Beyond
The Standard Model of Cosmology

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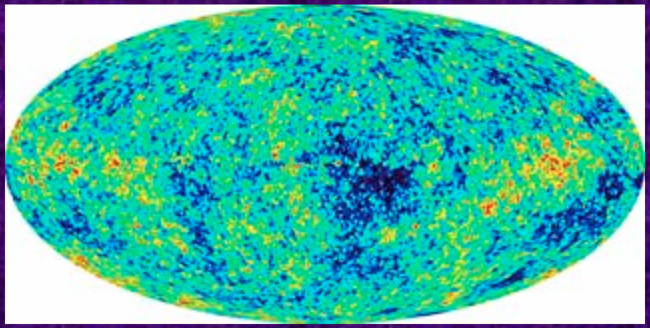
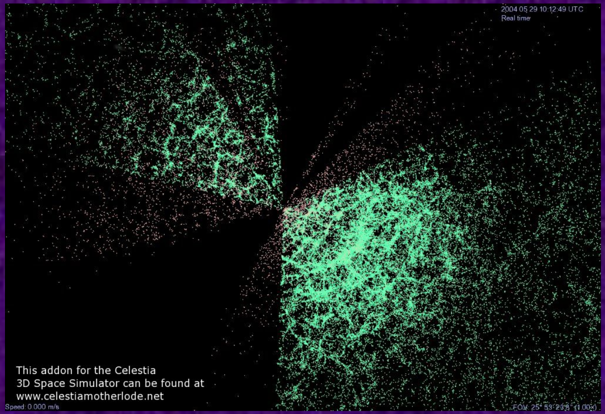
Cosmology, from ***fiction*** to being ***science*****….**



Cosmic Microwave Background (CMB)

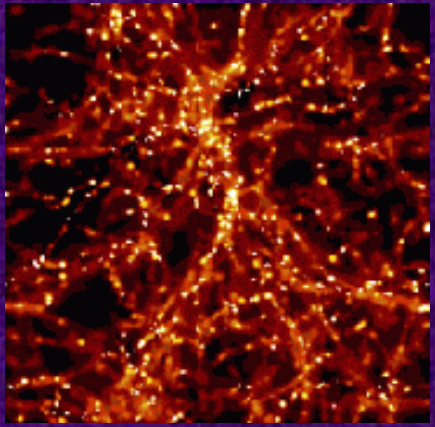
Cosmological Observations



Large-scale structure

Gravitational Lensing

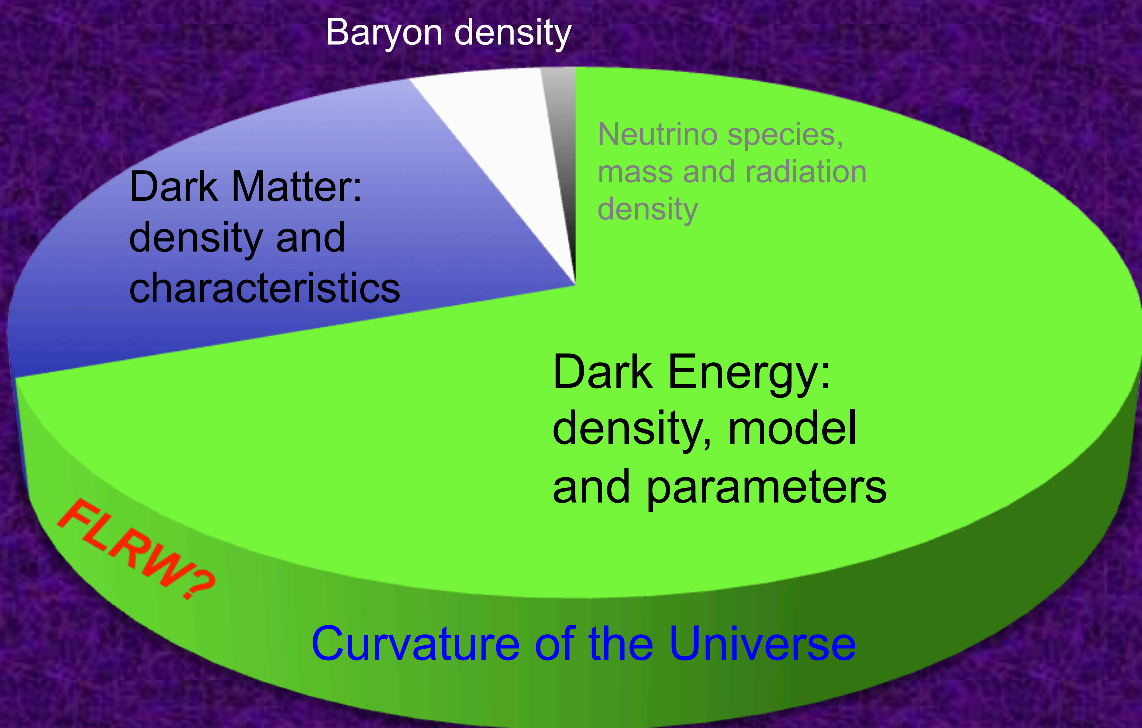
Type Ia supernovae



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.



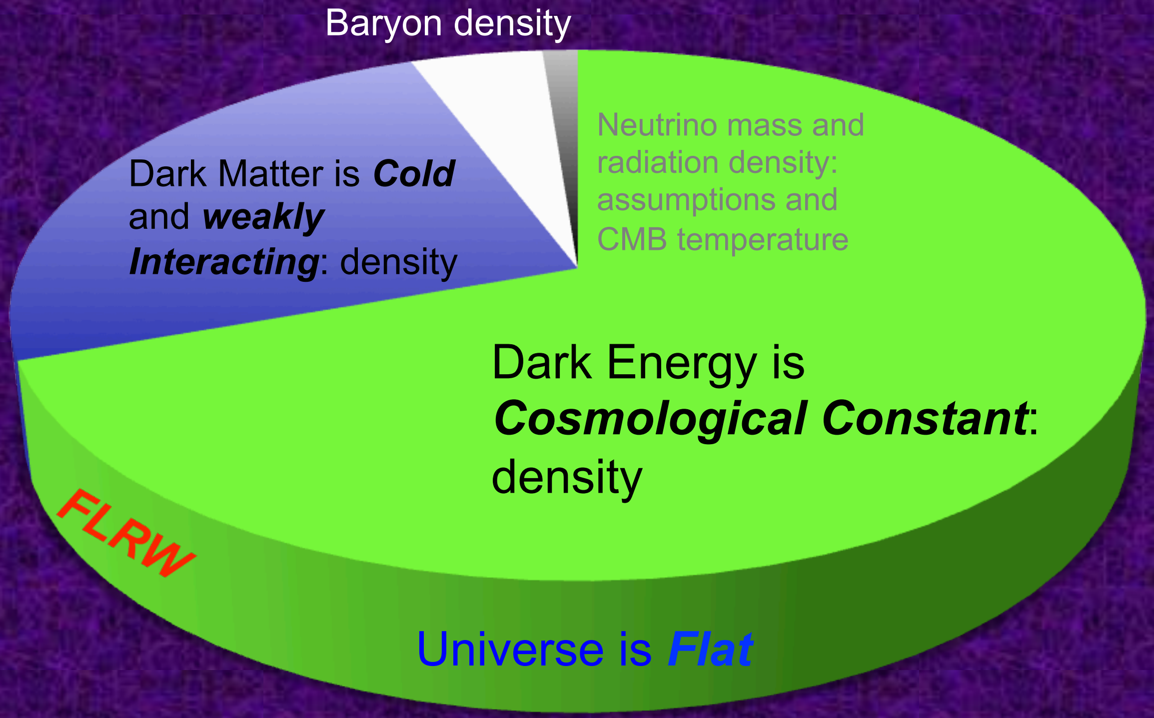
Initial Conditions: Form of the Primordial Spectrum and Model of Inflation and its Parameters

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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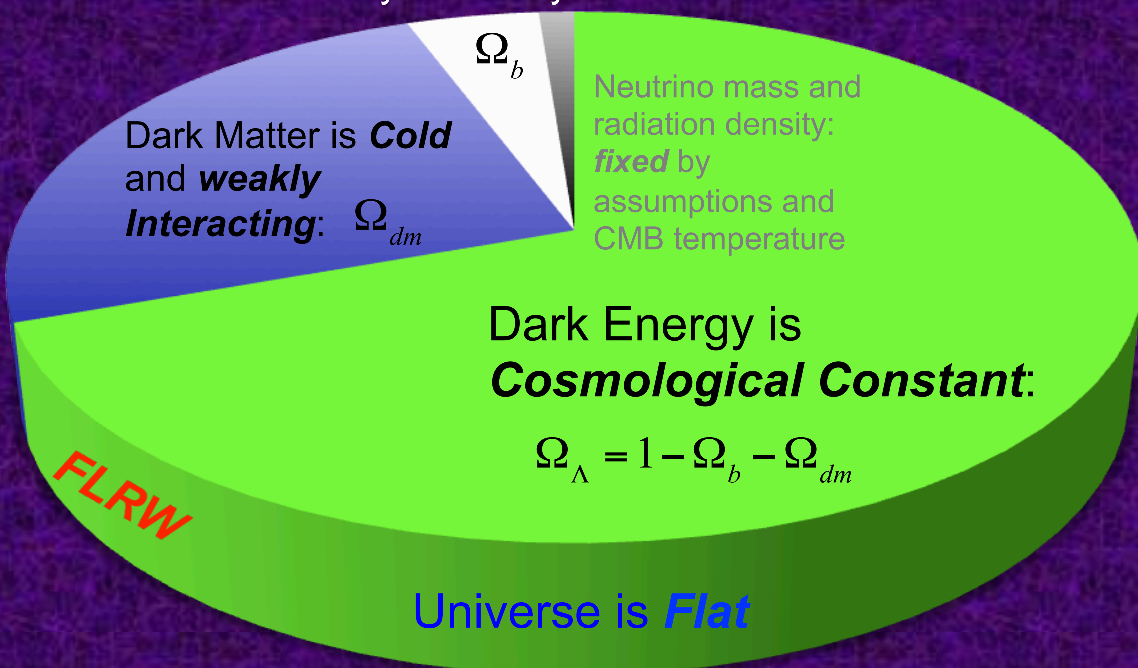


Initial Conditions:
Form of the Primordial Spectrum is ***Power-law***

$$\boxed{n_s, A_s}$$

Epoch of reionization

$$\boxed{\tau}$$

Hubble Parameter and the Rate of Expansion

$$\boxed{H_0}$$

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

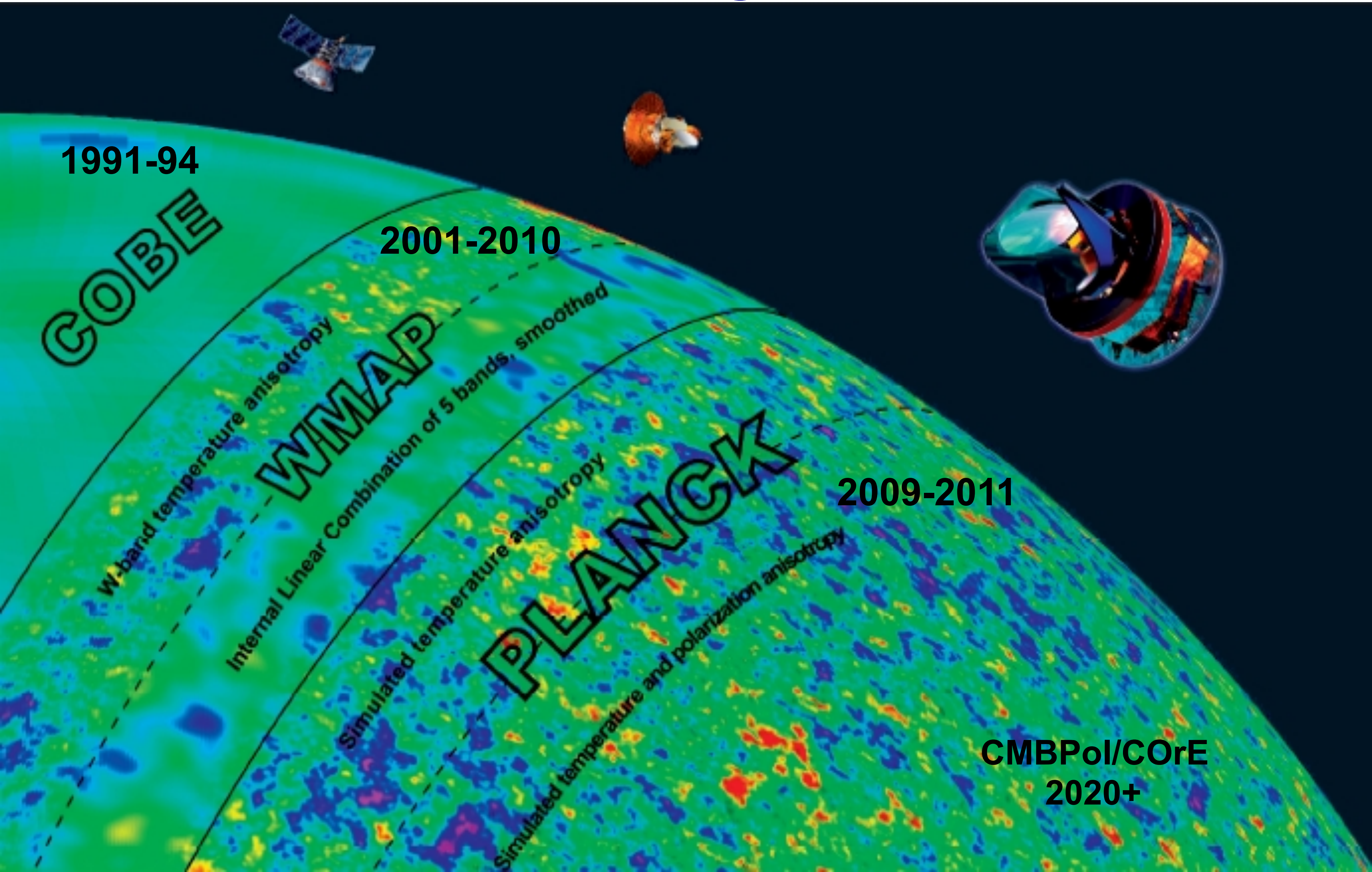
Epoch of reionization

τ

Hubble Parameter and the Rate of Expansion

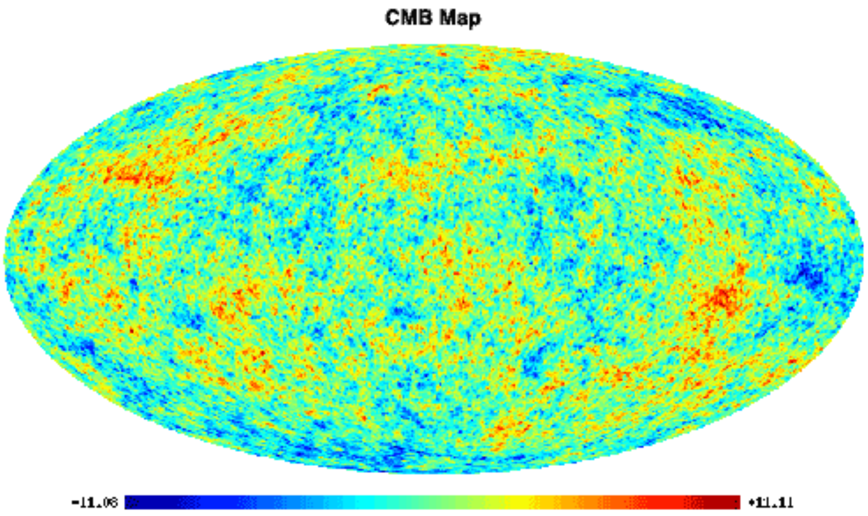
H_0

Why such assumptions?
Hints from Cosmological Observations



Statistics of CMB

CMB Anisotropy Sky map => Spherical Harmonic decomposition



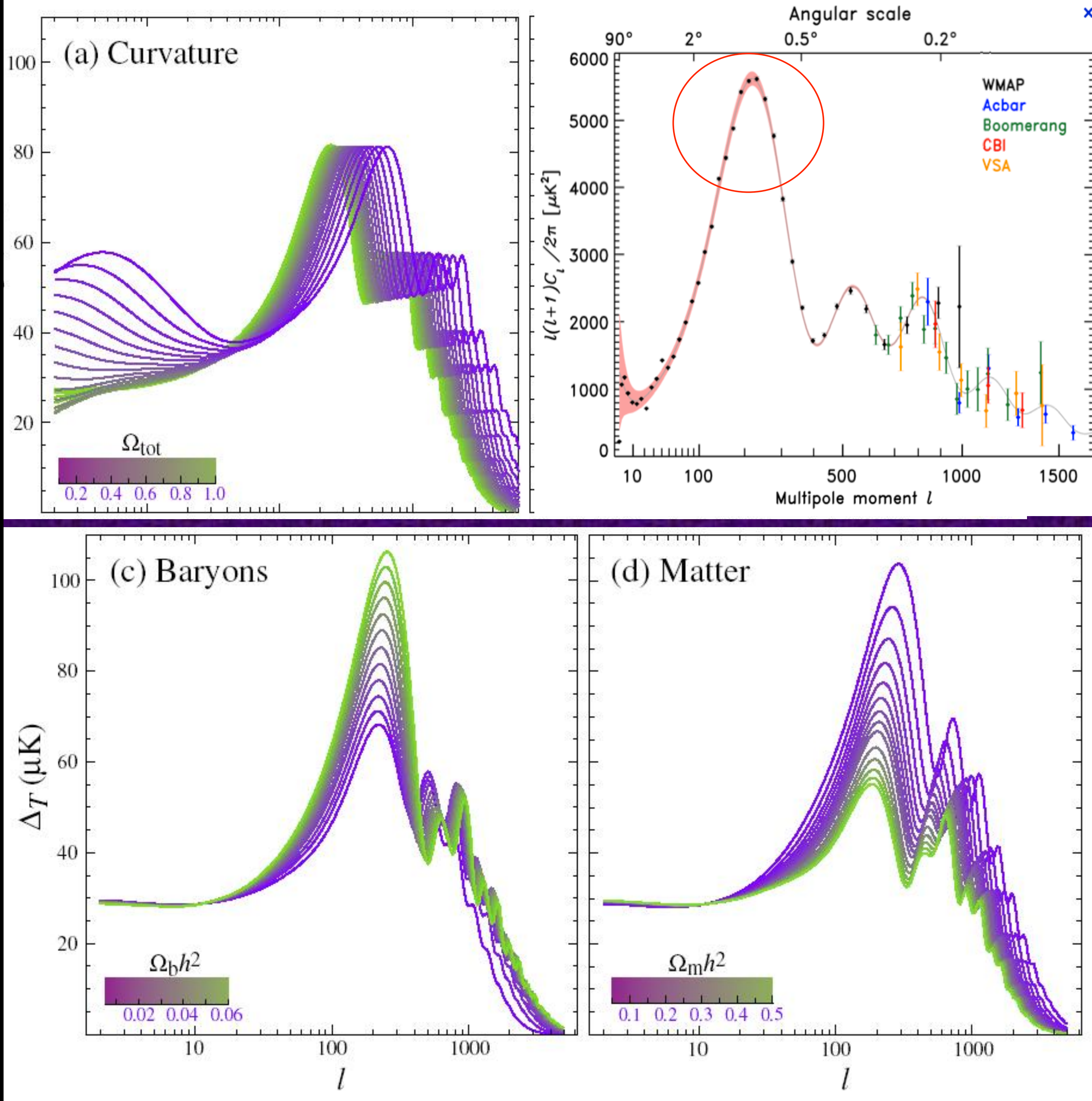
$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

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

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.

