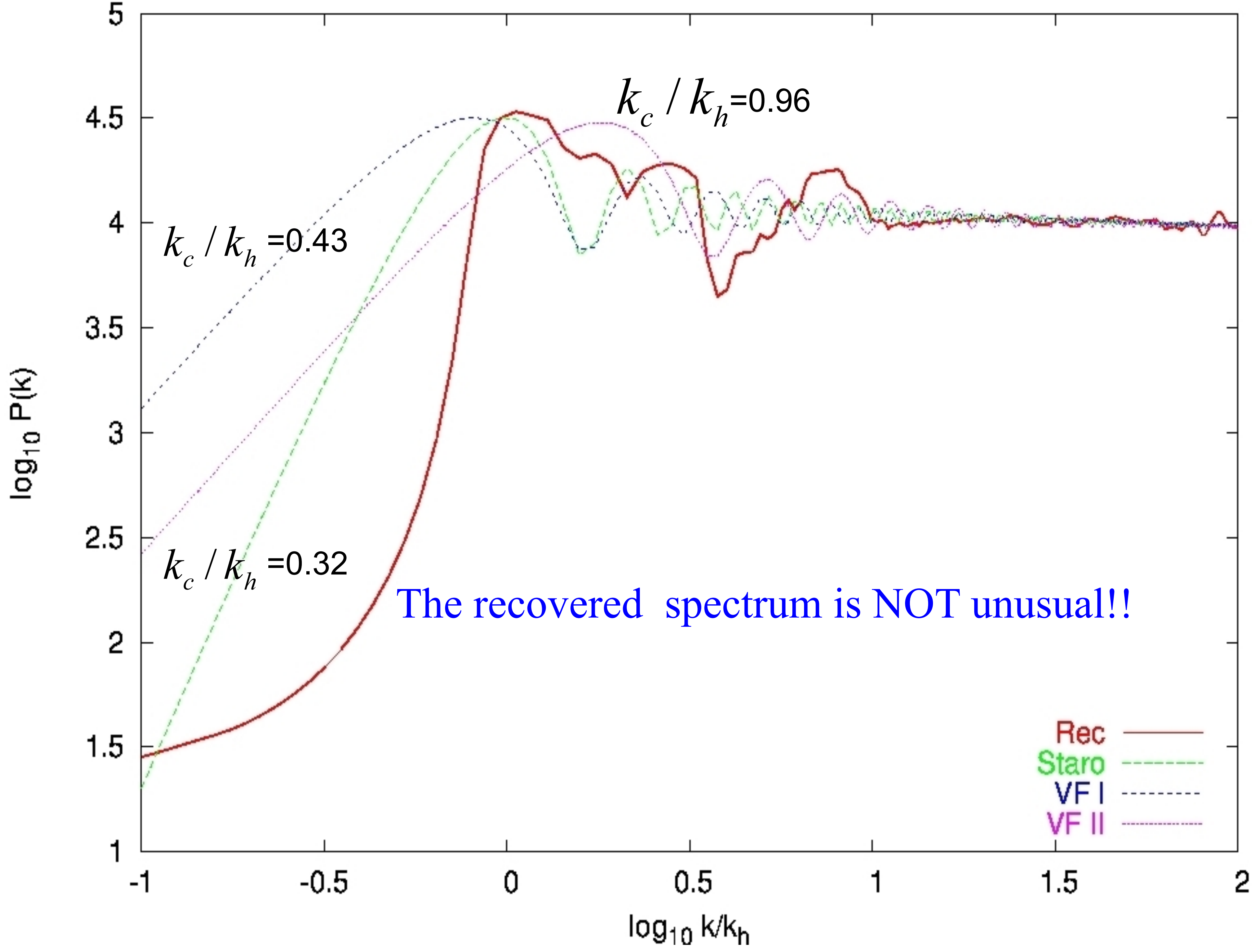
$$P(k) = P_0(k)D(k,k_c,r) = A_s k^{1-n_s}[1-3(r-1)\frac{1}{y}((1-\frac{1}{y^2})\sin 2y + \frac{2}{y}\cos 2y + \frac{9}{2}(r-1)^2\frac{1}{y^2}((1+\frac{1}{y^2})\cos 2y - \frac{2}{y}\sin 2y)]$$

Starobinsky

$$y = k / k_c$$

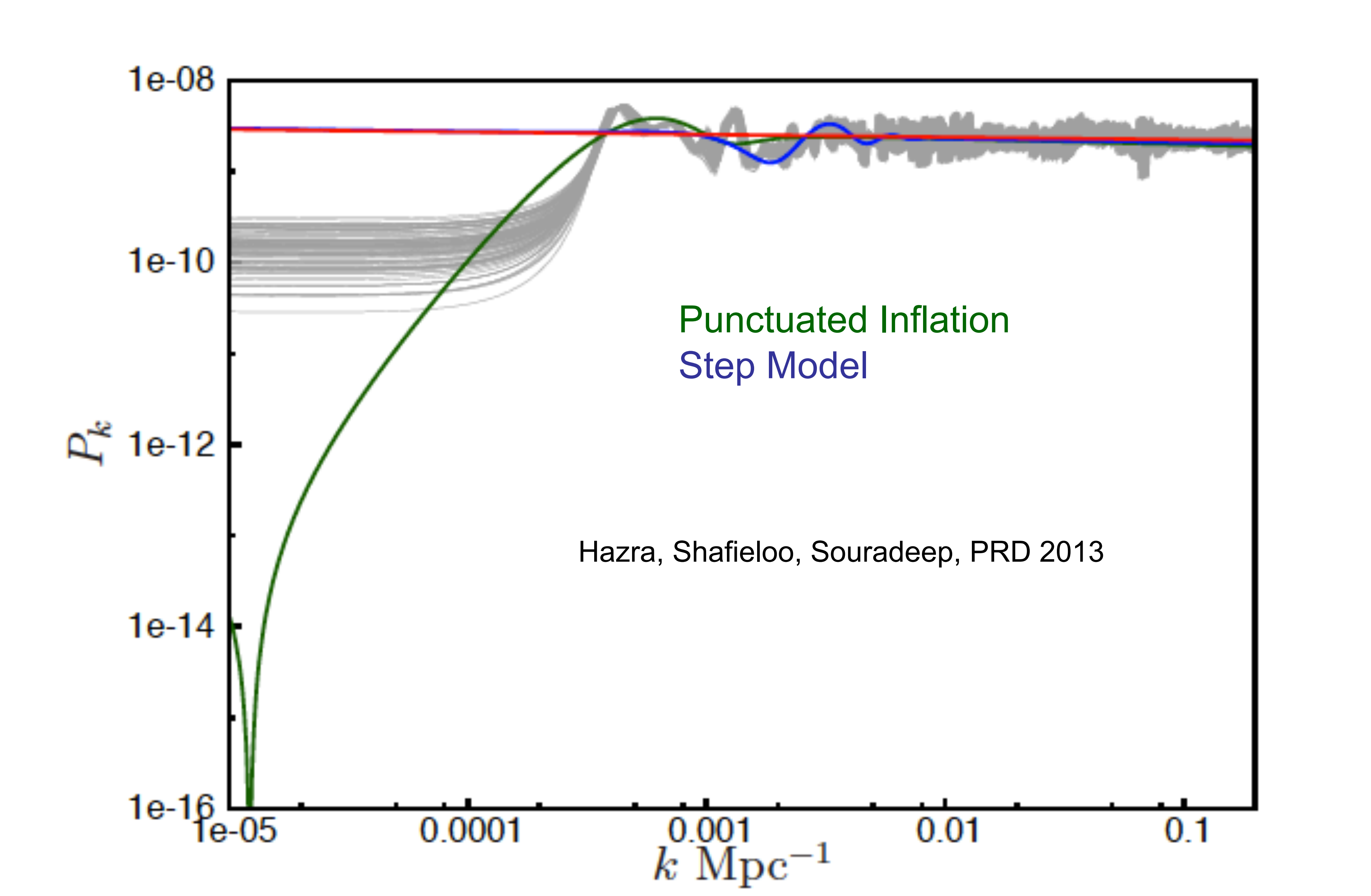
$$P(k) = A_s k^{1-n_s}\frac{1}{4y^4}\,|\,e^{-2iy}(1+2iy)-1-2y^2\,|^2$$