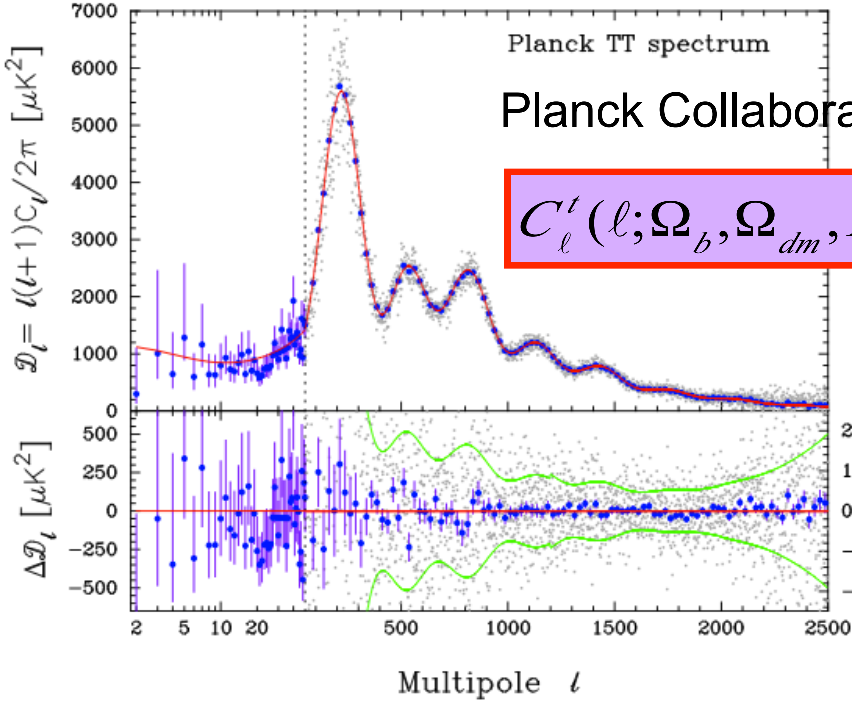
Total density

Dark Energy

Baryon density and

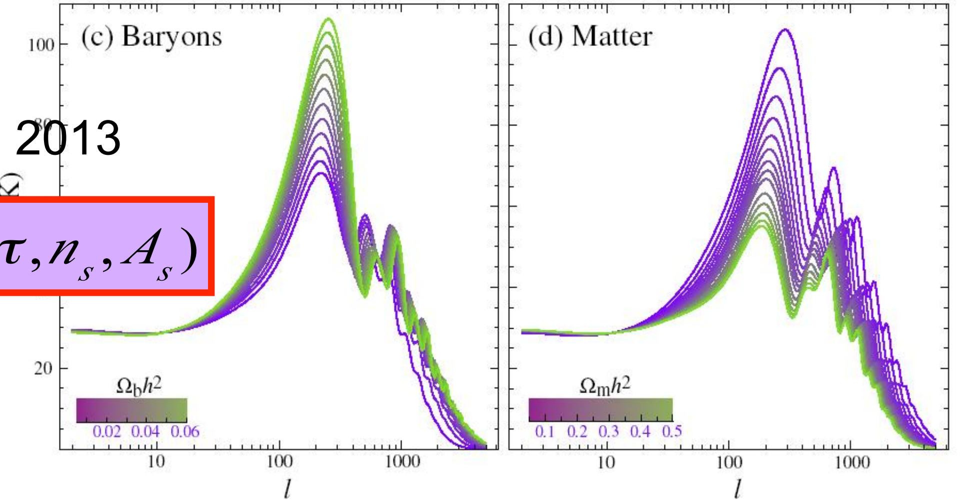
Matter density.

From Hu & Dodelson, 2002

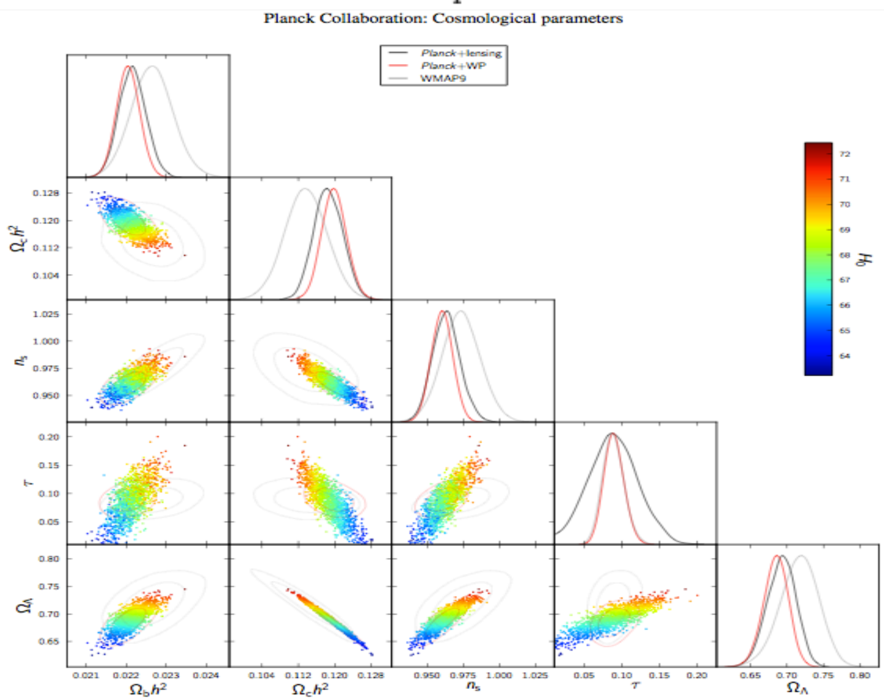


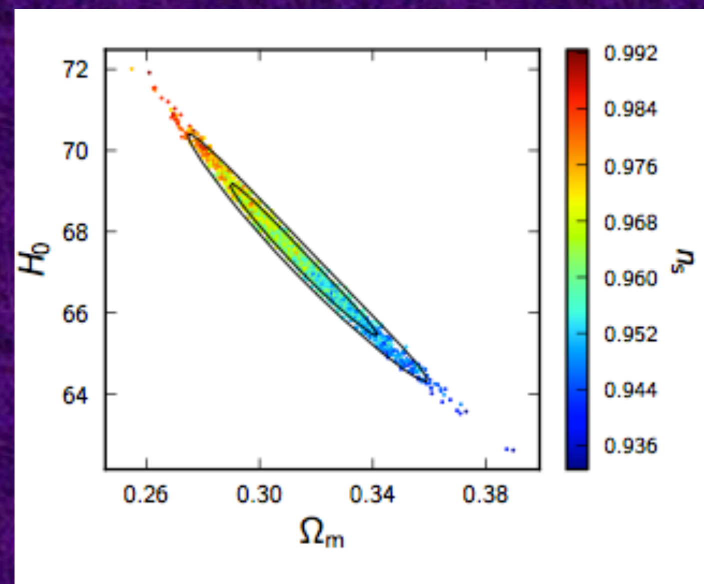
Planck Collaboration 2013

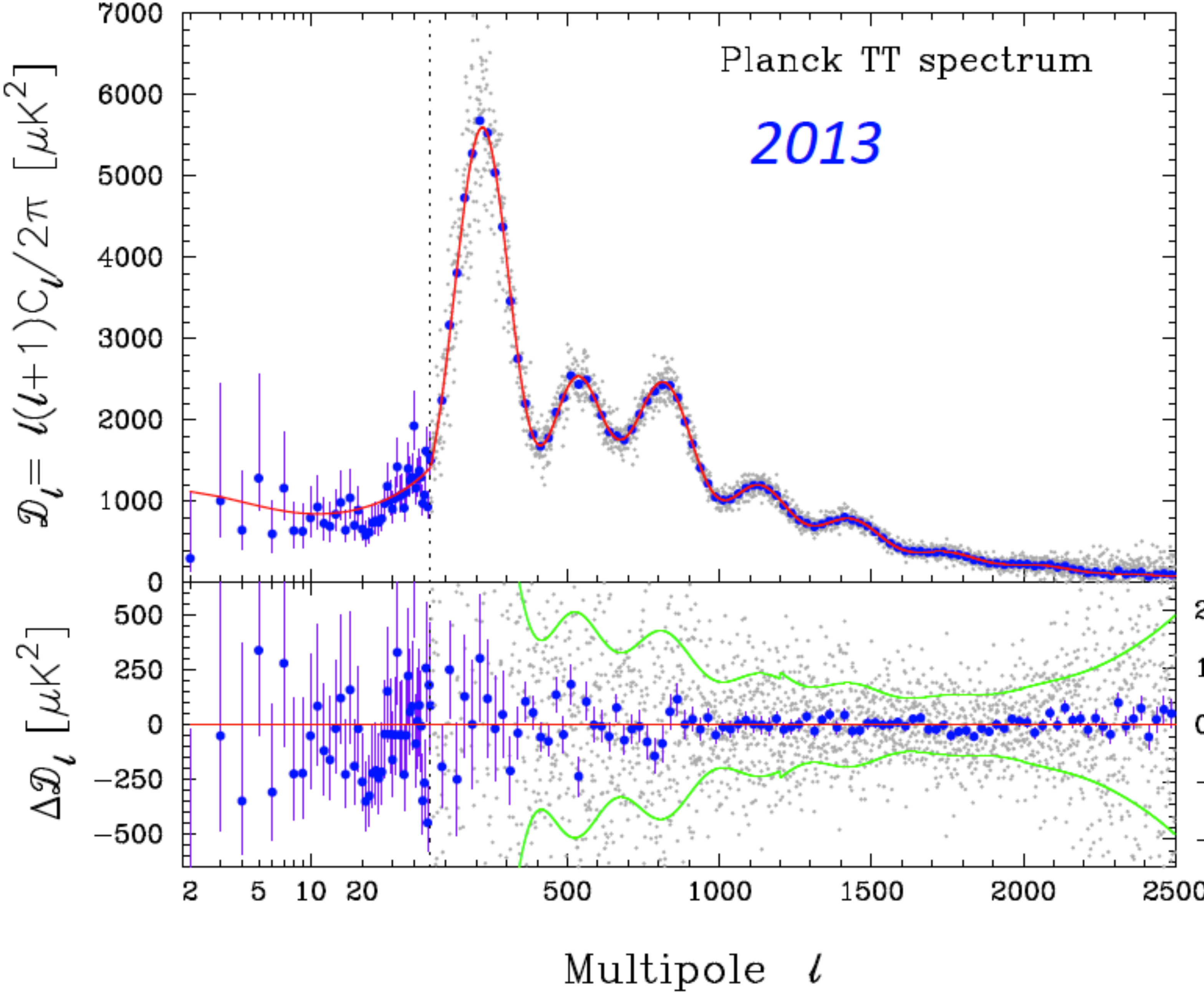
$$C_\ell^t(\ell;\Omega_b,\Omega_{dm},H_0,\tau,n_s,A_s)$$



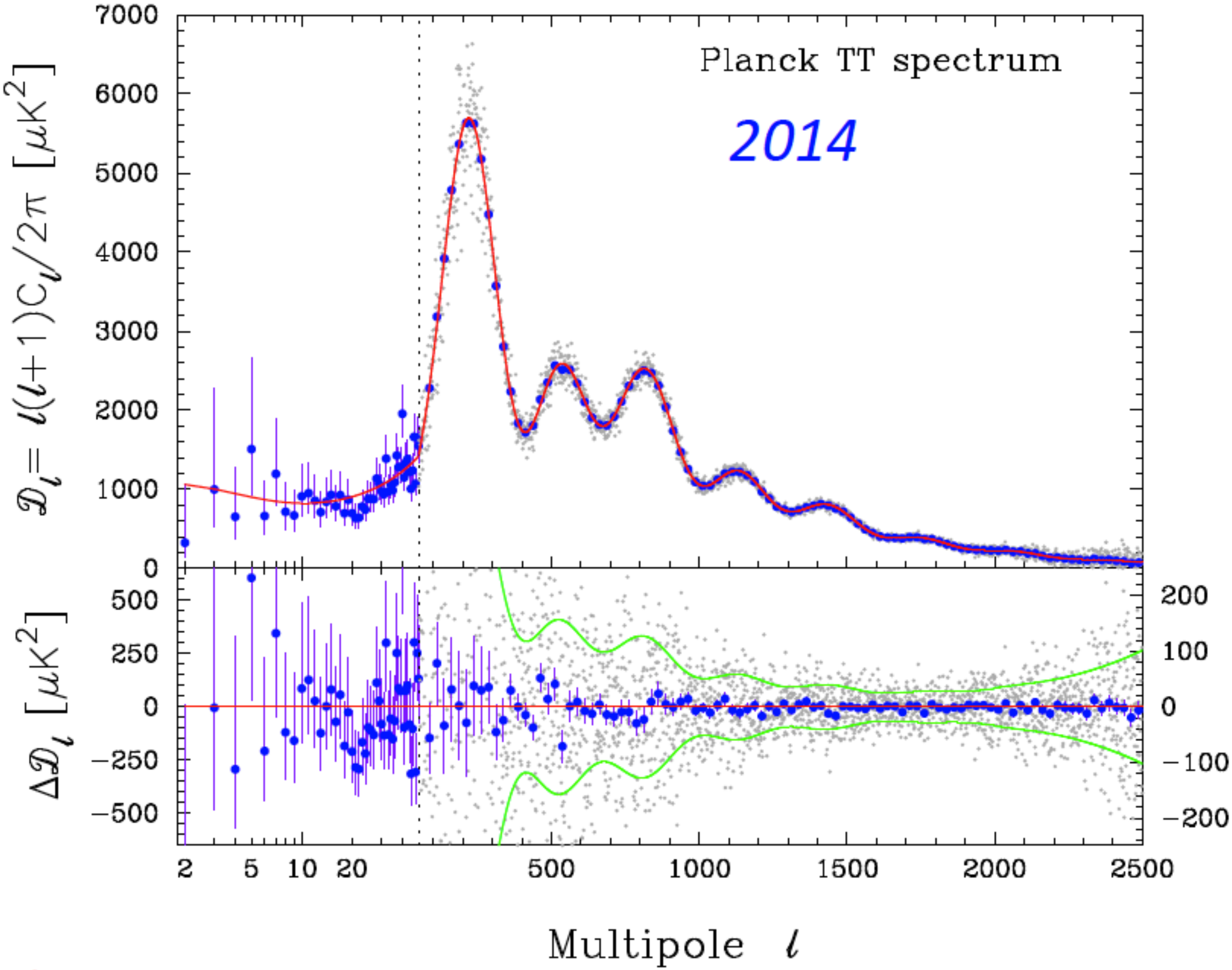
$$\chi^2 = \sum_{\ell=2}^{N} (C_\ell^t - C_\ell^e)^T Cov^{-1} (C_\ell^t - C_\ell^e)$$



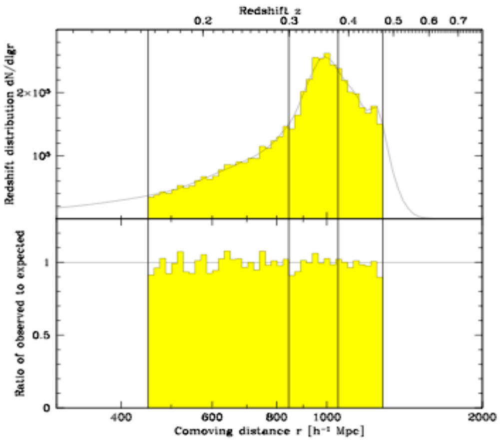


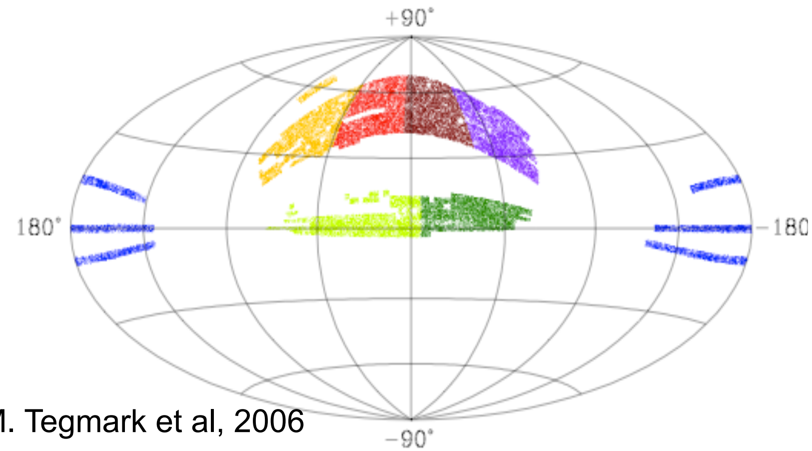


Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ

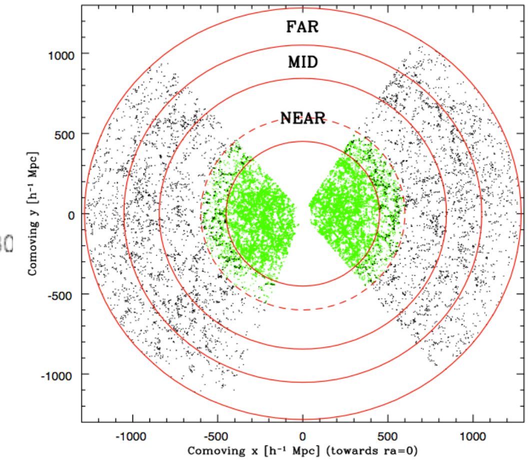


preliminary



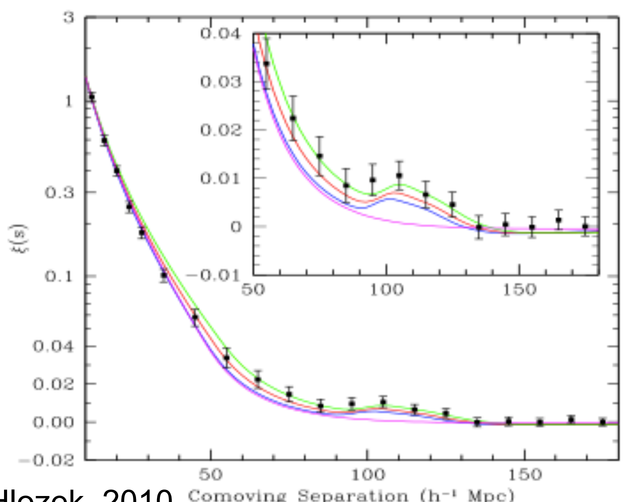


M. Tegmark et al, 2006



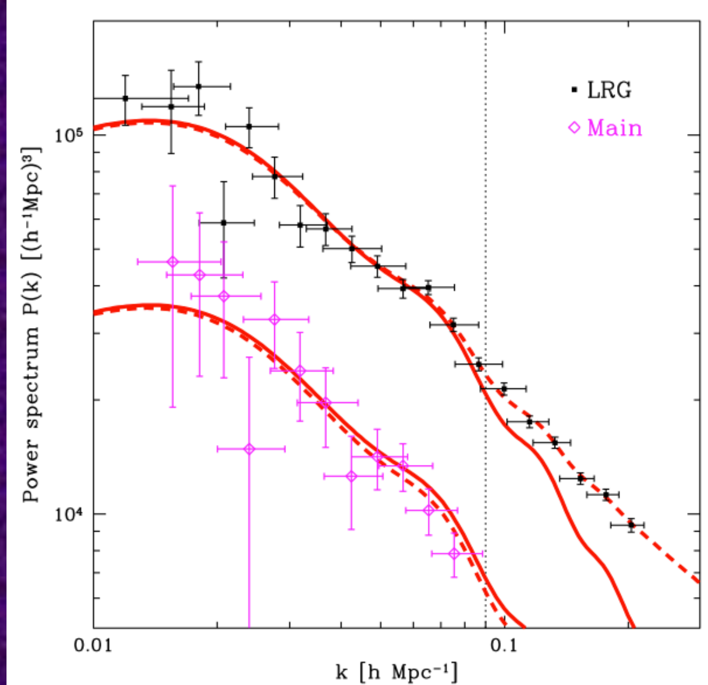
Large Scale Structure Data and Distribution of Galaxies

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



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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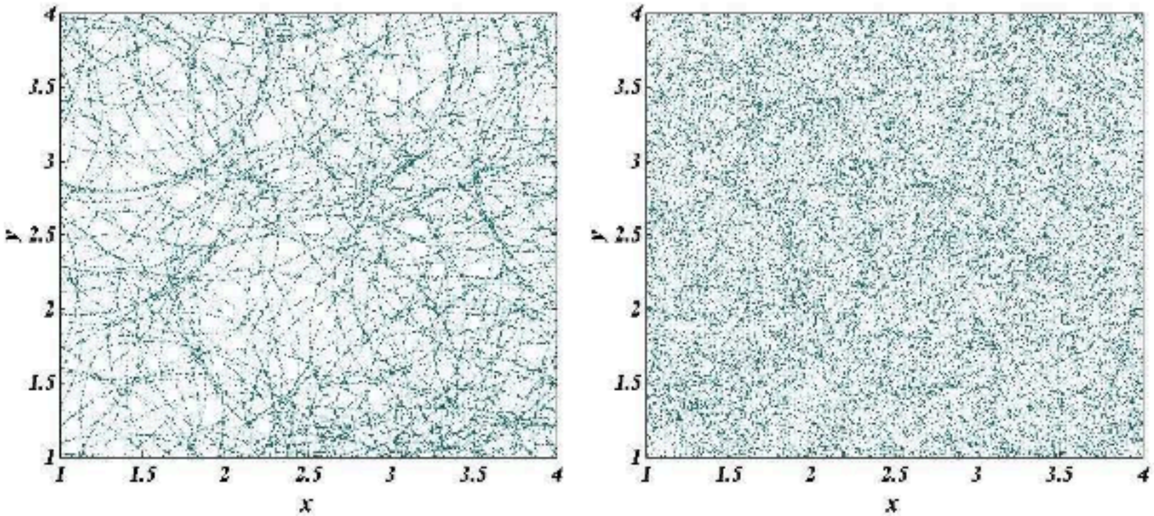
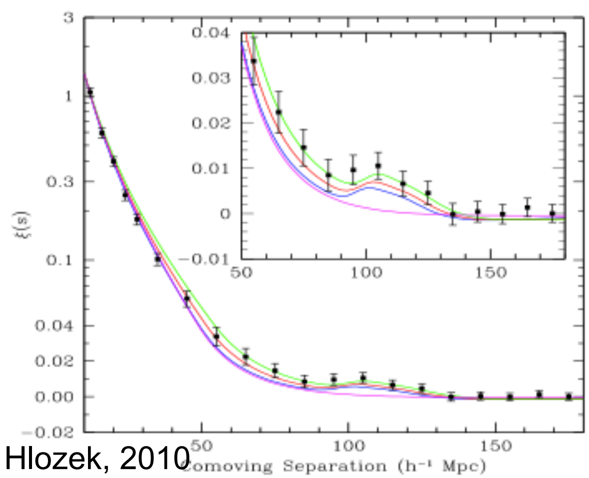


Fig. 1.5. Rings of power superposed. Schematic galaxy distribution formed by placing the galaxies on rings of the same characteristic radius L. The preferred radial scale is clearly visible in the left hand panel with many galaxies per ring. The right hand panel shows a more realistic scenario - with 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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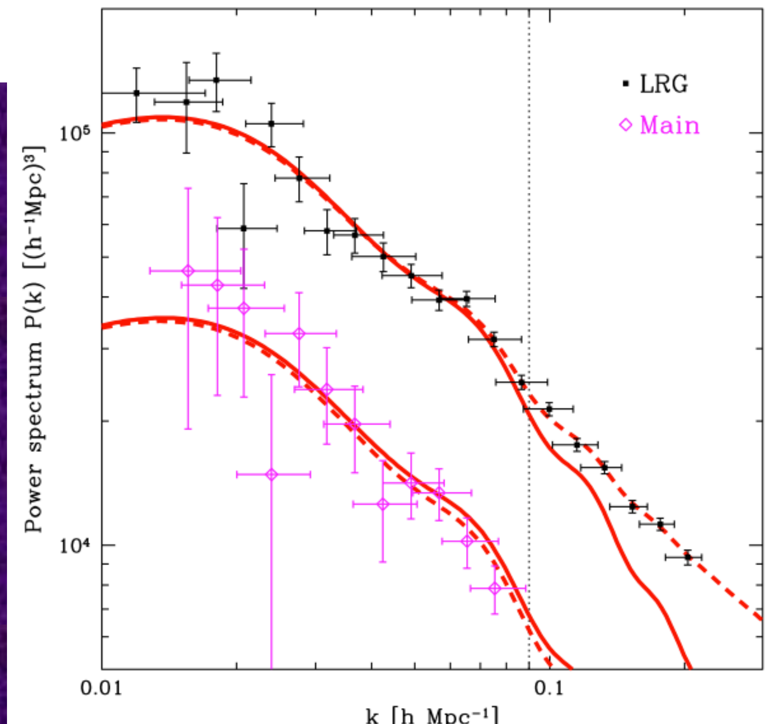
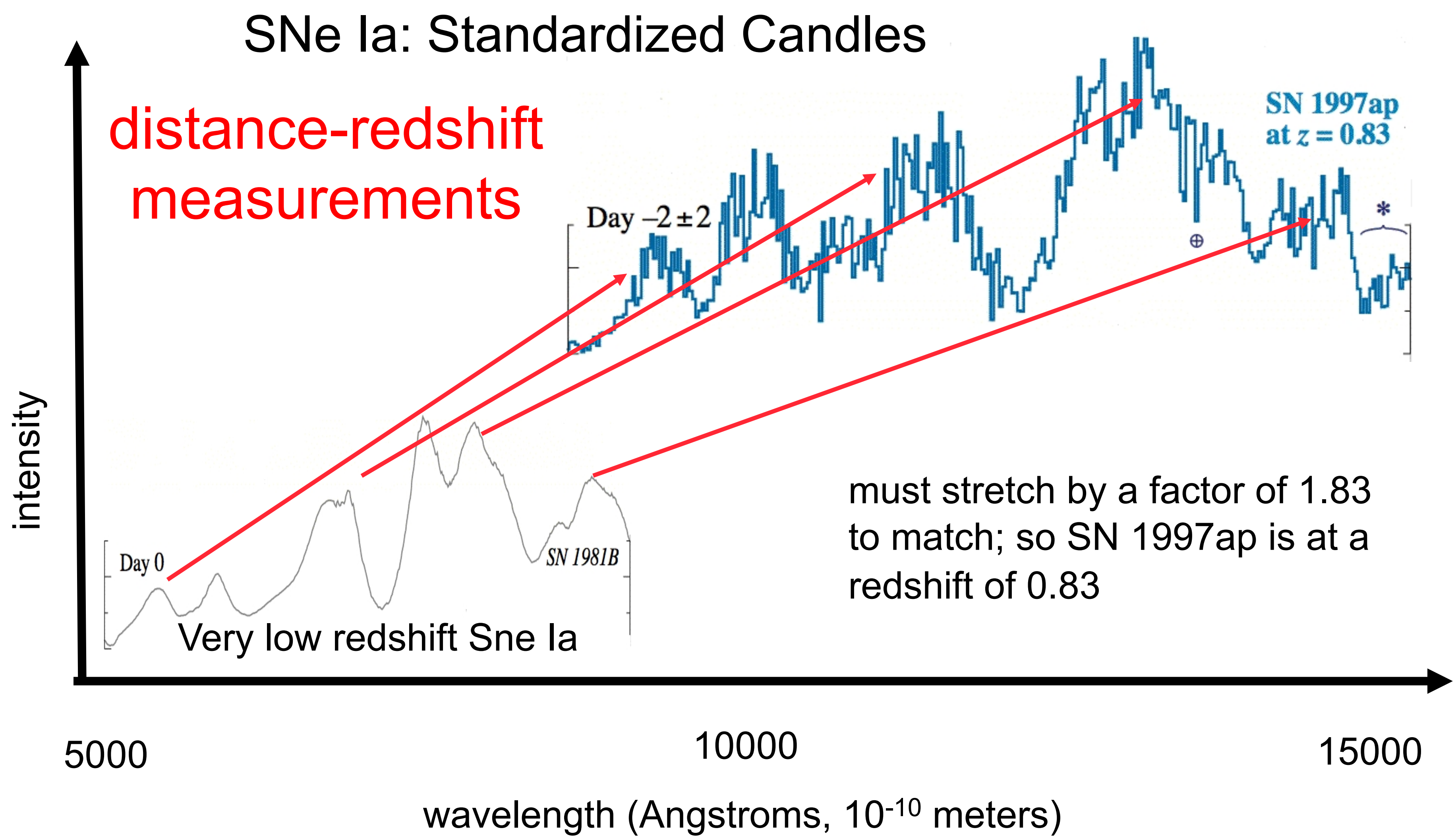
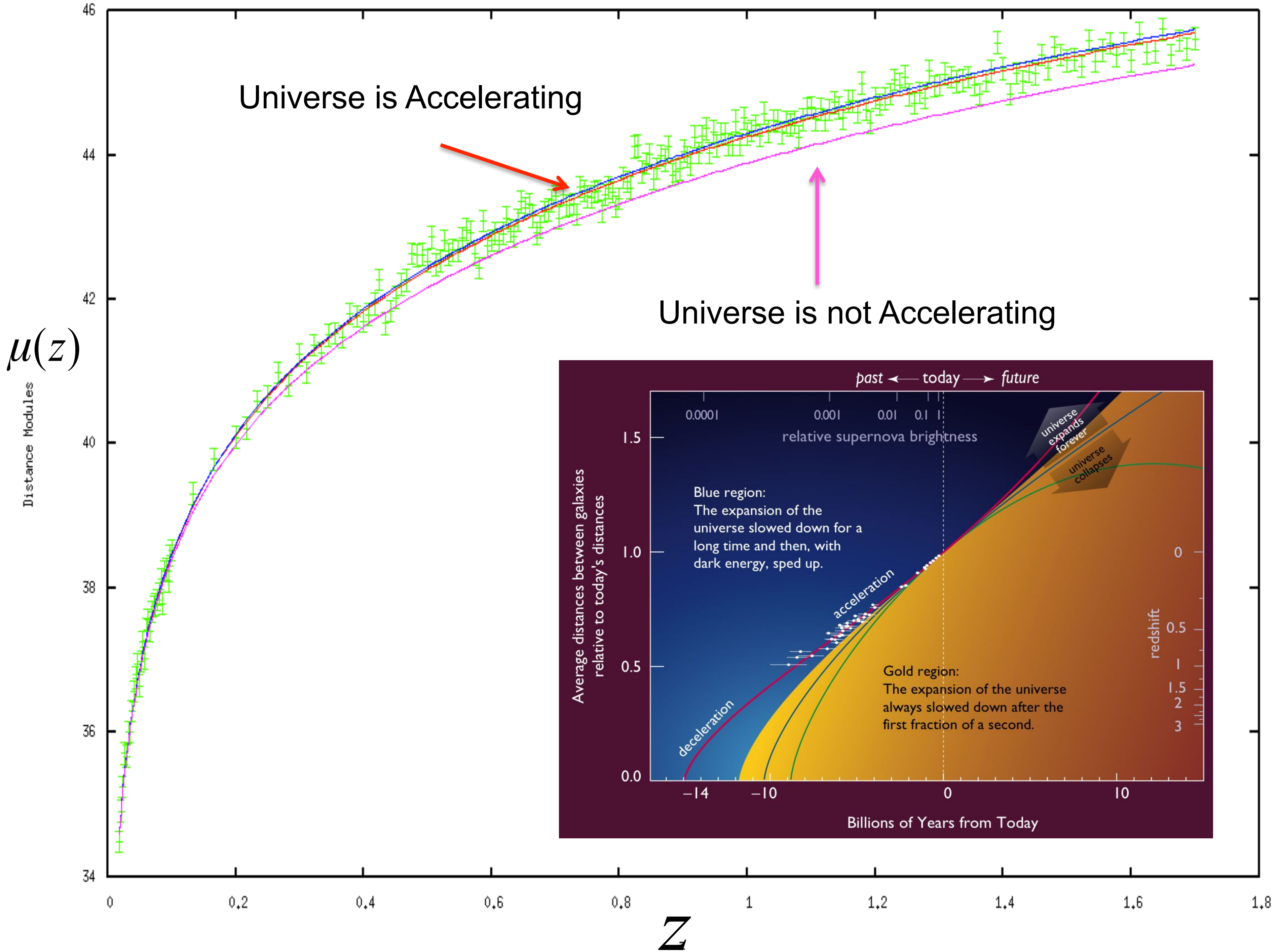
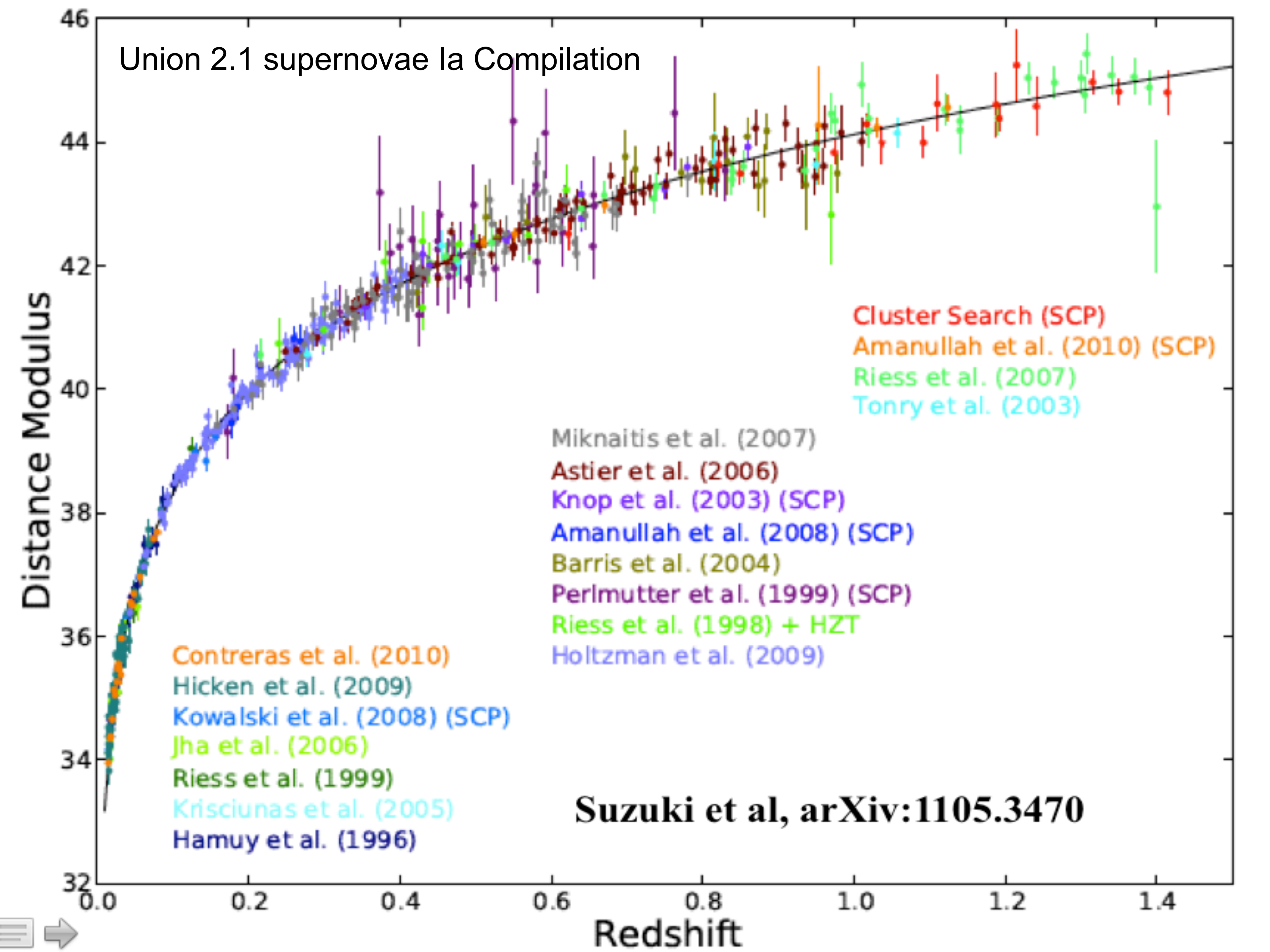


Measuring Distances in Astronomy



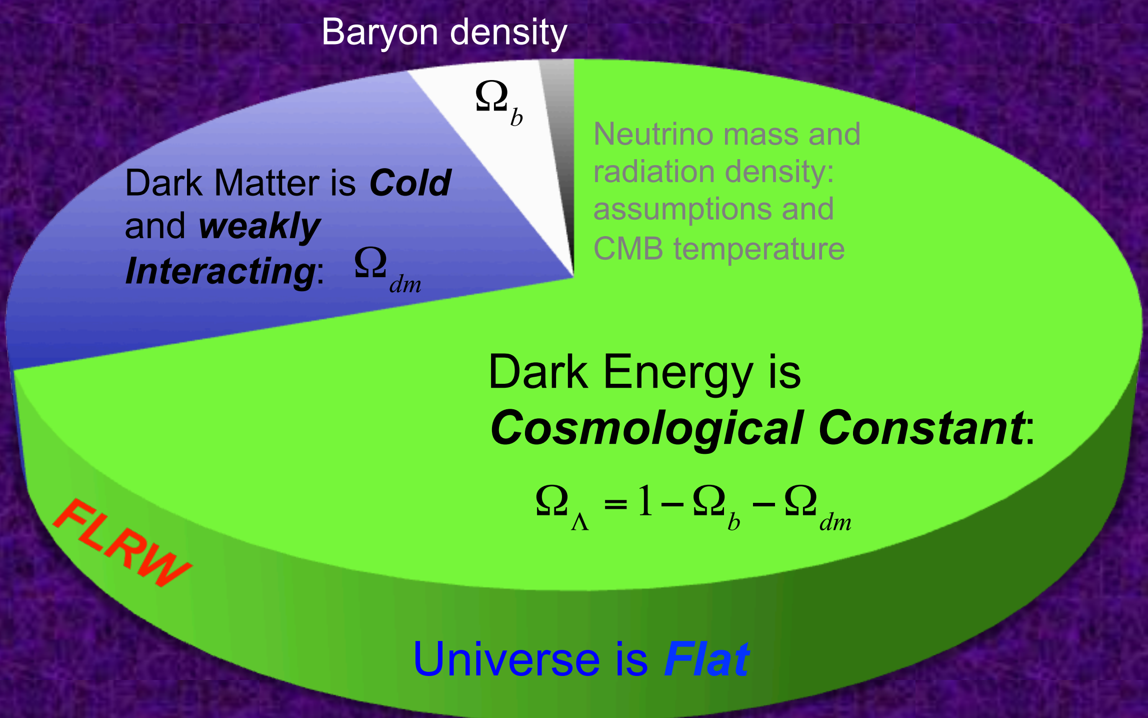


Universe is Accelerating
Universe is not Accelerating
$\mu(z)$
Distance Modules
z
46
44
42
40
38
36
34
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
past ← today → future
0.0001
0.001
0.01
0.1
1
relative supernova brightness
universe expands forever
universe collapses
Blue region:
The expansion of the universe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


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

Inflation

- Extreme accelerated expansion of the early universe.
- It can be realized by scalar fields (or some other mechanisms).
- So far the best theory that can resolve the magnetic monopole problem (absence of relics), flatness problem, horizon problem and explain the initial perturbations from quantum fluctuations.
- It has many many models.
- These models are different in their statistical properties and we may be able to distinguish between them using cosmological observations.