Vilenkin and Ford

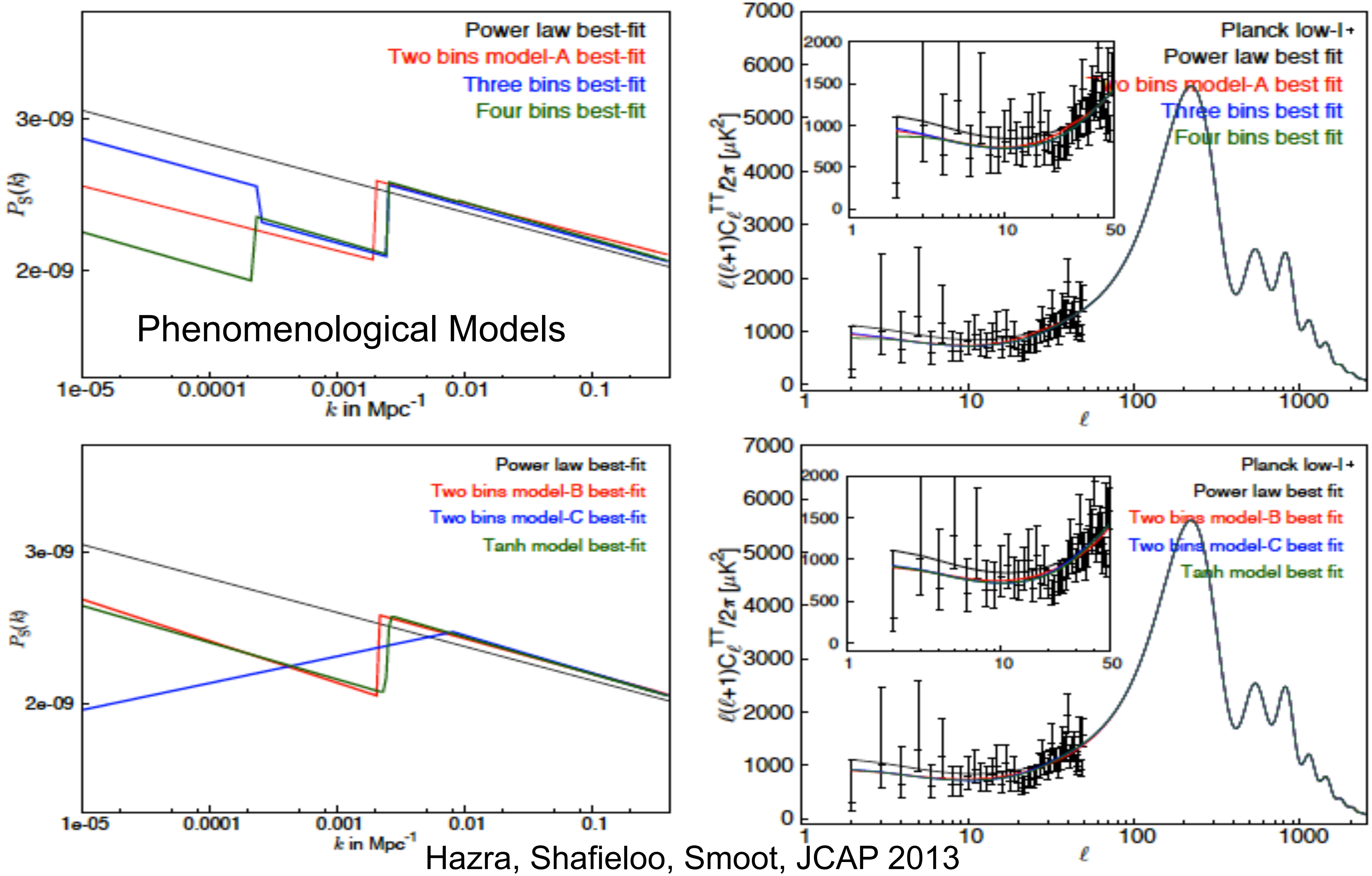


k_c / k_h=0.96
k_c / k_h =0.43
k_c / k_h =0.32
The recovered spectrum is NOT unusual!!
Rec
Staro
VF I
VF II
$\log_{10} P(k)$
$\log_{10} k/k_h$
5
4.5
4
3.5
3
2.5
2
1.5
1
-1
-0.5
0
0.5
1
1.5
2

Motivating Inflationary Scenarios

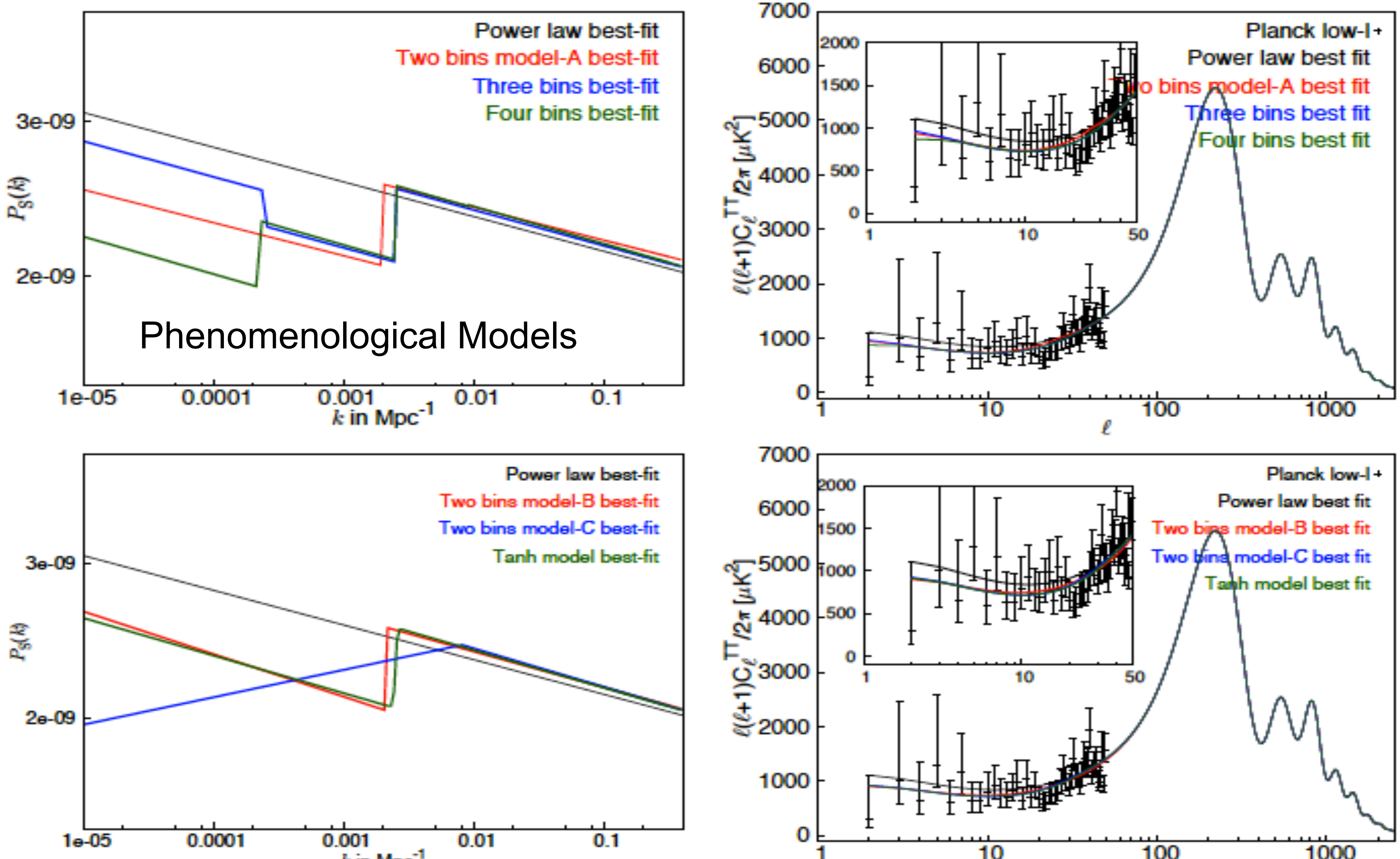


Beyond Power-Law: there are some other models consistent to the data.

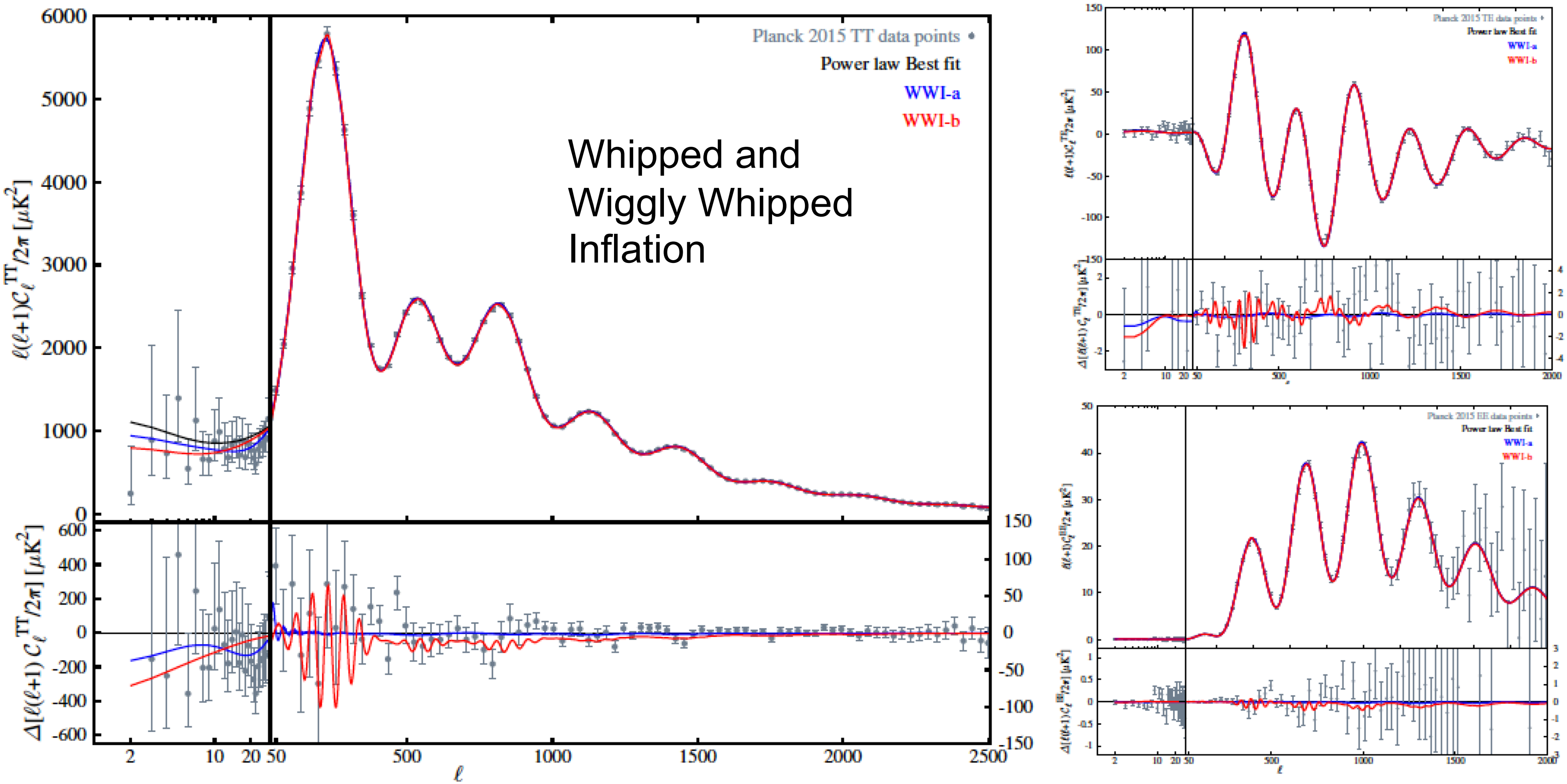


Hazra, Shafieloo, Smoot, JCAP 2013

Beyond Power-Law: there are some other models consistent to the data.



Hazra, Shafieloo, Smoot, JCAP 2013



Beyond Power-Law:

there are some other models consistent to the data.