Constraints on inflationary scenarios from cosmological observations:

- 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)

Parameterization and Model Fitting

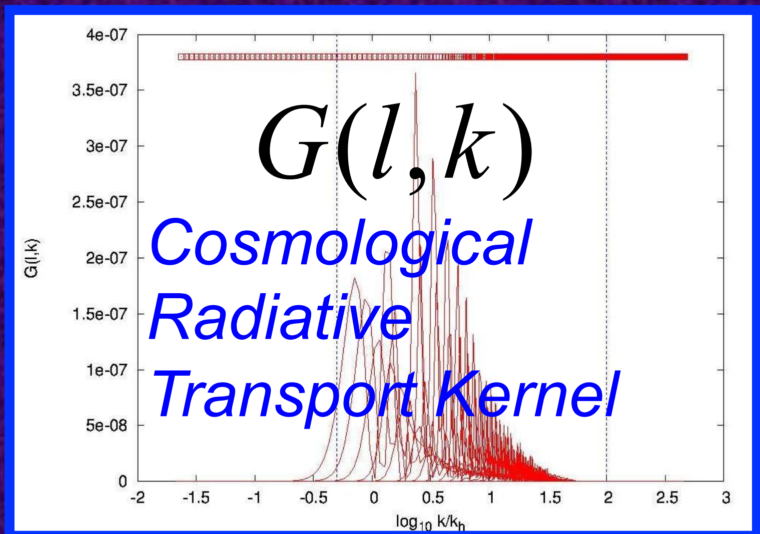
$P(k)$

Primordial Power Spectrum

?

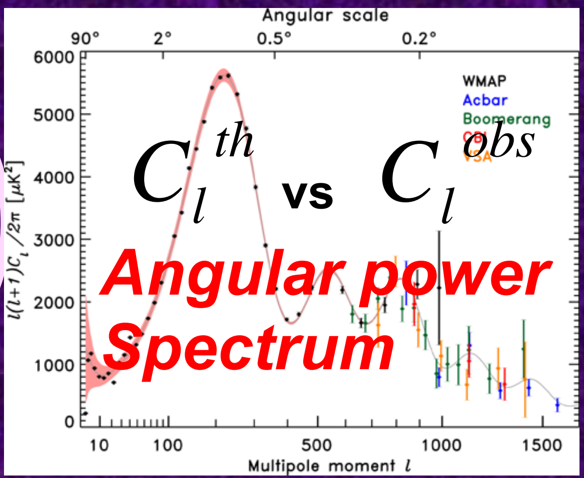
Suggested by Model of Inflation

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



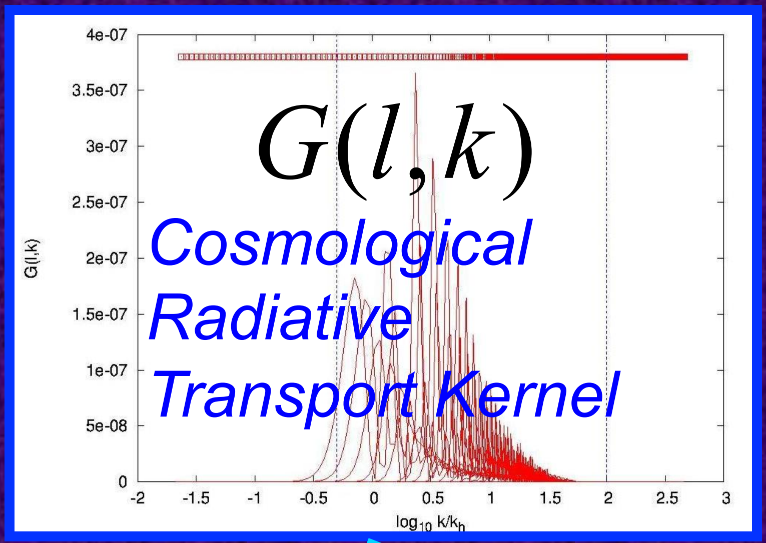
Determined by background model and cosmological parameters

Detected by observation

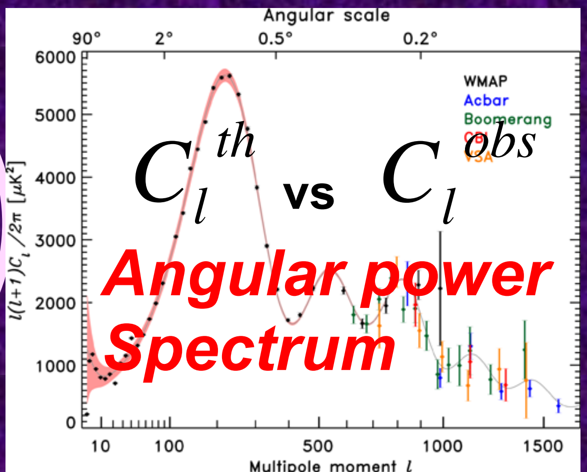


We cannot anticipate the unexpected !!

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



Determined by background model and cosmological parameters



Detected by observation

DIRECT TOP DOWN Reconstruction

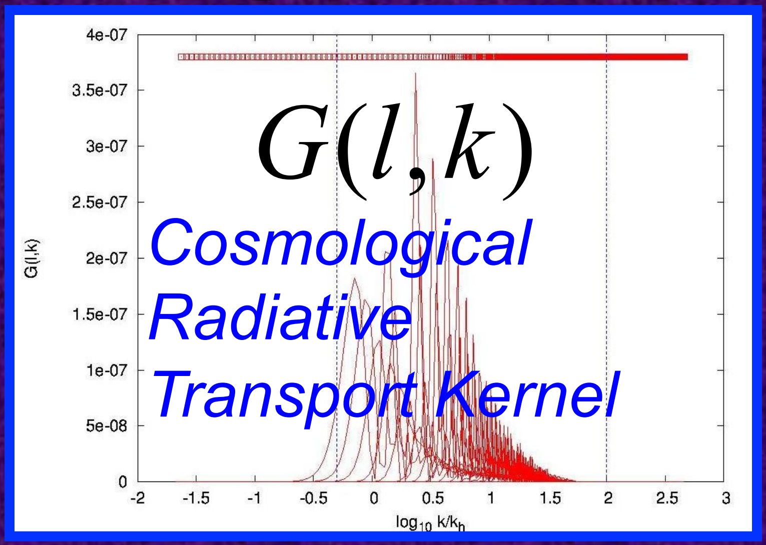
$P(k)$

Primordial Power Spectrum

?

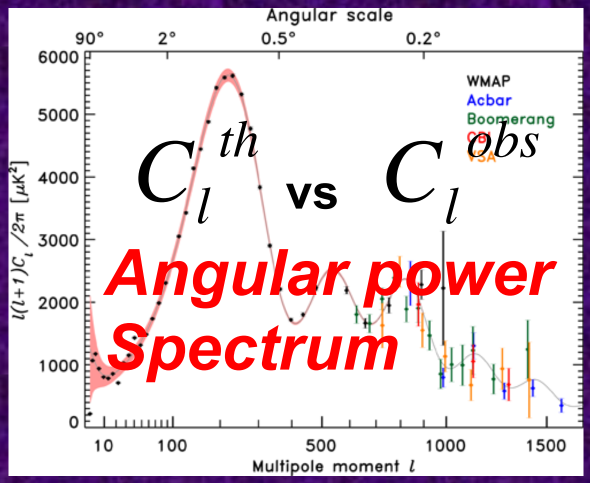
Reconstructed by Observations

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



Determined by background model and cosmological parameters

Detected by observation



Modified Richardson-Lucy Deconvolution

- ➔ Iterative algorithm.
- ➔ Not sensitive to the initial guess.
- ➔ Enforce positivity of P(k).

[$G(l,k)$ is positive definite and C_l is positive]

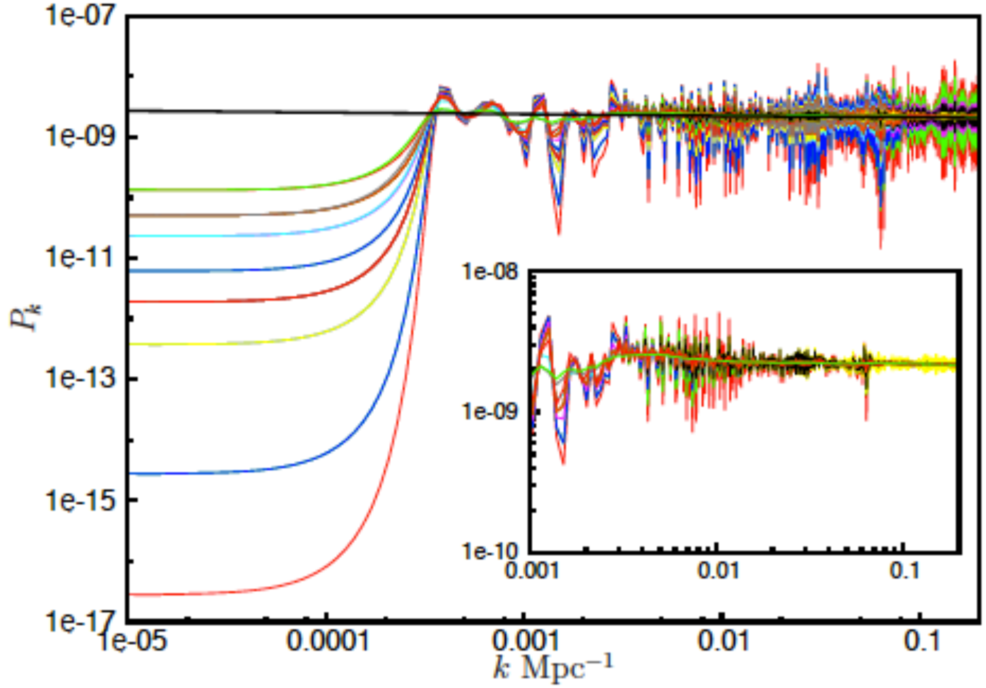
$$C_\ell = \sum_i G_{\ell k_i} P_{k_i}$$

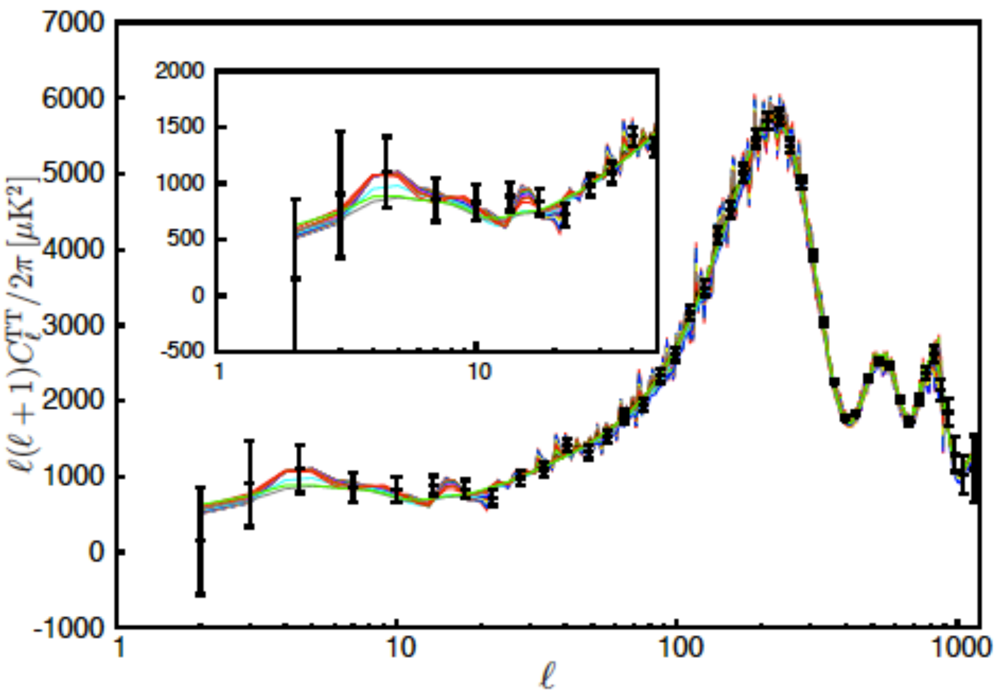
$$P_k^{(i+1)} - P_k^{(i)} = P_k^{(i)} \times \left[\sum_{\ell=2}^{\ell=900} \widetilde{G}_{\ell k}^{\text{un-binned}} \left\{ \left(\frac{C_\ell^{\rm D} - C_\ell^{\rm T(i)}}{C_\ell^{\rm T(i)}} \right) \tanh^2 \left[Q_\ell (C_\ell^{\rm D} - C_\ell^{\rm T(i)}) \right] \right\}_{\text{un-binned}} + \sum_{\ell_{\text{binned}} > 900} \widetilde{G}_{\ell k}^{\text{binned}} \left\{ \left(\frac{C_\ell^{\rm D} - C_\ell^{\rm T(i)}}{C_\ell^{\rm T(i)}} \right) \tanh^2 \left[\frac{C_\ell^{\rm D} - C_\ell^{\rm T(i)}}{\sigma_\ell^{\rm D}} \right]^2 \right\}_{\text{binned}} \right], \quad (1)$$

$$Q_\ell = \sum_{\ell'} (C_{\ell'}^{\rm D} - C_{\ell'}^{\rm T(i)}) COV^{-1}(\ell, \ell'),$$

Shafieloo & Souradeep PRD 2004 ;
Shafieloo et al, PRD 2007;
Shafieloo & Souradeep, PRD 2008;
Nicholson & Contaldi JCAP 2009
Hamann, Shafieloo & Souradeep JCAP 2010
Hazra, Shafieloo & Souradeep PRD 2013
Hazra, Shafieloo & Souradeep JCAP 2013
Hazra, Shafieloo & Souradeep JCAP 2014

Theoretical Implication: Importance of the Features in the primordial spectrum

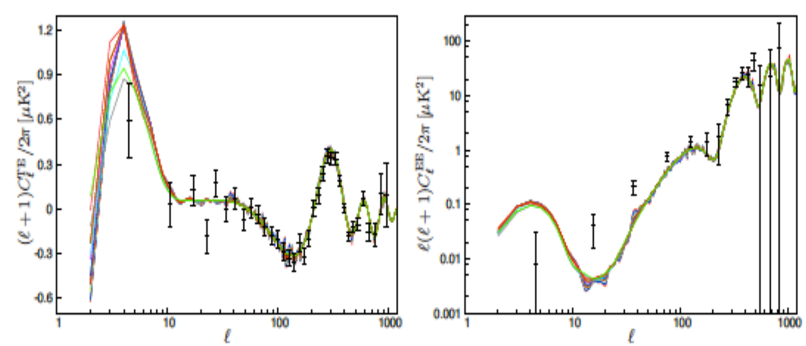




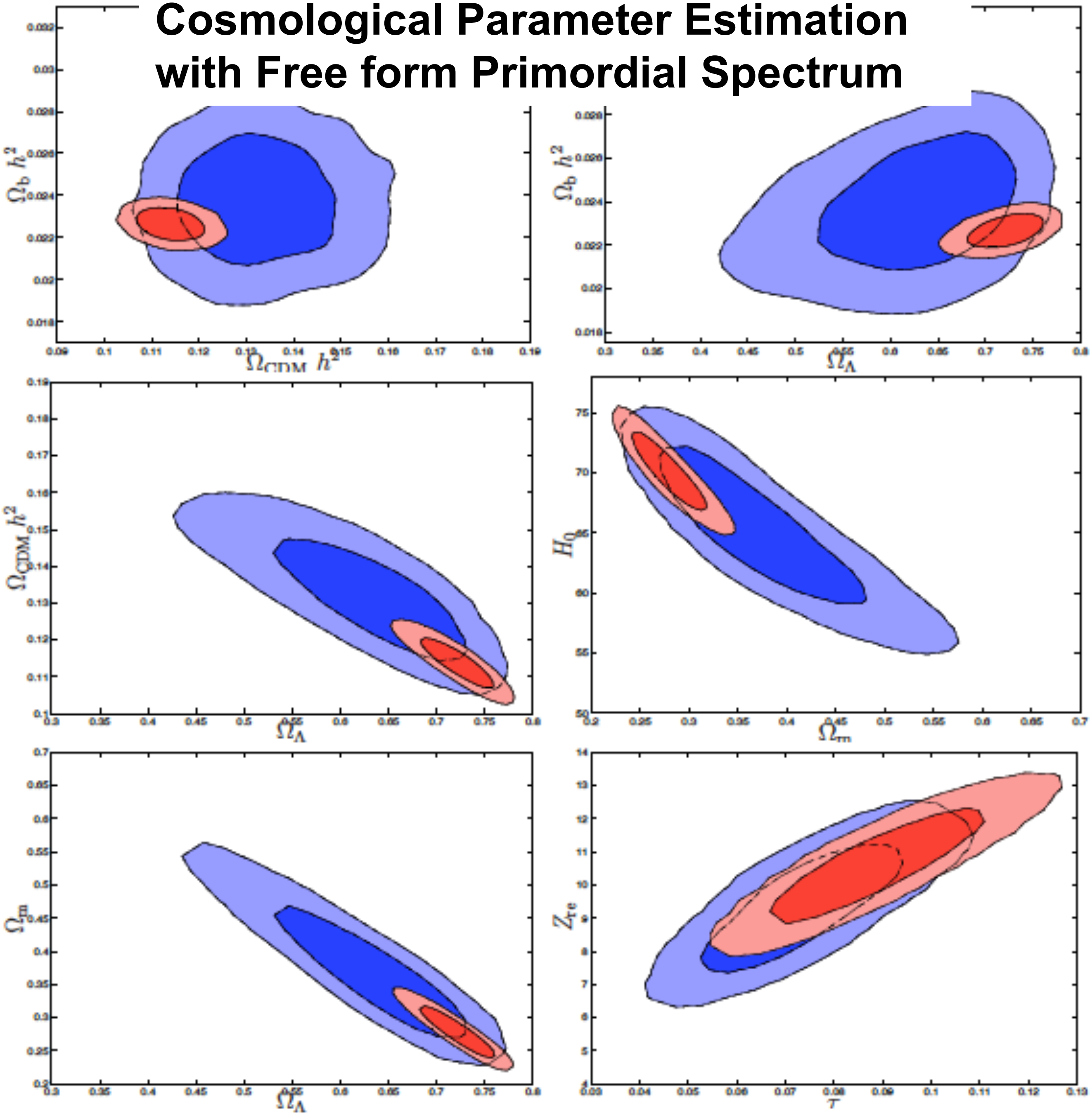
WMAP 9 analysis

The reconstructed primordial power-spectra (on top) and the corresponding angular power spectra (at the bottom) that provide a better fit ranging from *2− 300* in effective chi square (derived from WMAP 9 likelihood code) compared to the power law model.