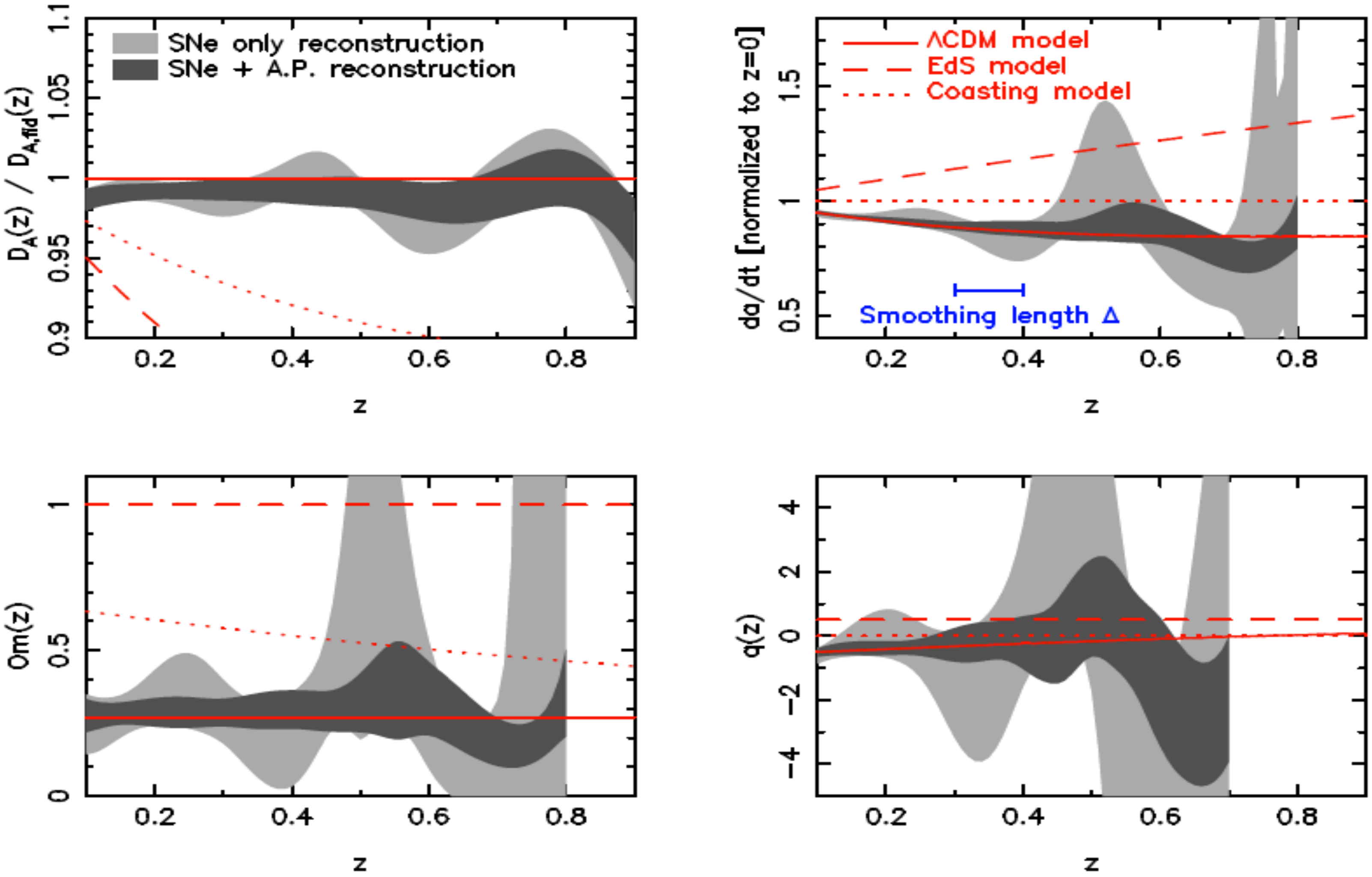
Hazra, Shafieloo, Smoot, JCAP 2013
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014A
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014B
Hazra, Shafieloo, Smoot, Starobinsky, Phys. Rev. Lett 2014
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2016

Dark Energy in 2016

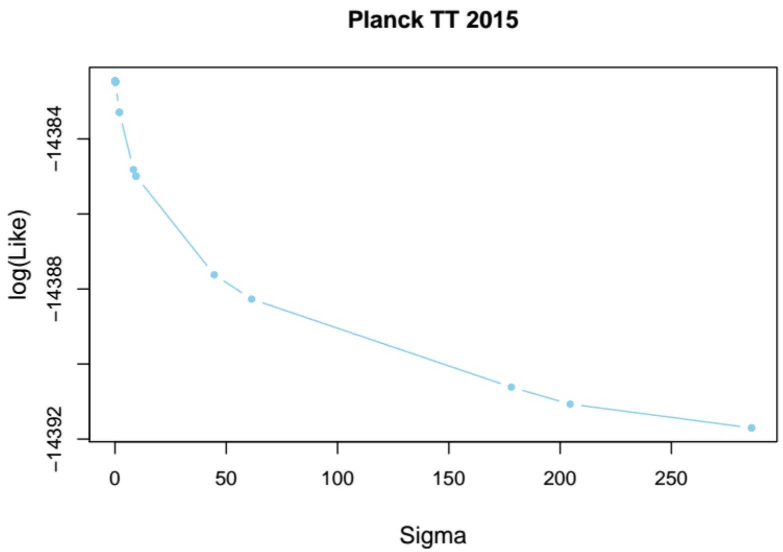
LSS

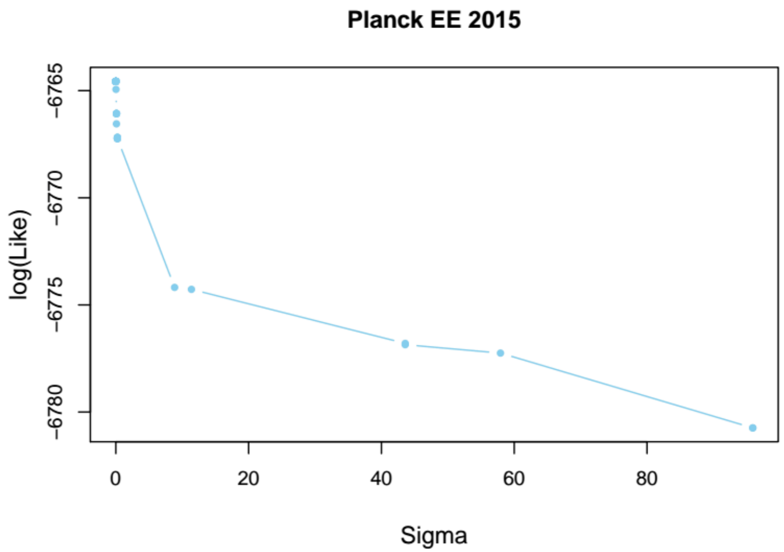
18 years after discovery of the acceleration of the universe:

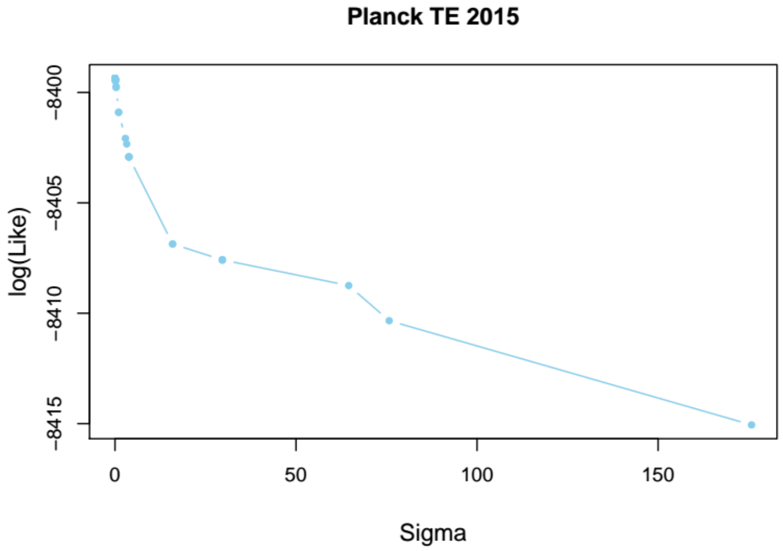
WiggleZ collaboration ,
Blake et al, MNRAS 2012