Hazra, Shafieloo & Souradeep, JCAP 2013



Cosmological Parameter Estimation with Free form Primordial Spectrum



Red Contours: Power Law PPS

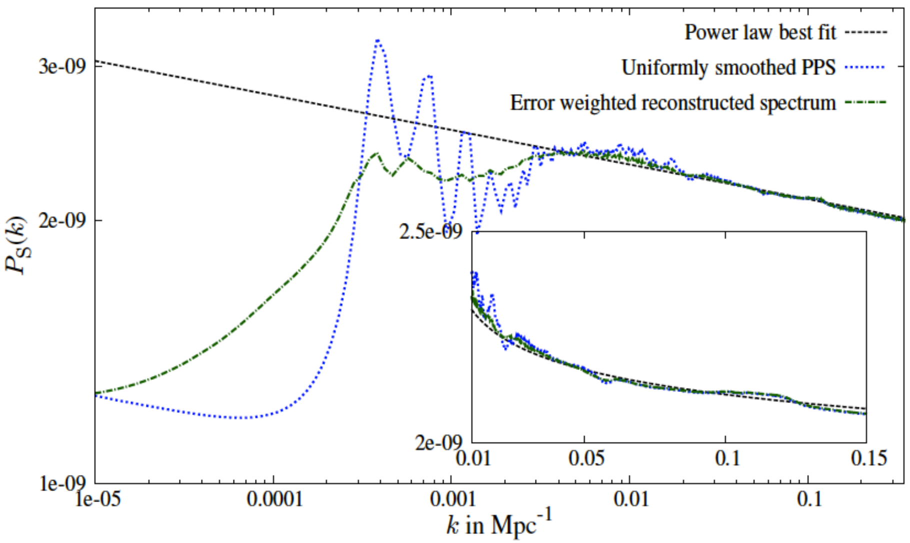
Blue Contours: Free Form PPS

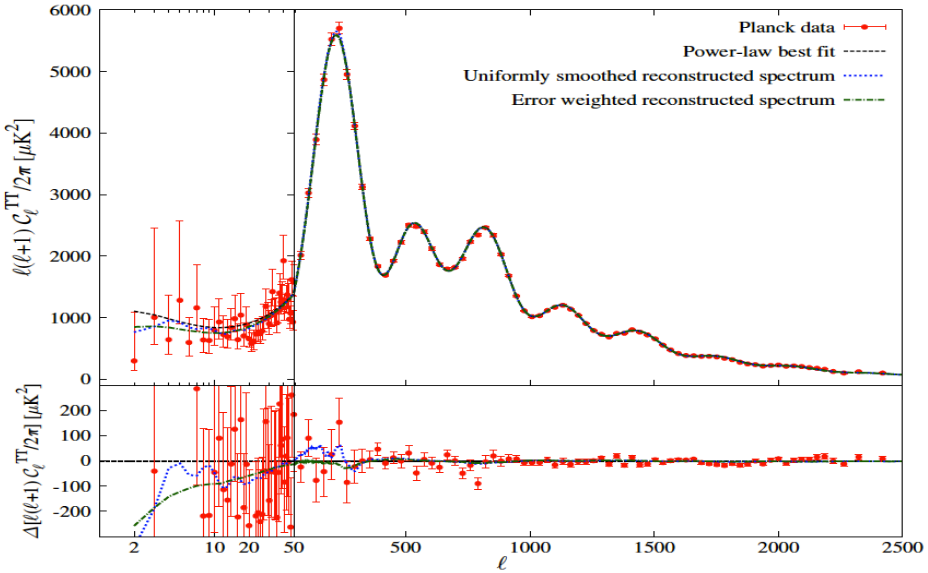
Hazra, Shafieloo & Souradeep, PRD 2013

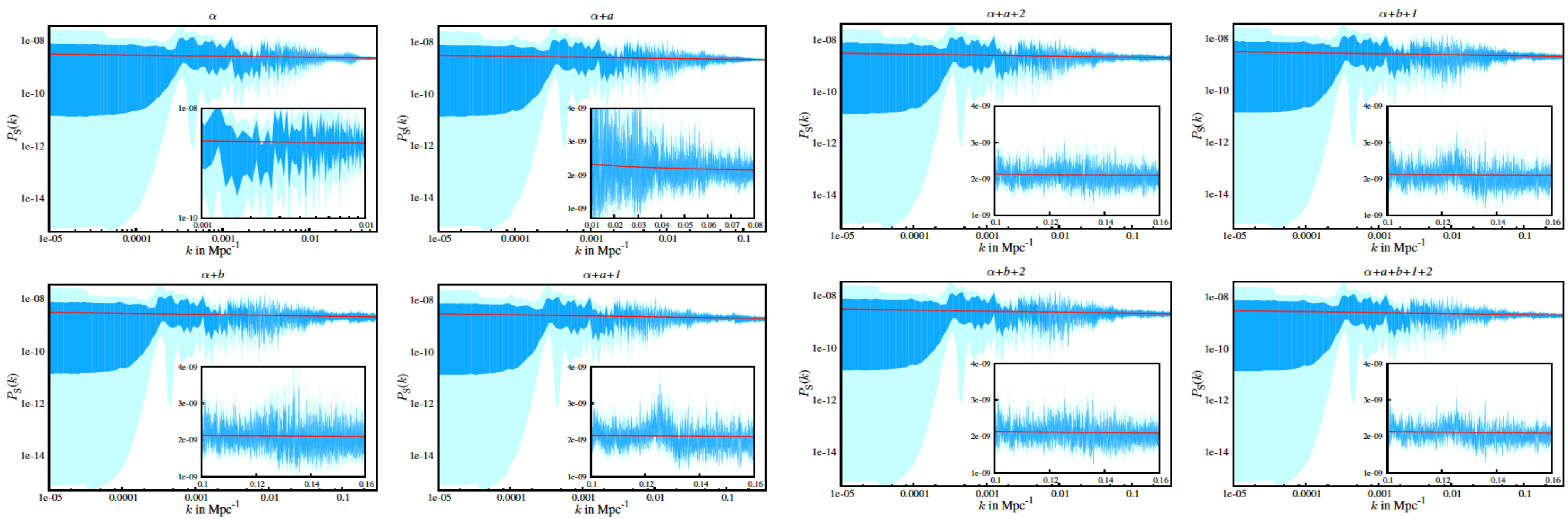
Our symbol	Spectra	Multipoles(ℓ)	Scales
α	low-ℓ	2-49	Largest scales
a	100 GHz × 100 GHz	50-1200	Intermediate scales
b	143 GHz × 143 GHz	50-2000	Intermediate scales
1	217 GHz × 217 GHz	500-2500	Small scales
2	143 GHz × 217 GHz	500-2500	Small scales

Primordial Power Spectrum from Planck

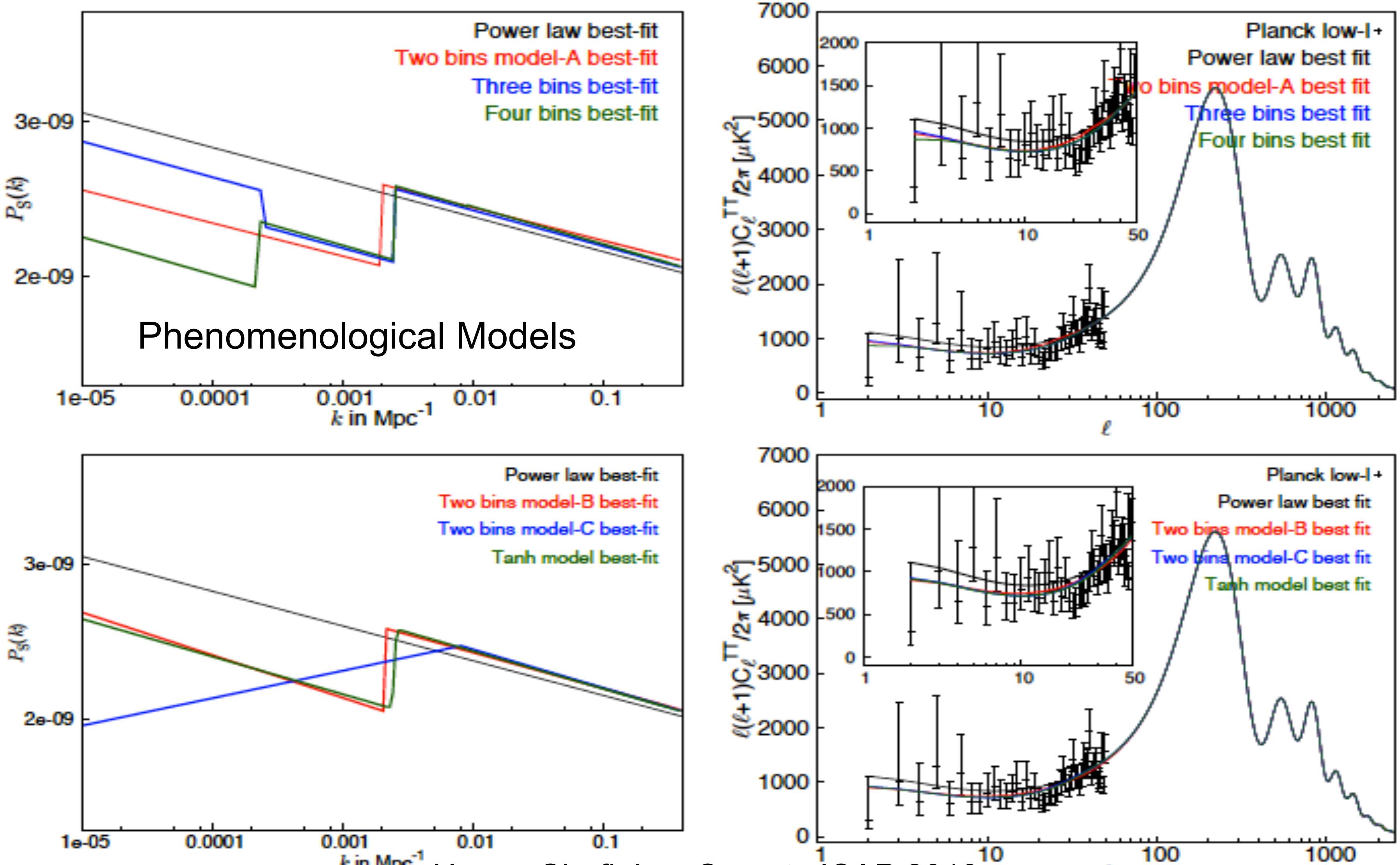
Hazra, Shafieloo & Souradeep, JCAP 2014







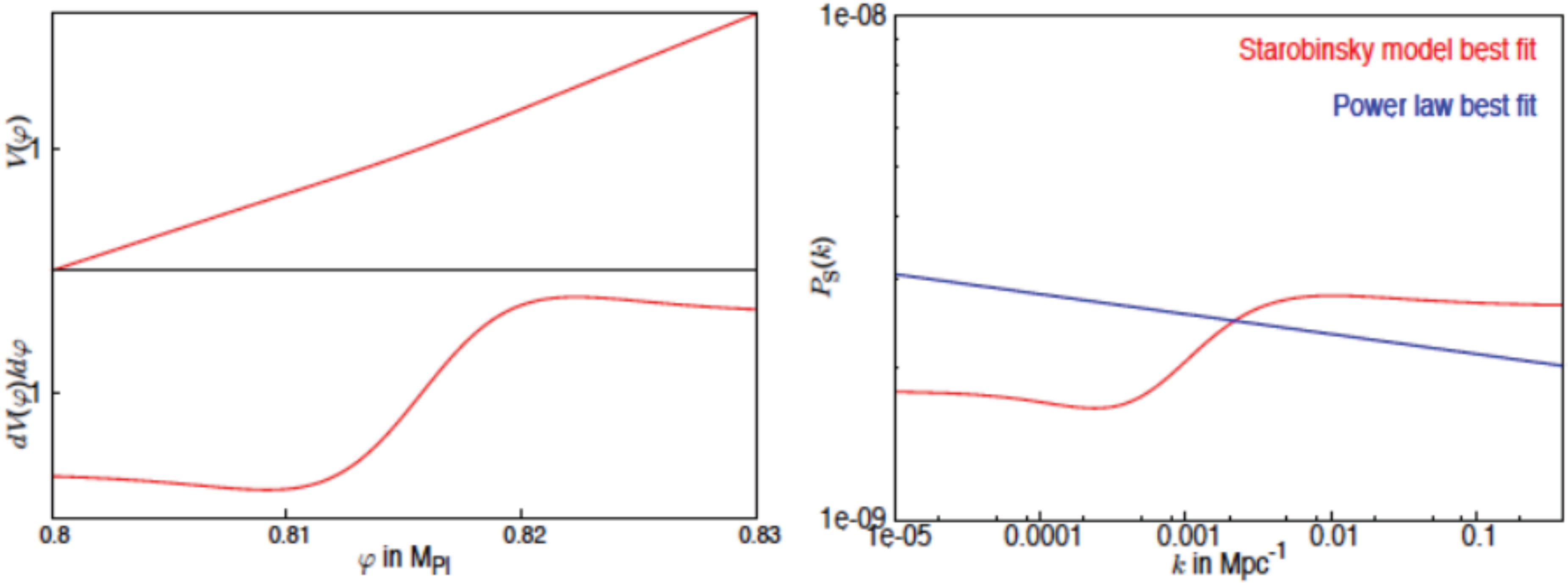
Beyond Power-Law: there are some other models consistent to the data.



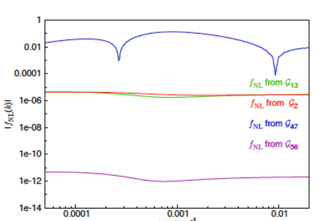
Hazra, Shafieloo, Smoot, JCAP 2013

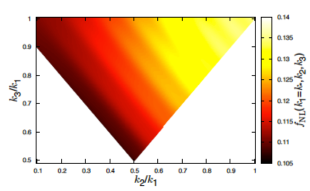
Beyond Power-Law: there are some other models consistent to the data.

Starobinsky linear field potential, with broken power law.

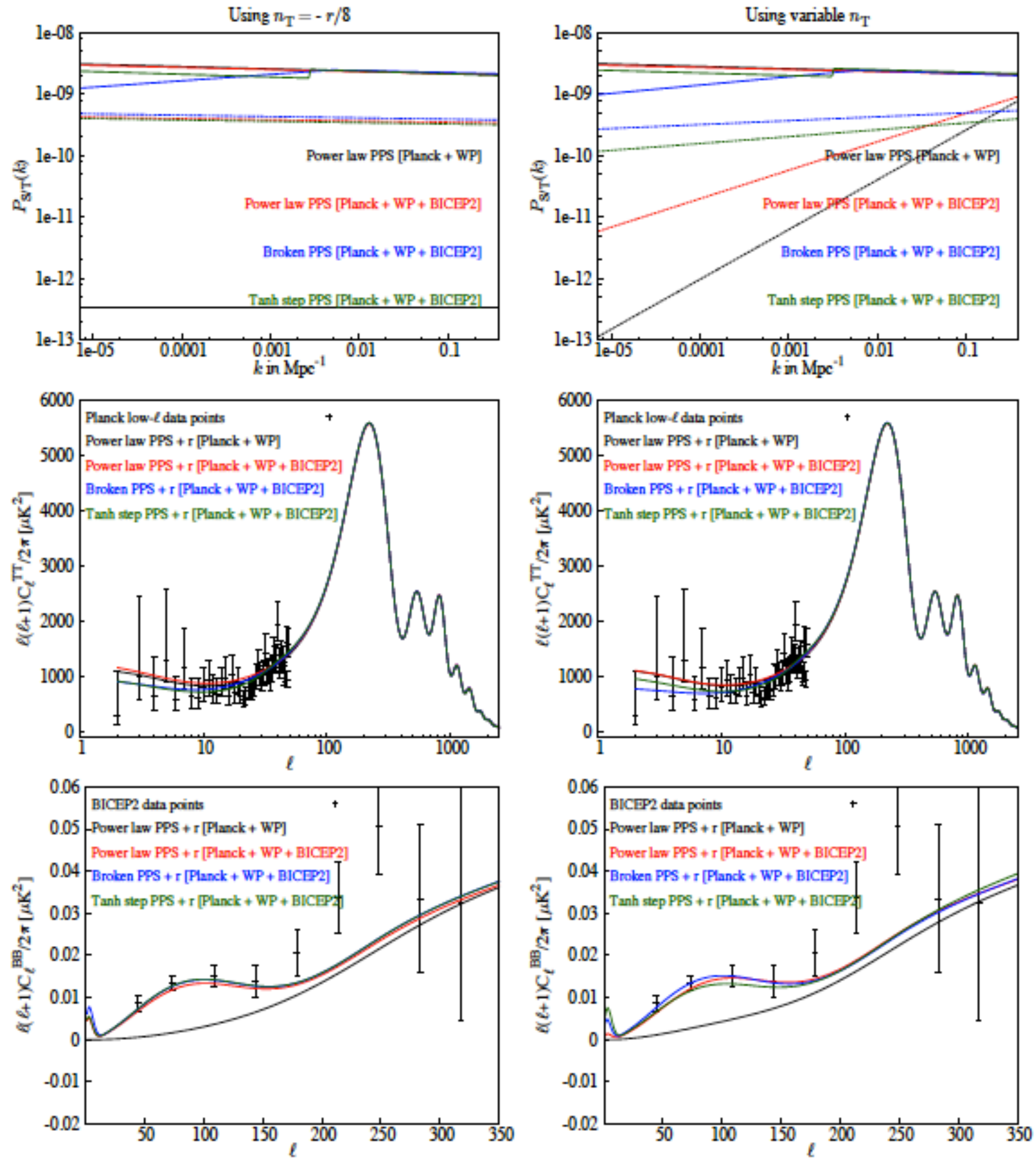


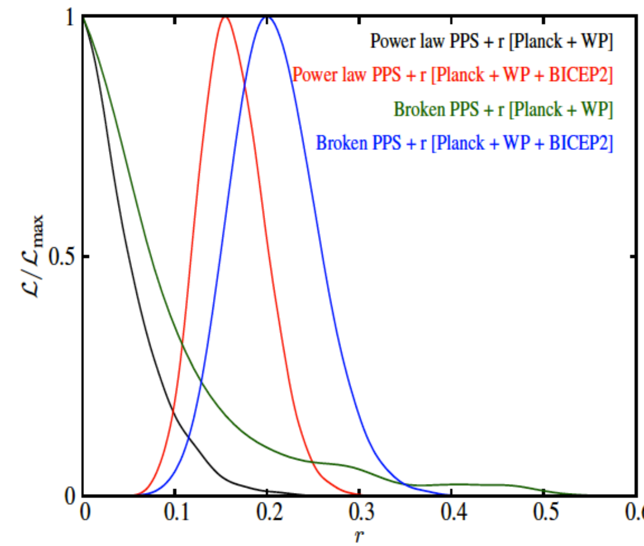
Hazra, Shafieloo, Smoot 1310.3038 (JCAP 2013)