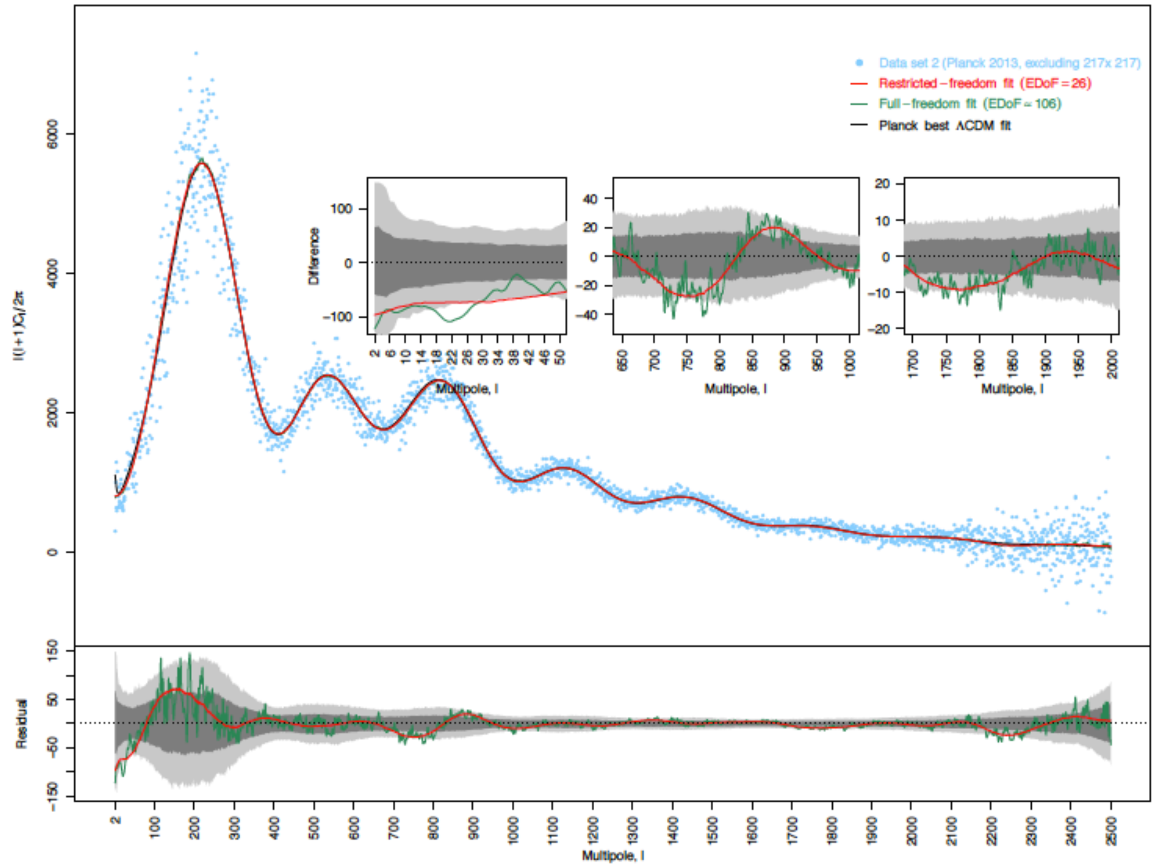
Planck 2015: Testing Concordance Model using GP and its hyper-parameters



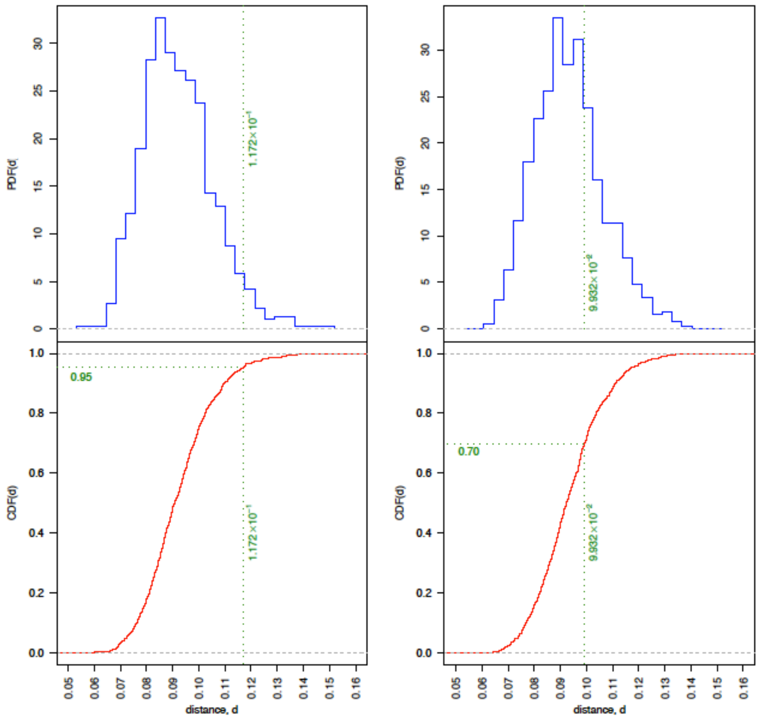




Aghamousa, Shafieloo, Hamann 2016 (in prep)



Calibrated REACT



Aghamousa and Shafieloo, JCAP 2015

Consistent only at 2~3 sigma CL

Excluding 217 Ghz, consistent at 1~2 sigma CL

- Target: Finding deviation from Lambda
- Tools: Litmus tests such as Om, Om3 and Omh2 applicable on the observables, non-parametric reconstruction of the cosmic expansion and growth.
- Aim: To be well prepared for the actual DESI data. All to be applied on SDSS4 prior to DESI.

From 2D to 3D

Using LSS data to test early universe scenarios

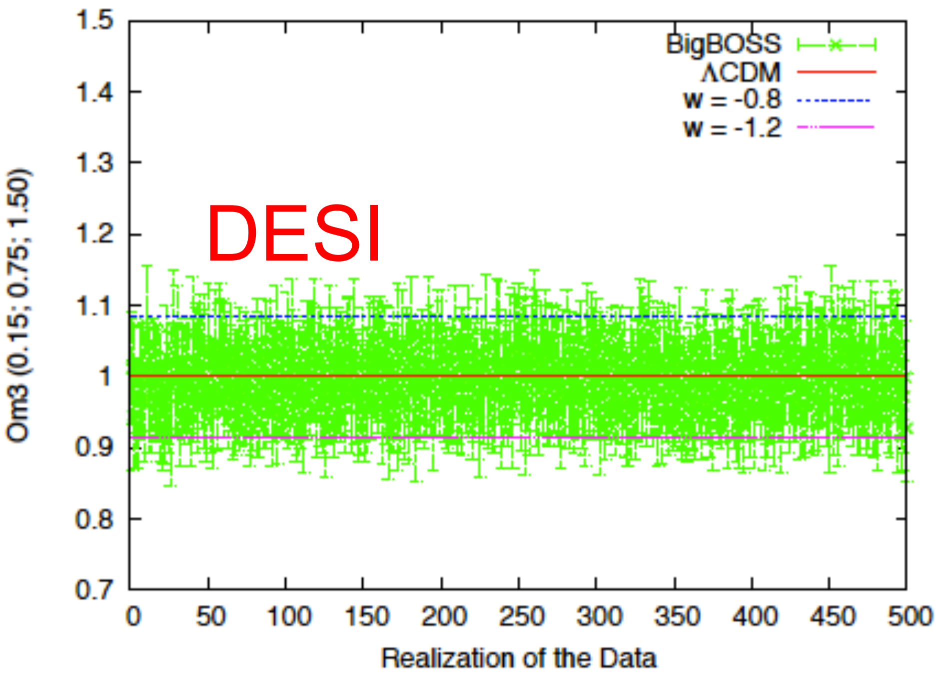
•Targets: Features in PPS, primordial non-Gaussianity, spherical asymmetry