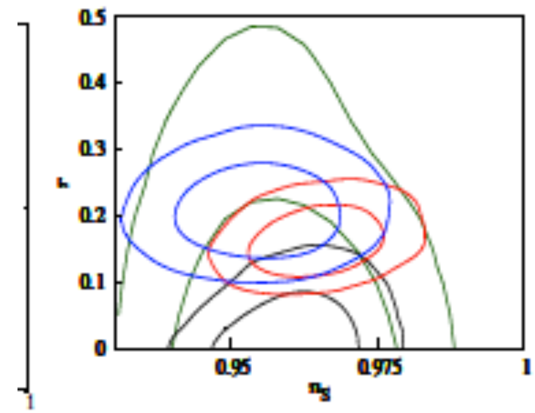




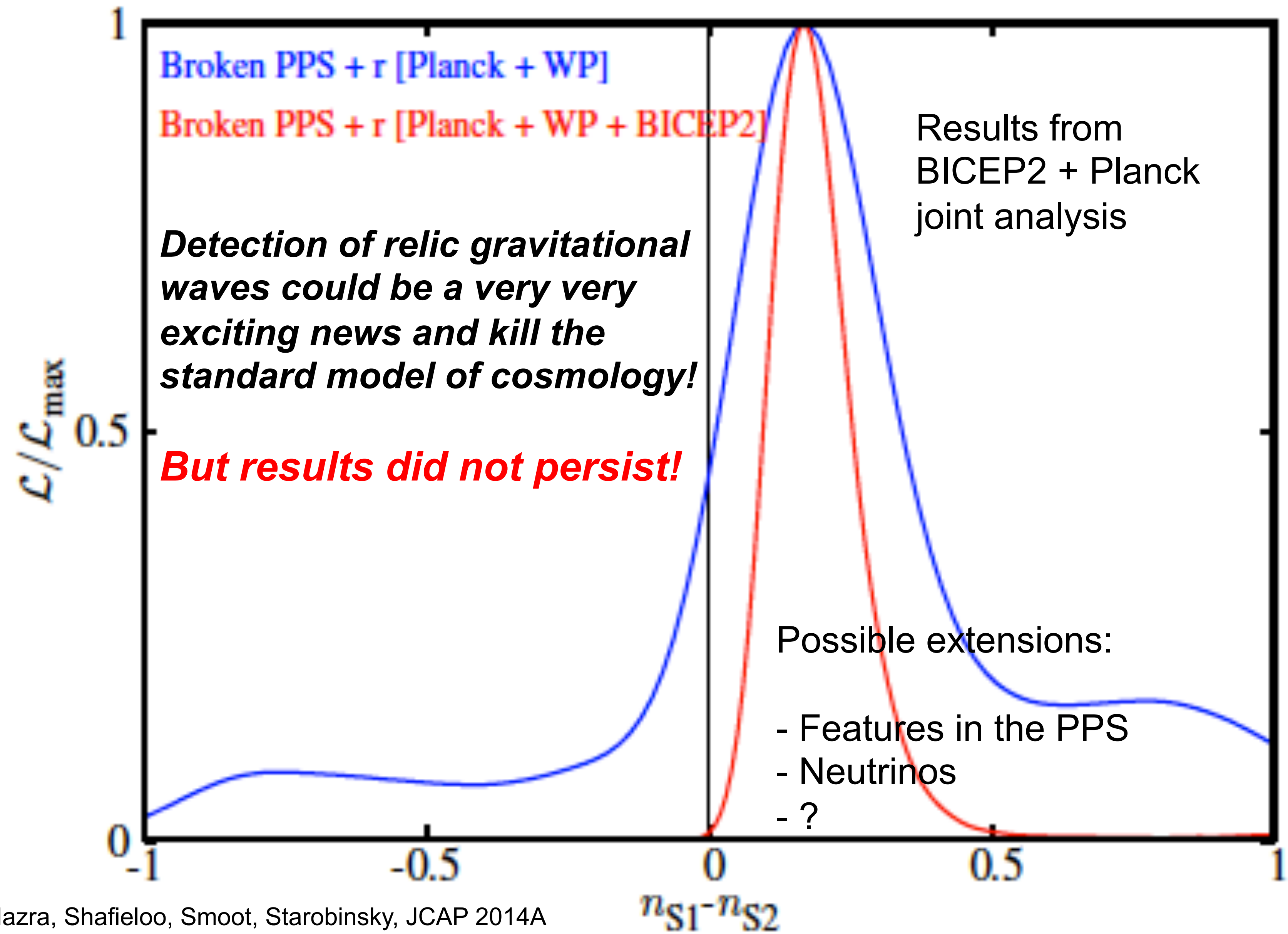
Results from BICEP2 + Planck joint analysis







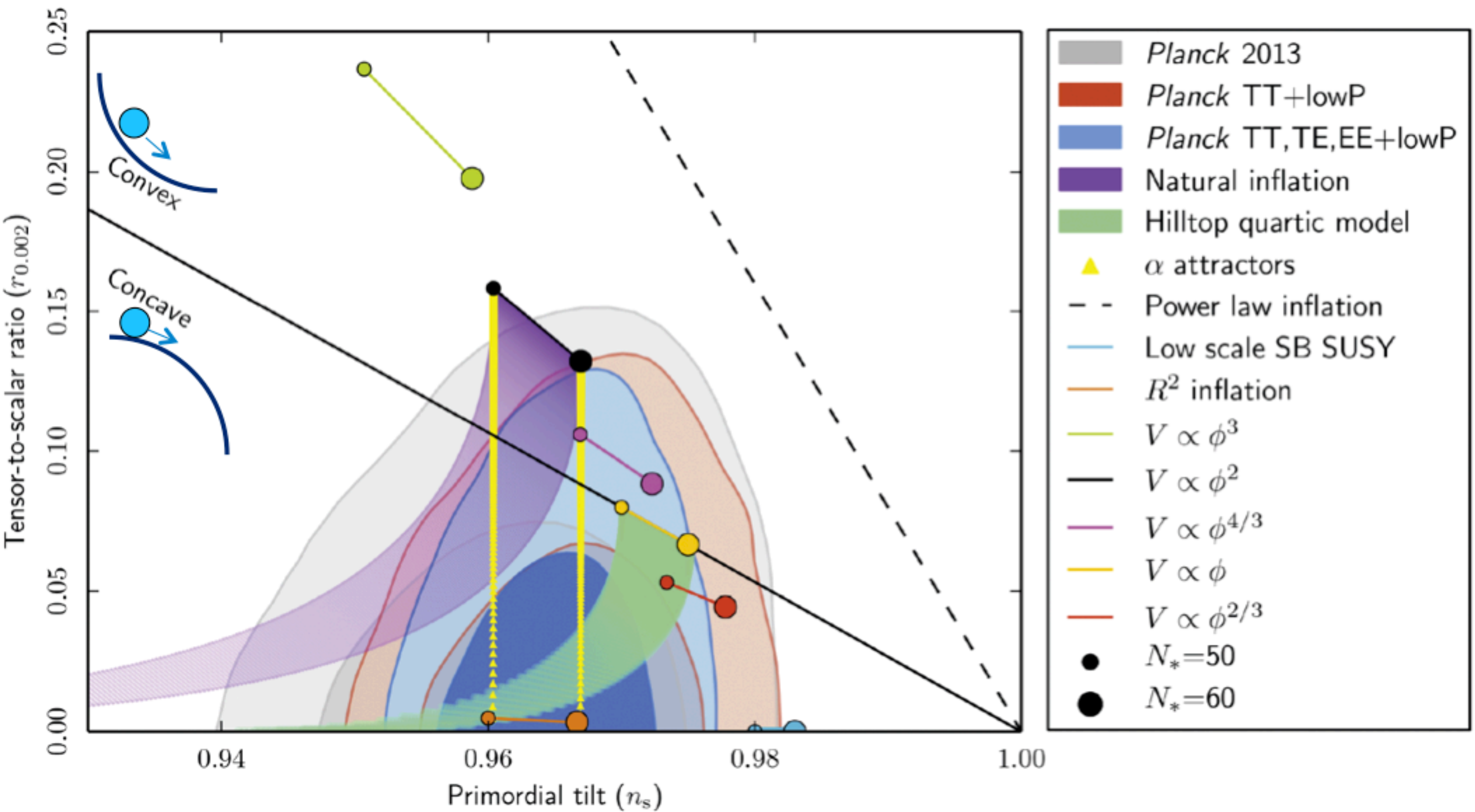
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014A



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

Planck 2015: No detectable primordial G-waves

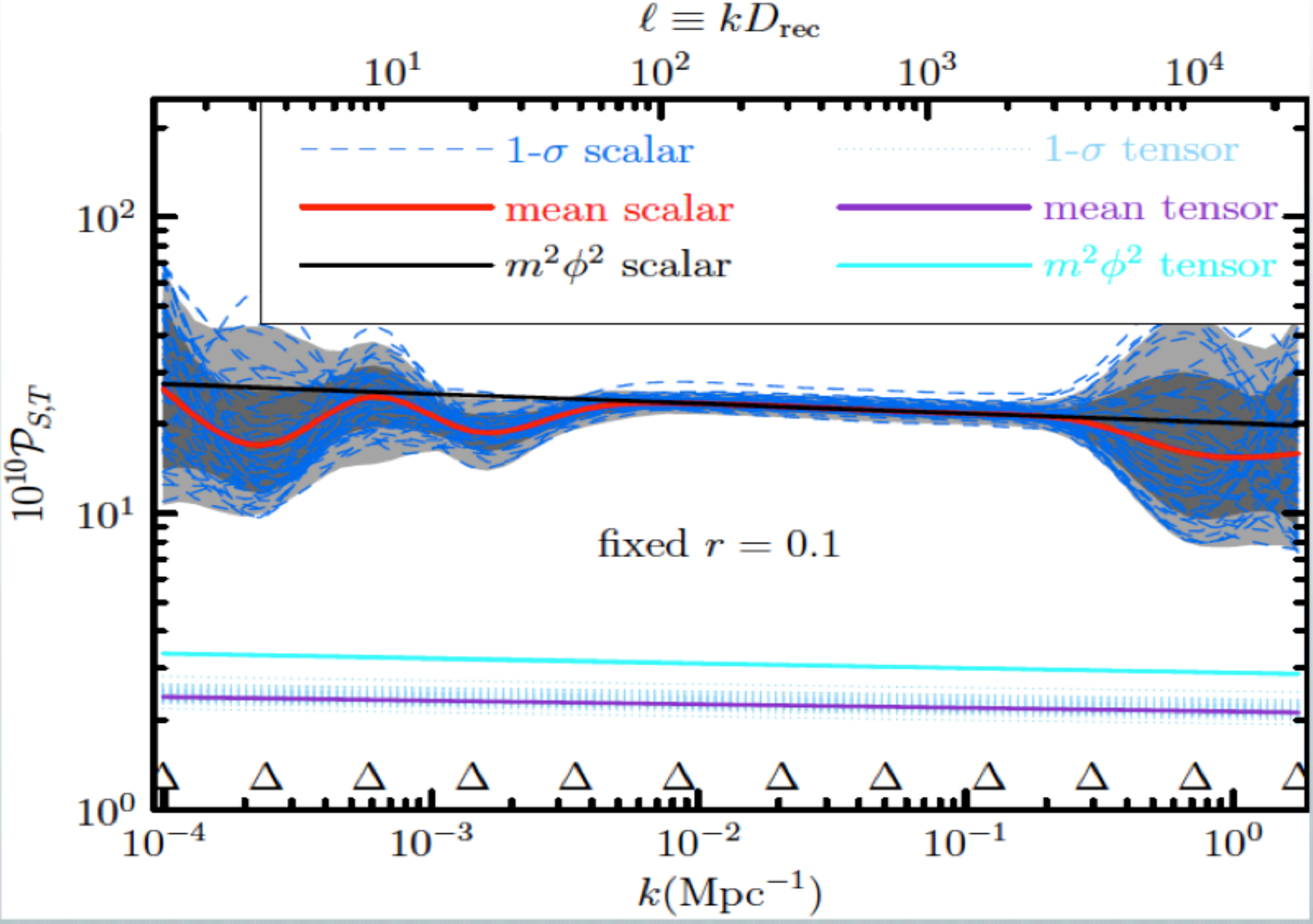
Planck 2015: n_s vs r



Planck 2015: No feature

Power spectra reconstruction

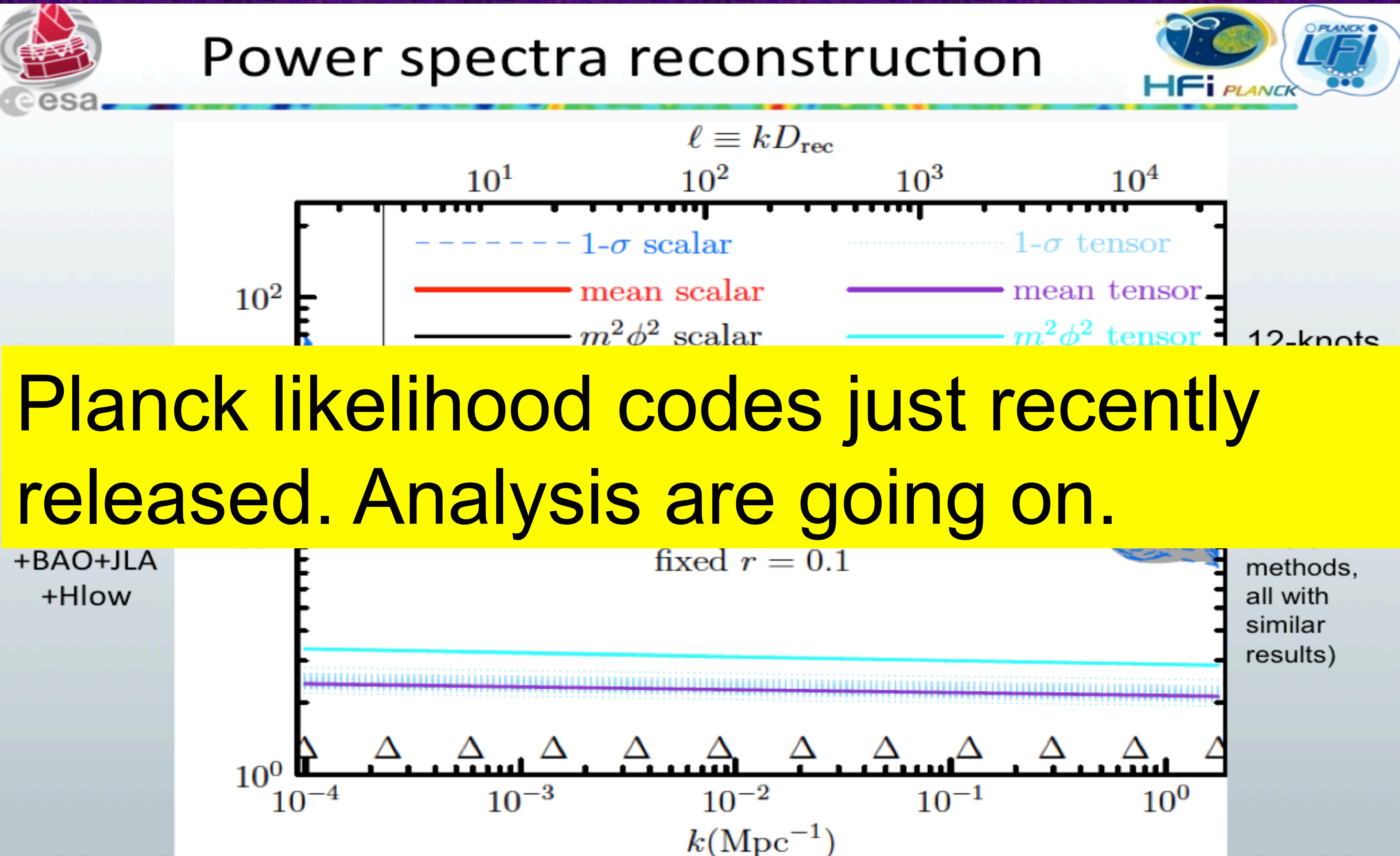
2015
TT+lowP
+BAO+JLA
+Hlow



12-knots power spectra

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

Planck 2015: No feature



Planck likelihood codes just recently released. Analysis are going on.

(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

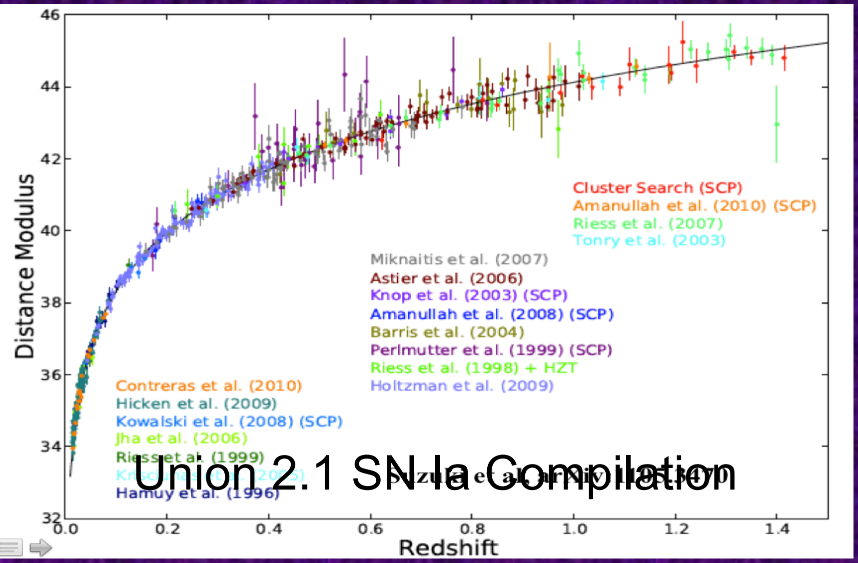
Era of Accelerating Universe

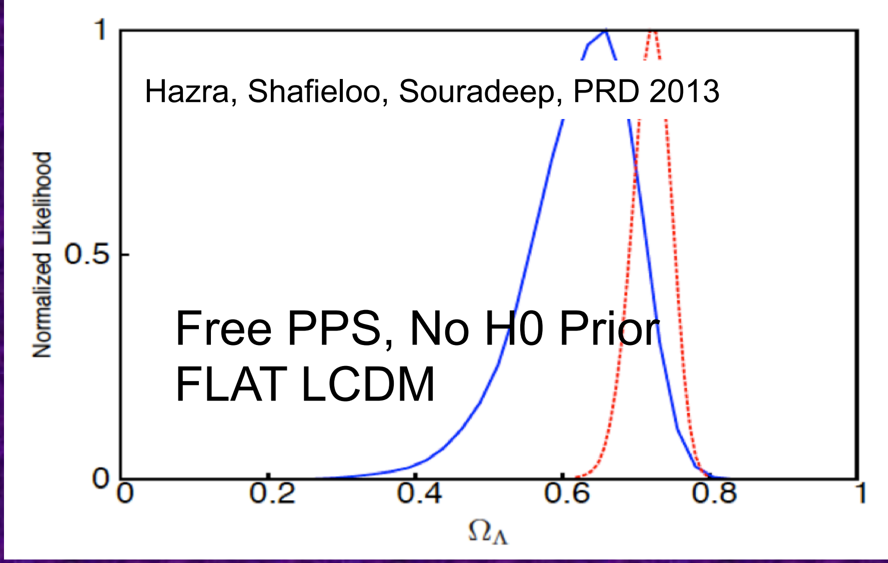
- Mid 90's: Indirect evidences were seen in the distribution of the galaxies where SCDM could not explain the excess of power at large scales.

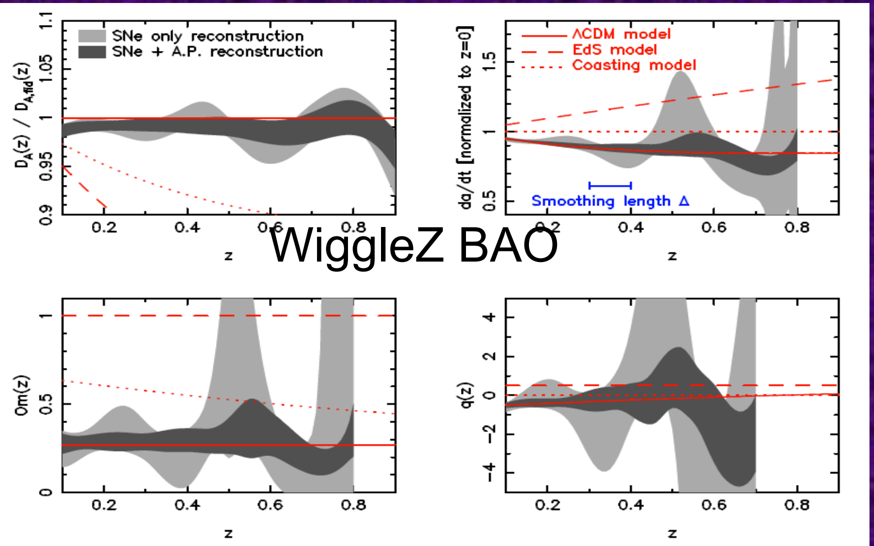
- 1998: Direct evidence came by Supernovae Type Ia Observations. *Going to higher redshifts, supernovae are fainter than expected. One can explain this only (?!=Nobel Prize) by considering an accelerating universe.*

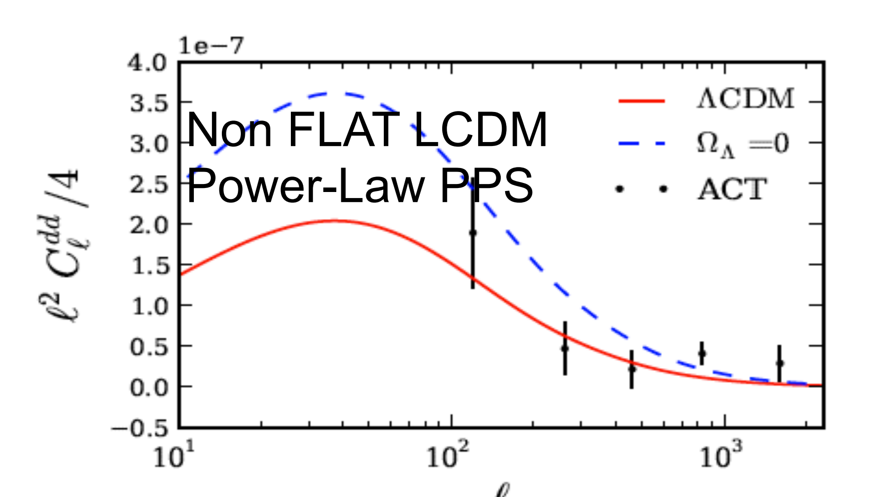
Accelerating Universe, Now-2015

Or better to say, ruling out zero-Lambda Universe



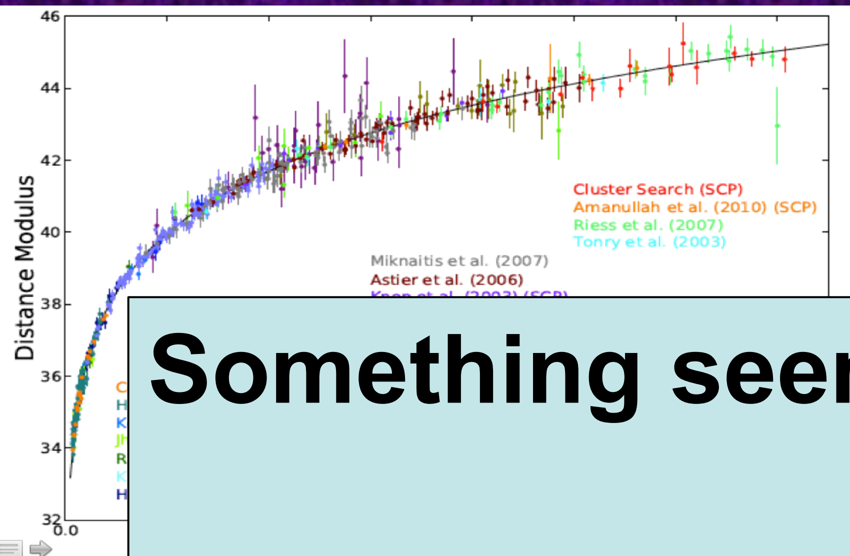


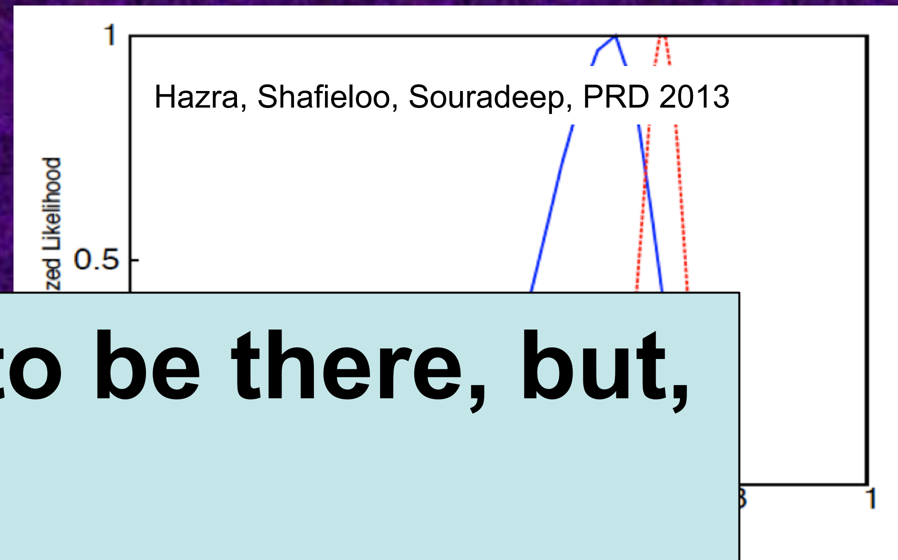




D. Sherwin et.al, PRL 2011

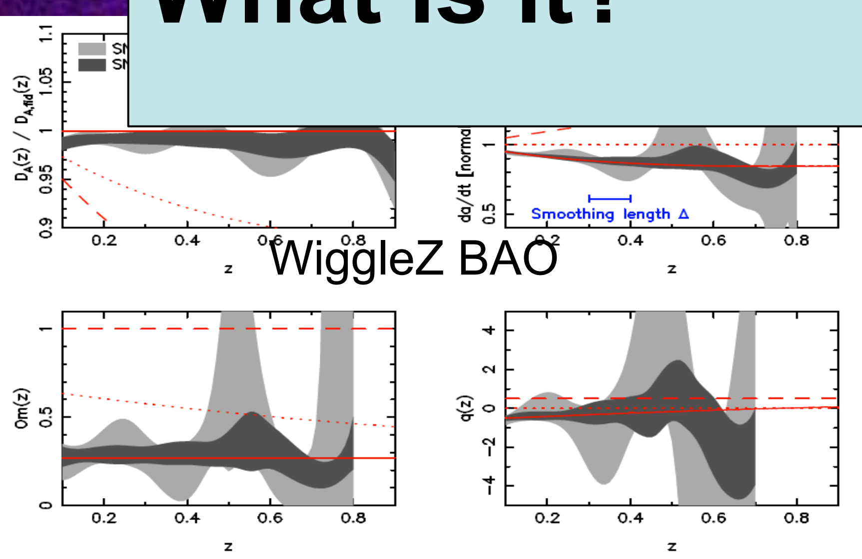
Accelerating Universe, Now

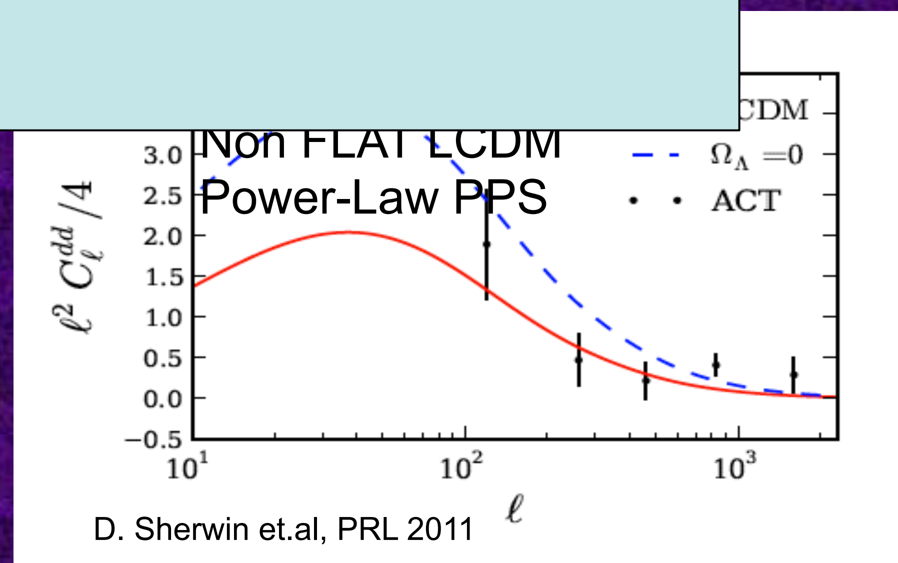




Something seems to be there, but,

What is it?

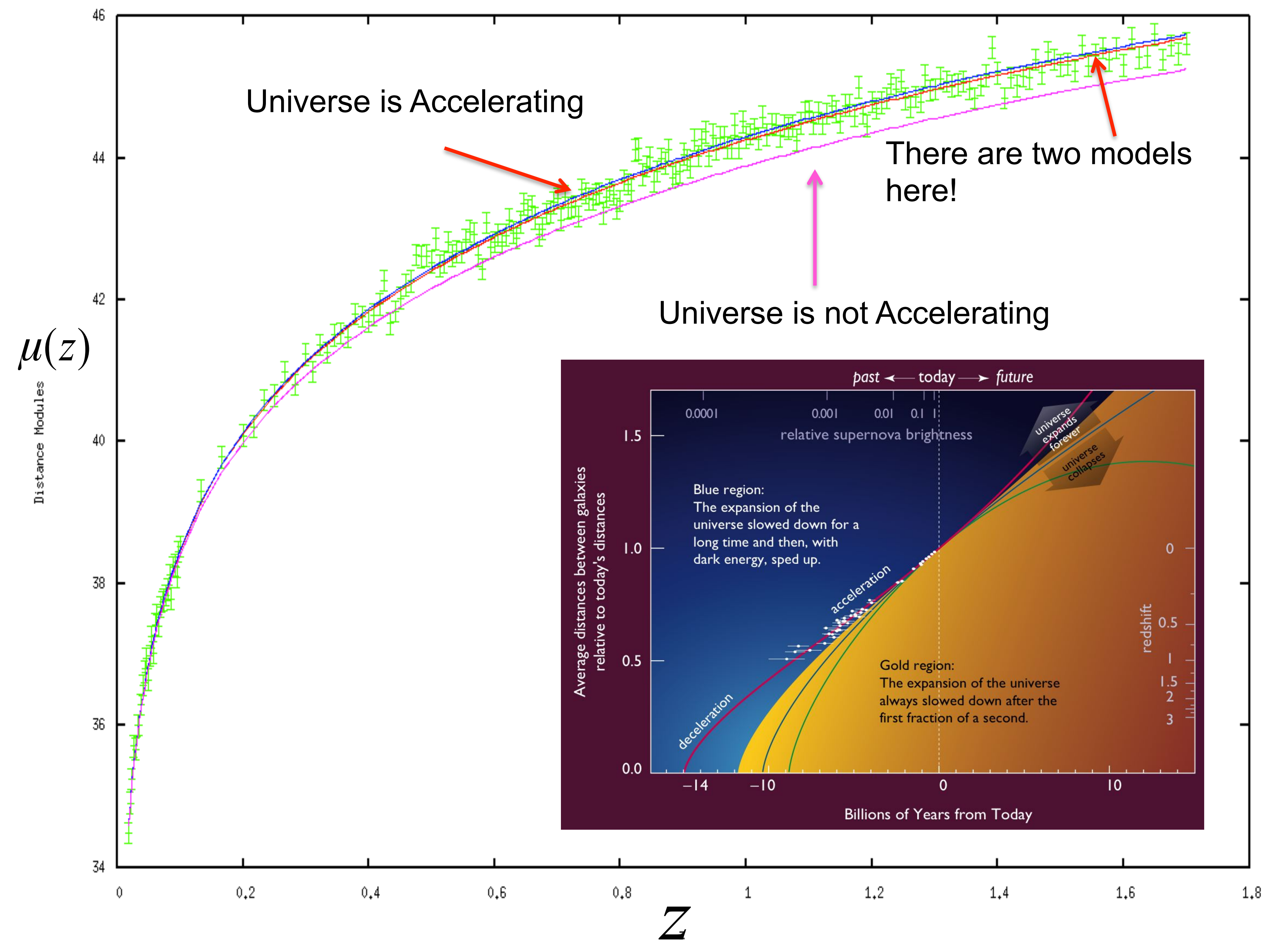




Dark Energy Models

- 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
$\mu(z)$
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
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
1.5
1.0
0.5
0.0
redshift
0
0.5
1
1.5
2
3
−14
−10
0
10
Billions of Years from Today

Reconstructing Dark Energy

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

1. Parametric methods

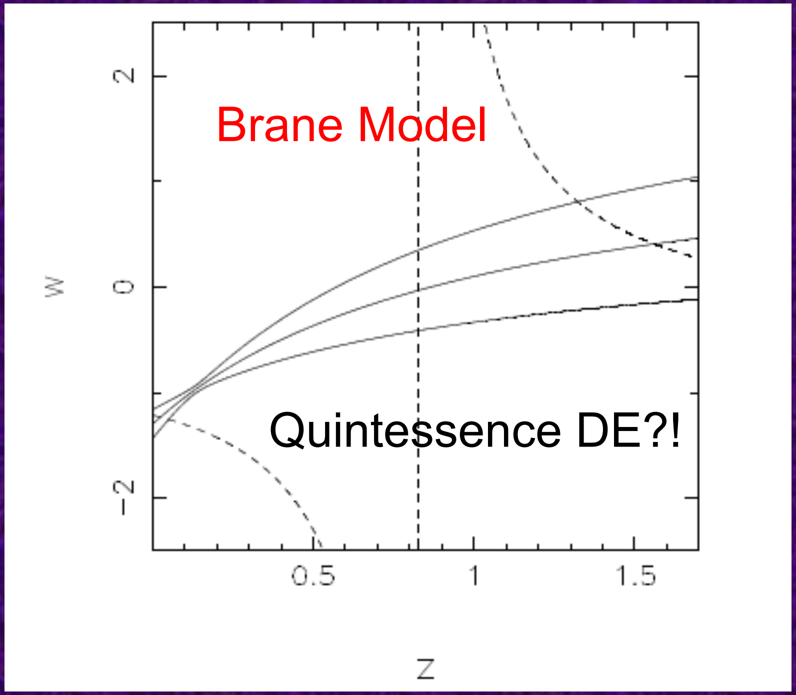
Easy to confront with cosmological observations to put constrains on the parameters, but the results are highly biased by the assumed models and parametric forms.

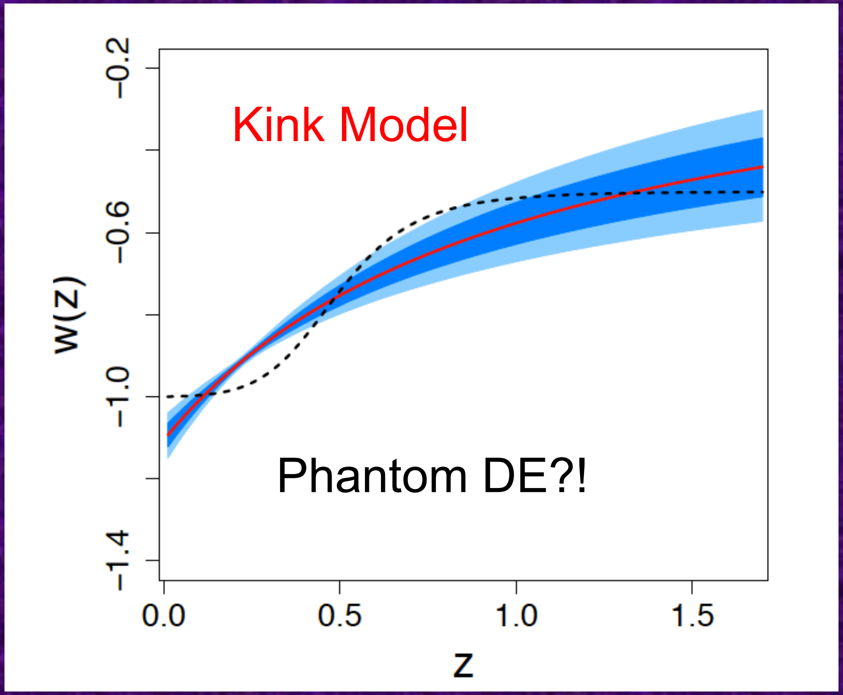
2. Non Parametric methods

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.

.

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).

Non Parametric methods of Reconstruction

Usually involves binning and smoothing

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

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

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

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

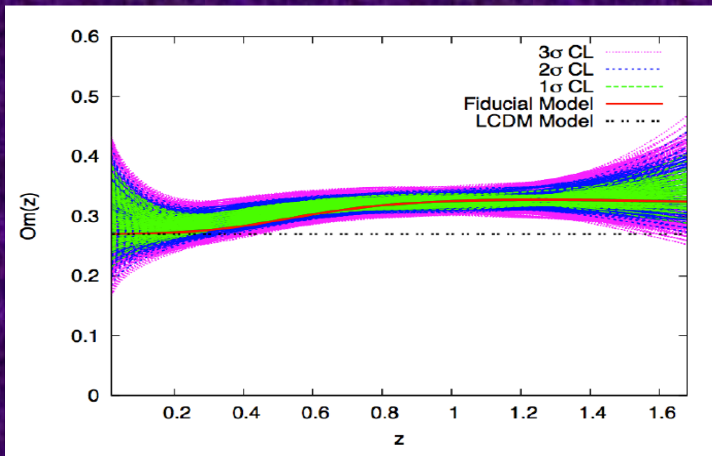
$$\omega_{DE} = \frac{\left(\frac{2(1+z)}{3}\frac{H'}{H}\right)-1}{1-\left(\frac{H_0}{H}\right)^2\Omega_{0M}(1+z)^3}$$

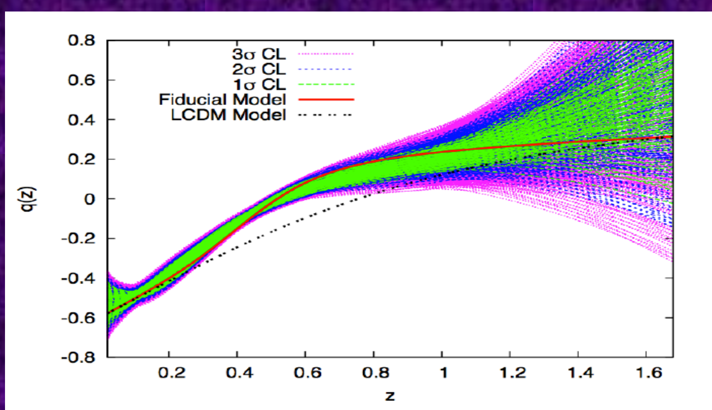
$$H(z) = \left[\frac{d}{dz}\left(\frac{d_L(z)}{1+z}\right)\right]^{-1}$$