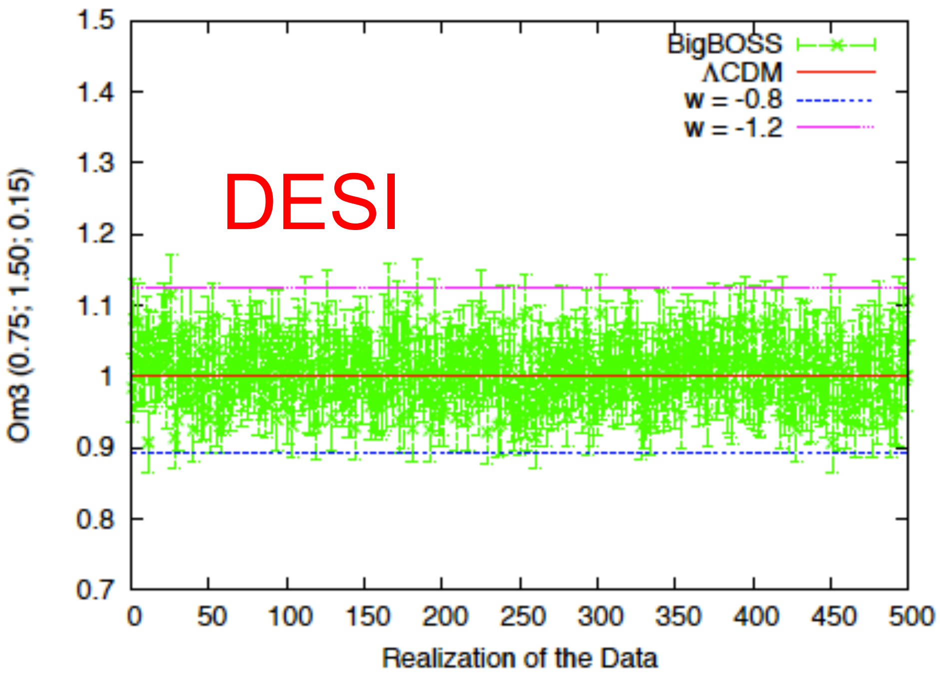
•Tools: Simulations, developing statistics, cross correlation with other data.

•Aim: To be well prepared for the future data (DESI).

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

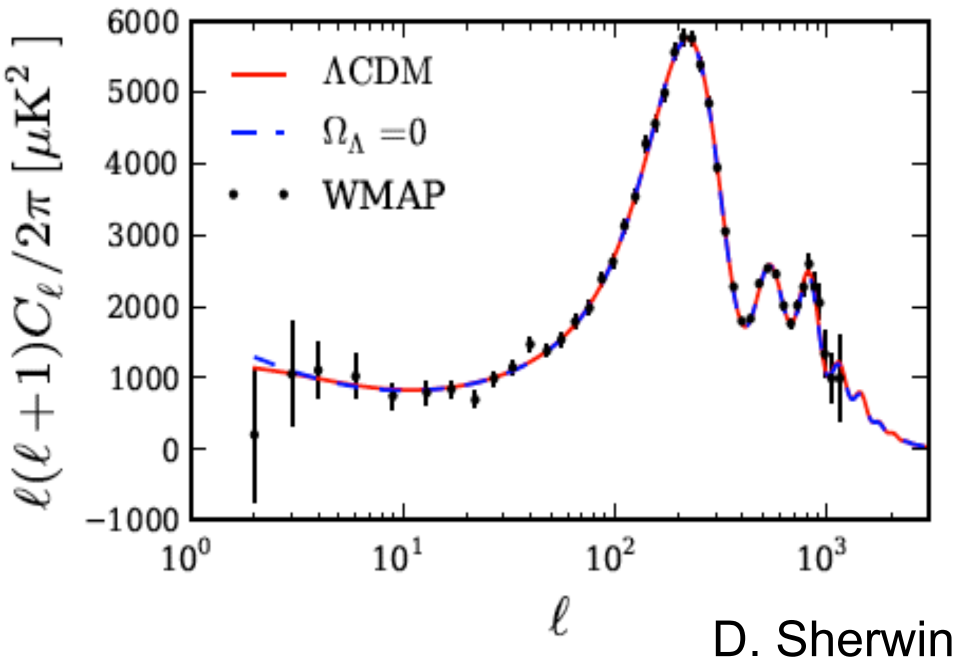
Dark Energy in 2016

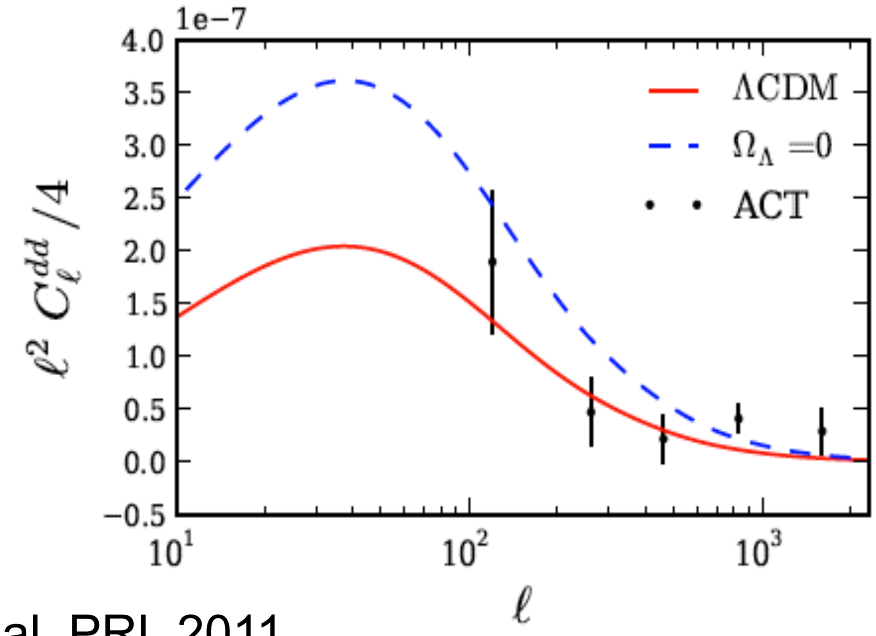
CMB

18 years after discovery of the acceleration of the universe:

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

ACT CMB Survey





D. Sherwin et.al, PRL 2011

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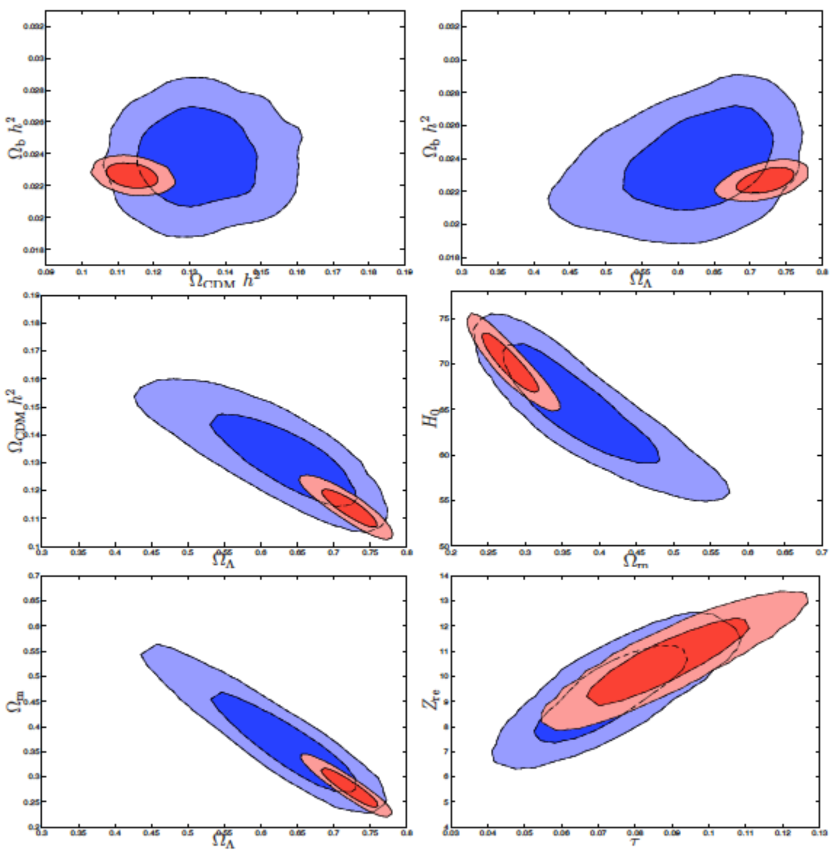


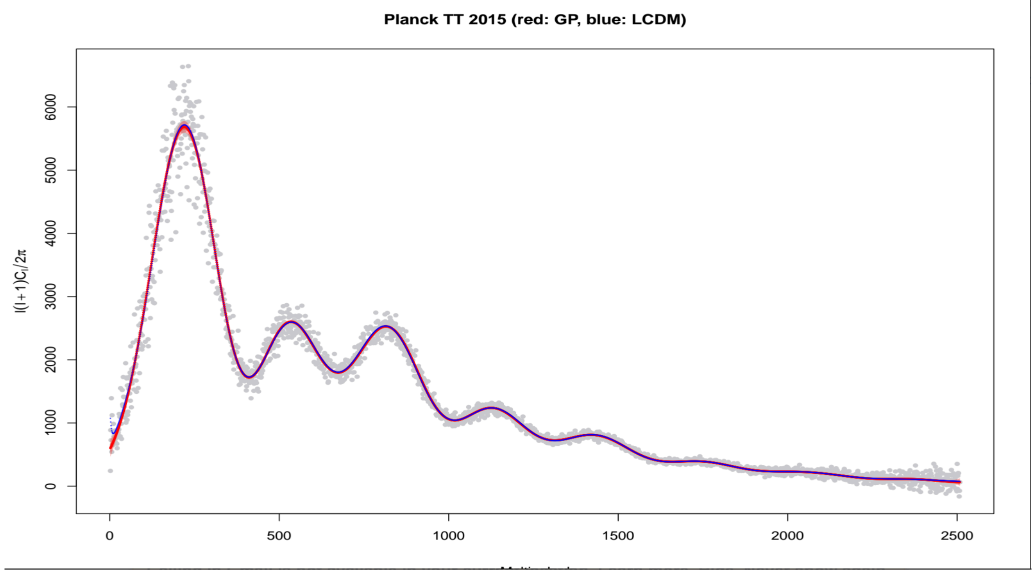
Cosmological Parameter Estimation with Free form Primordial Spectrum

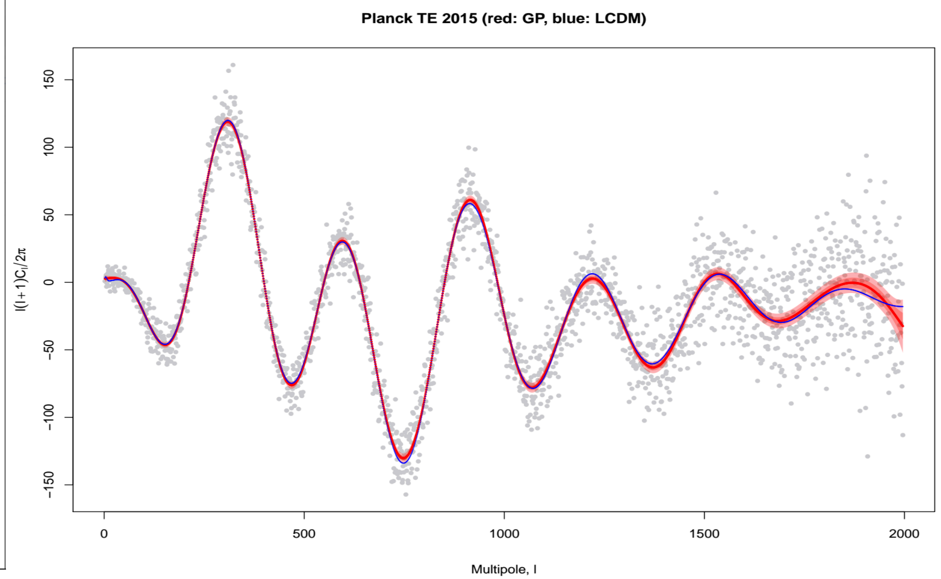
Red Contours: Power Law PPS

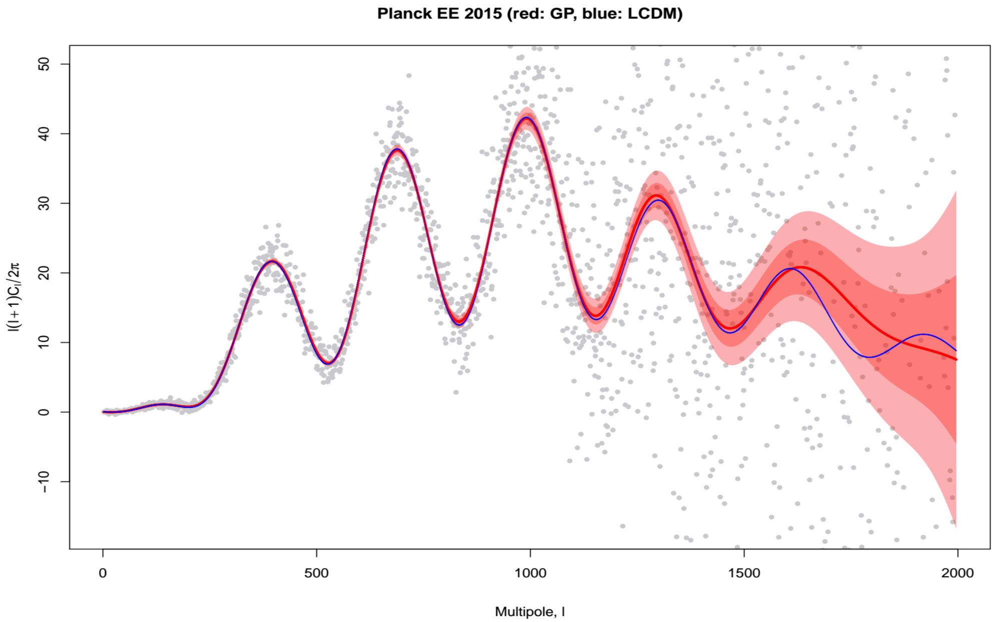
Blue Contours: Free Form PPS

Hazra, Shafieloo & Souradeep PRD 2013

Direct Reconstruction of angular power spectrum from Planck 2015 using Gaussian Processes



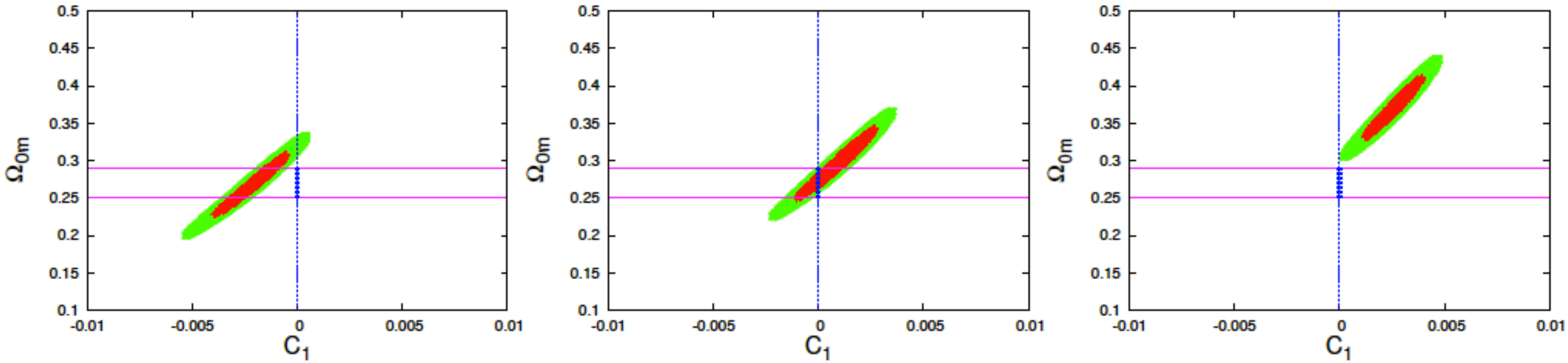




Aghamousa, Shafieloo, Hamann 2016 (in prep)

Crossing Statistic (Bayesian Interpretation)

Theoretical model Crossing function Comparing a model with its own variations



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

Chebishev Polynomials as Crossing Functions

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

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

Dark Energy in 2016

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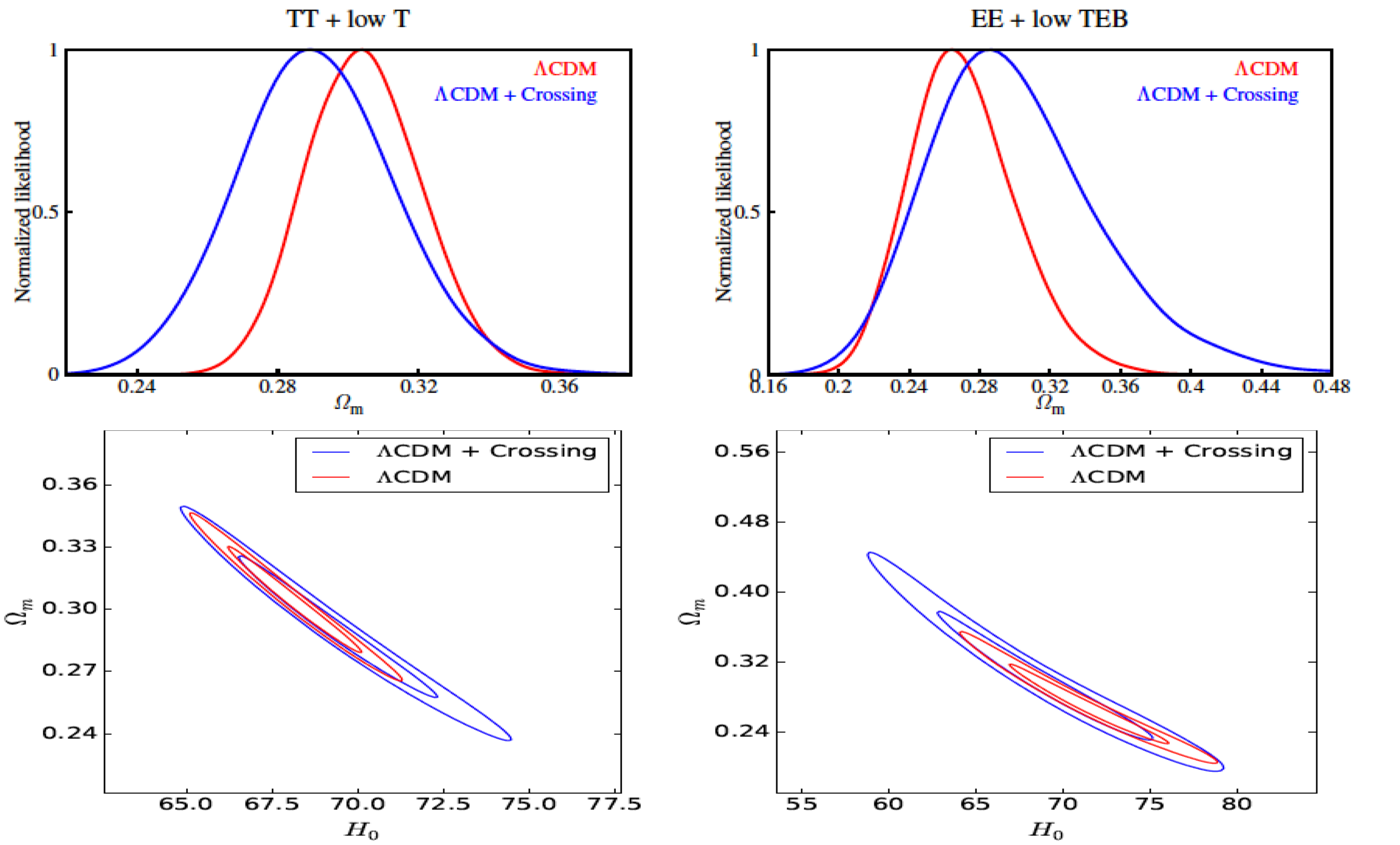

Hazra & Shafieloo
arXiv:1610.07402

Ruling out the zero-Lambda density LCDM model considering extra flexibility for the form of the angular power spectrum