$$q(z) = (1+z)\frac{H'(z)}{H(z)} - 1$$

Model independent reconstruction of the expansion history

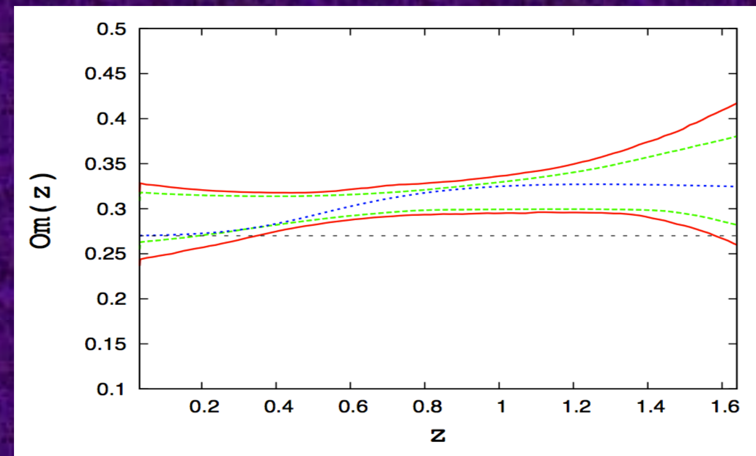
Crossing Statistic + Smoothing

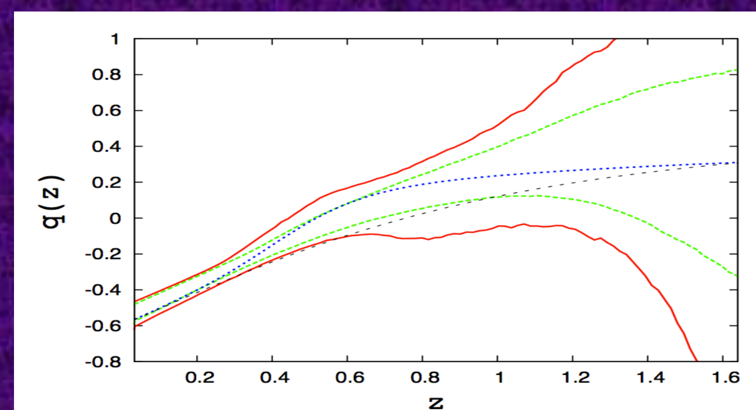




Shafieloo, JCAP (b) 2012

Gaussian Processes

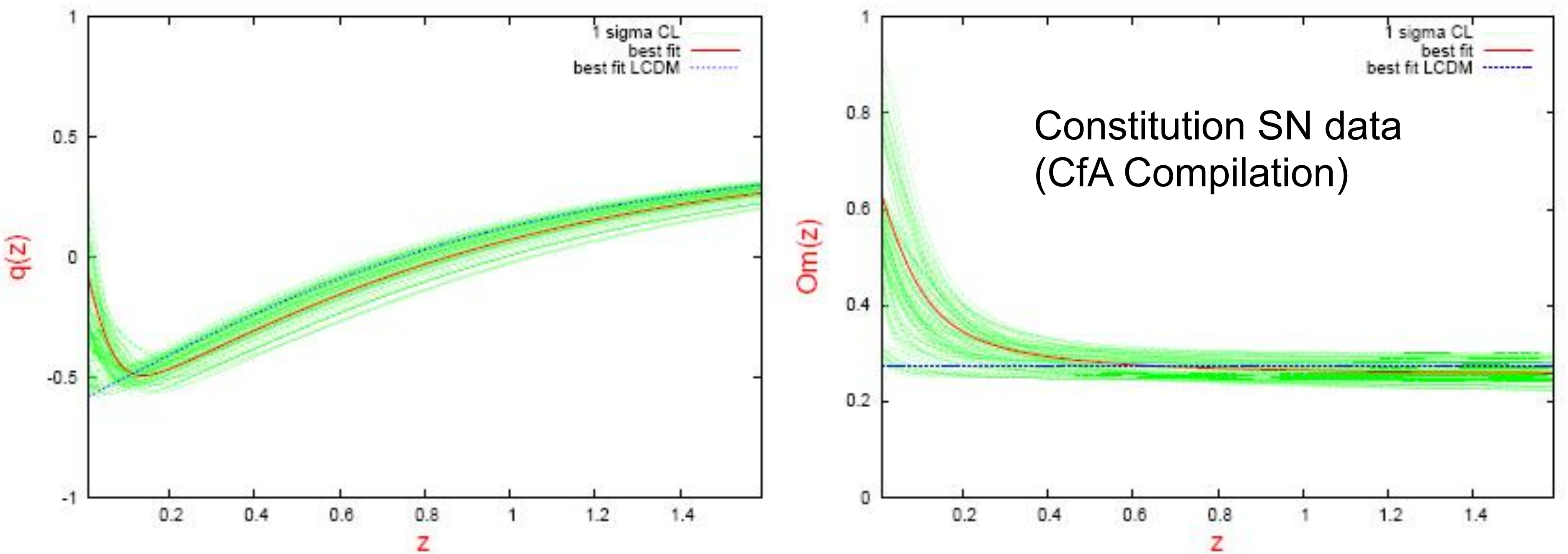




Shafieloo, Kim & Linder, PRD 2012

Theoretical application of direct reconstruction

IS COSMIC ACCELERATION SLOWING DOWN?



$$w(z) = -\frac{1+\tanh\left[\left(z-z_t\right)\Delta\right]}{2}$$

$\Delta\chi^2 = -0.6$ with respect to CPL

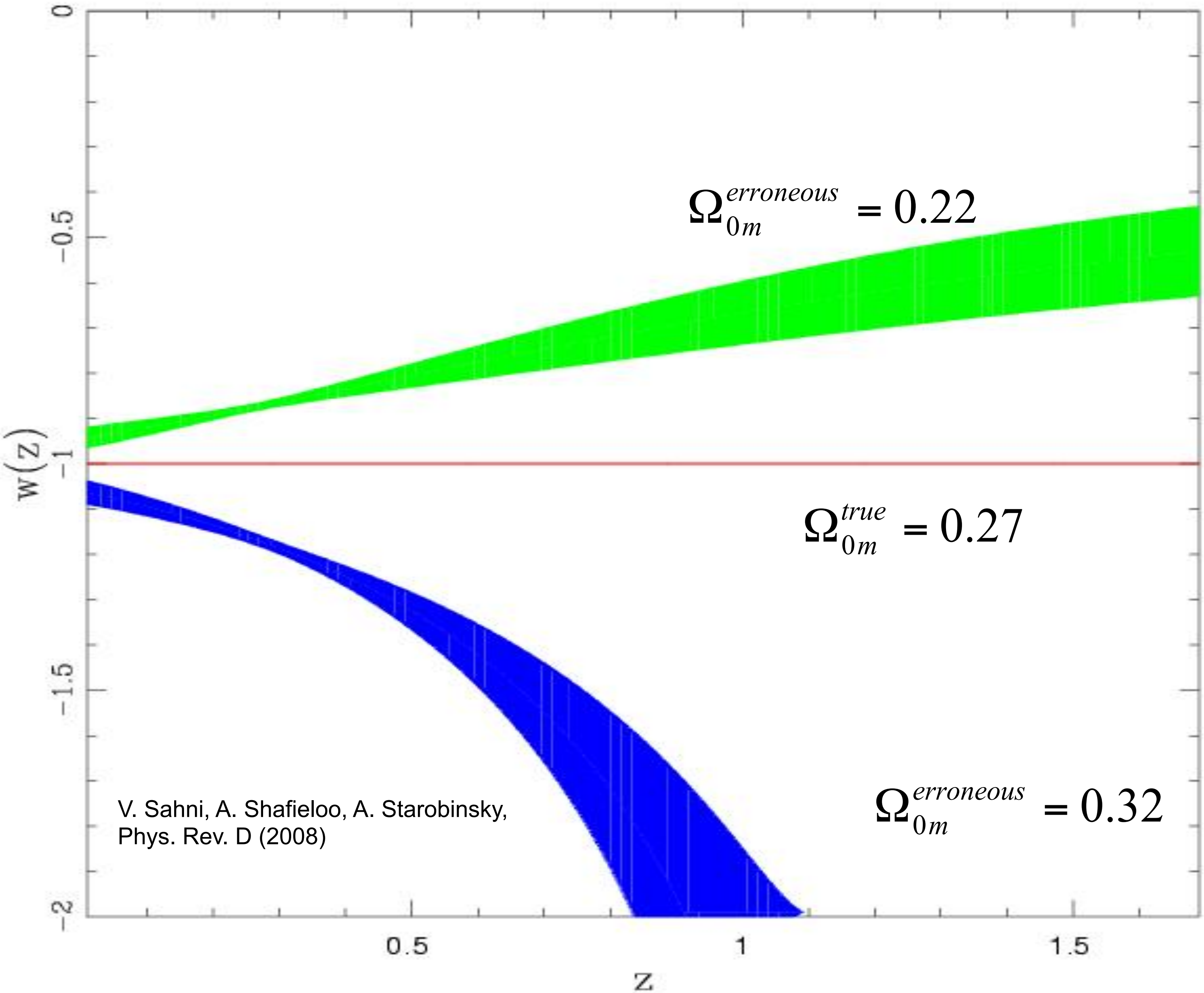
A. Shafieloo, V. Sahni, A. Starobinsky, Phys. Rev. D Rapid Communication 2009 [Reported in Nature and New Scientist]

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).

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

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



$\Omega_{0m}^{erroneous} = 0.22$
$\Omega_{0m}^{true} = 0.27$
$\Omega_{0m}^{erroneous} = 0.32$
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:

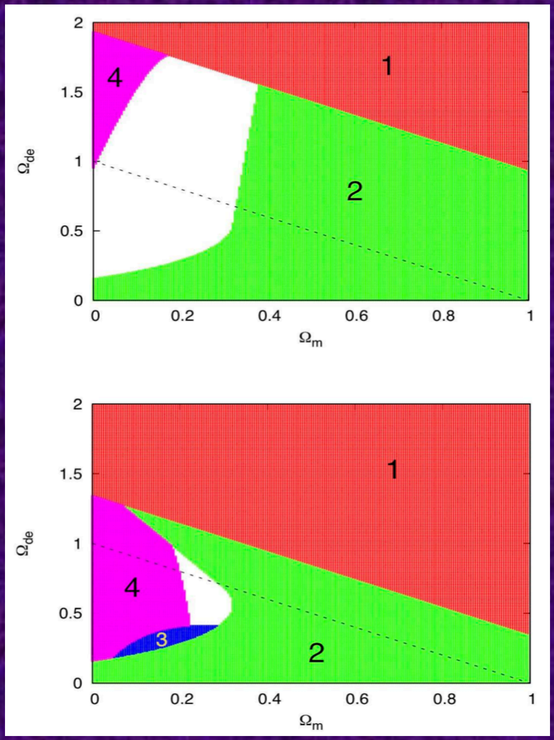
Cosmographic Degeneracy

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

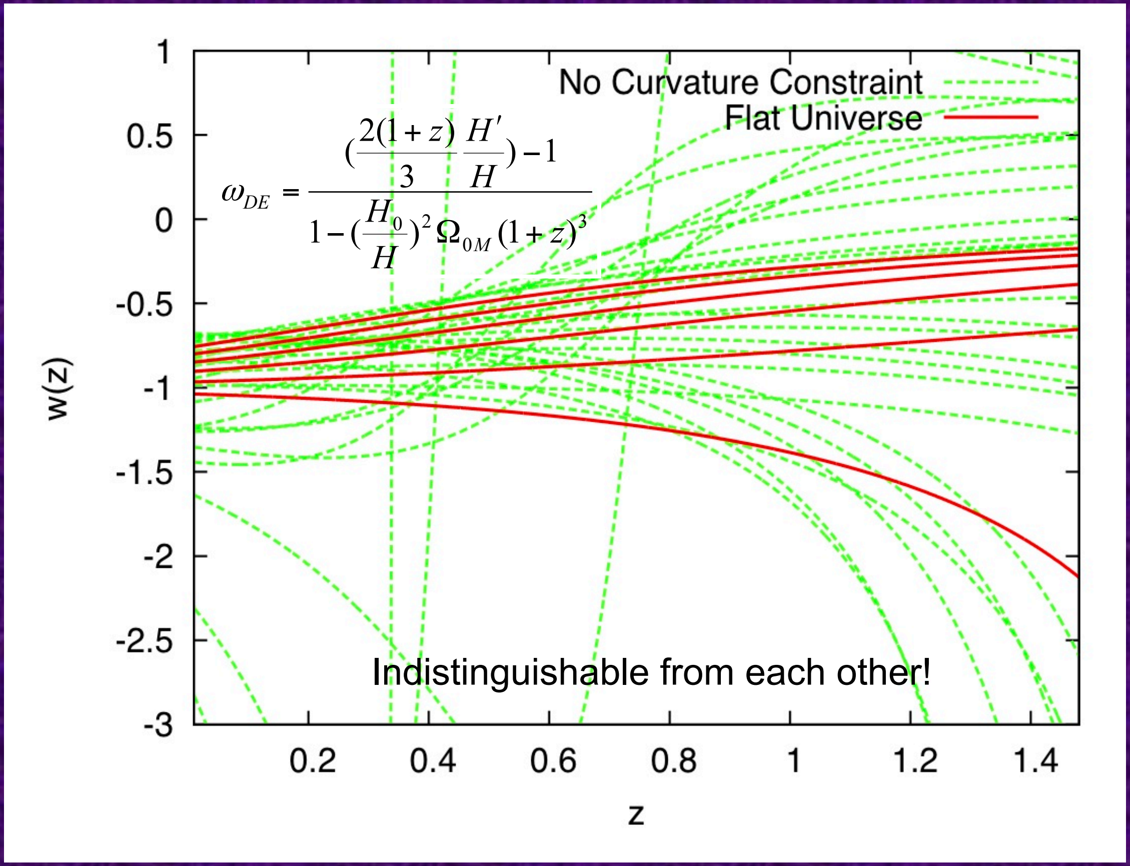
$$\begin{aligned} h(z)^2 &\equiv [H(z)/H_0]^2 \equiv (\dot{a}/a)^2 \\ &= \Omega_m(1+z)^3 + (1-\Omega_m-\Omega_{de})(1+z)^2 \\ &\quad + \Omega_{de} \exp\left[3\int_0^z \frac{dz'}{1+z'}[1+w(z')]\right] , \end{aligned}$$

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.

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

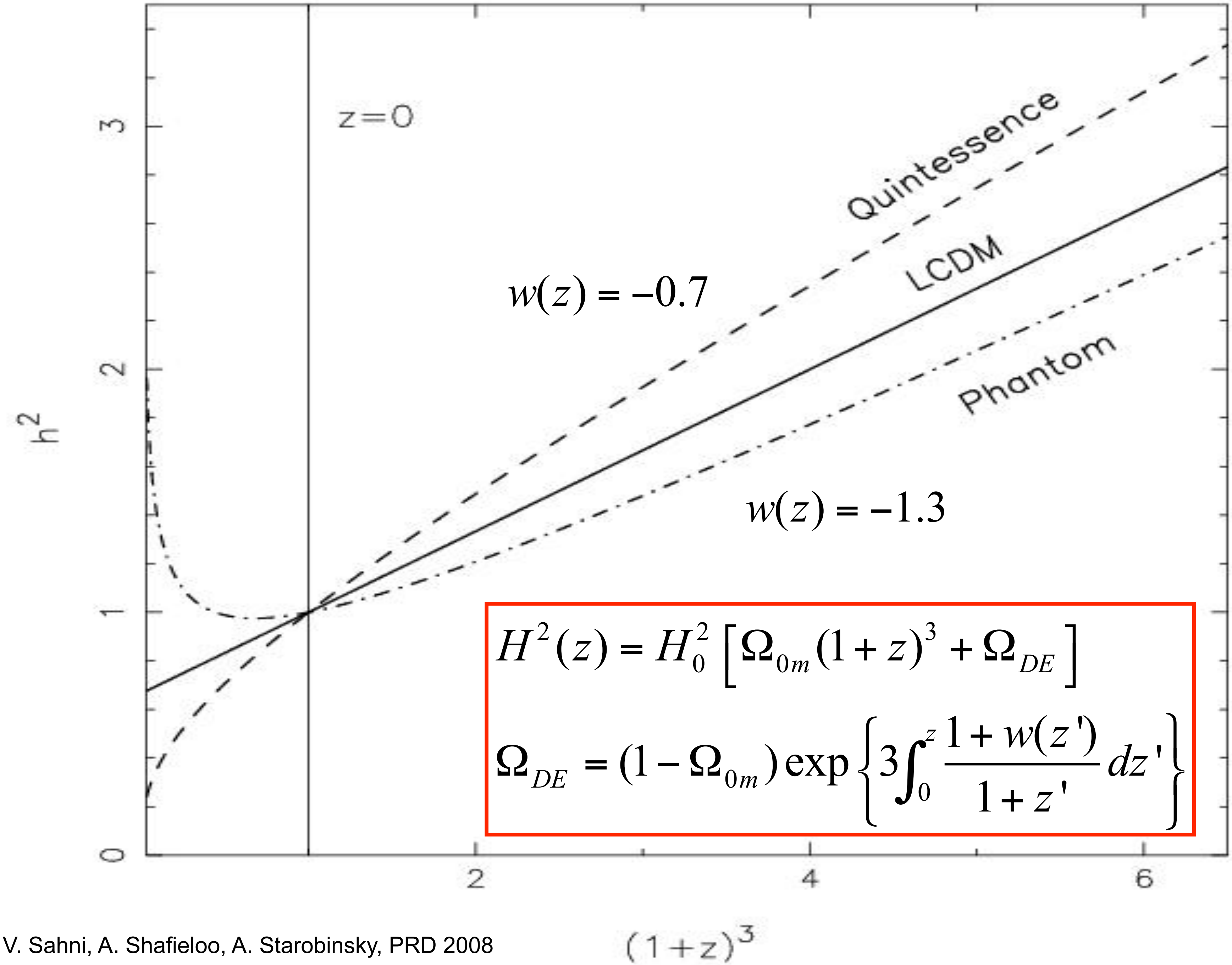
But, How?

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

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

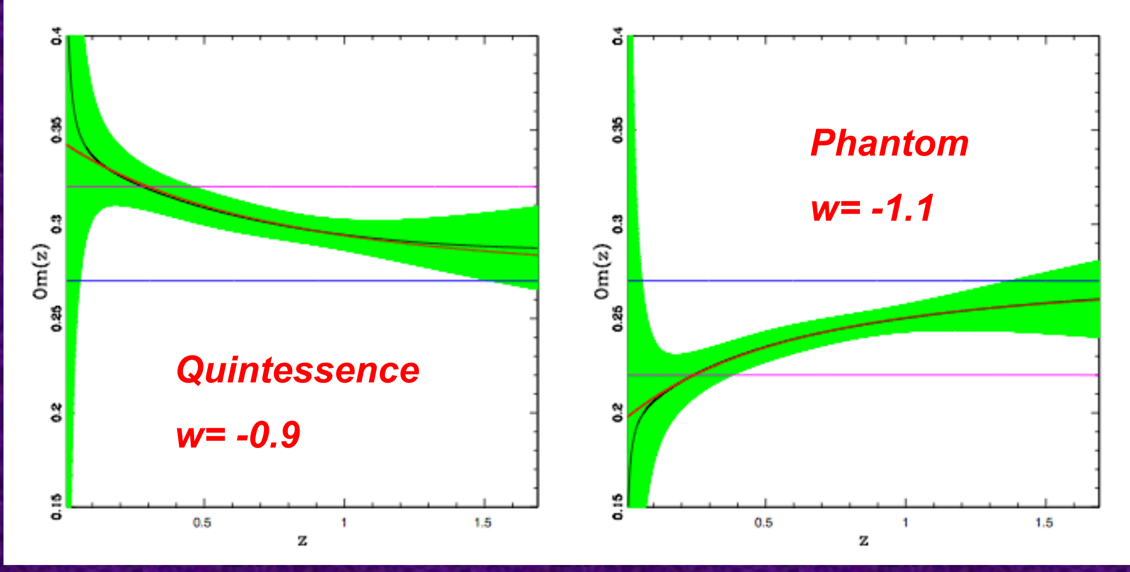
We Only Need h(z)

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

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

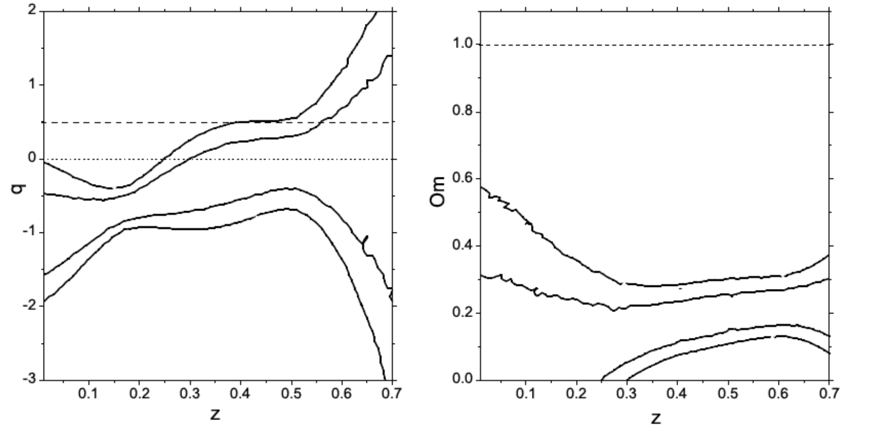


Figure 12. Confidence levels (1σ and 2σ) for the deceleration parameter as a function of redshift and Om(z) reconstructed from the compilation of geometric measurements in tables 2 and 3. H_0 is marginalised over with an HST prior. The dotted line in the left panel demarcates accelerating expansion (below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

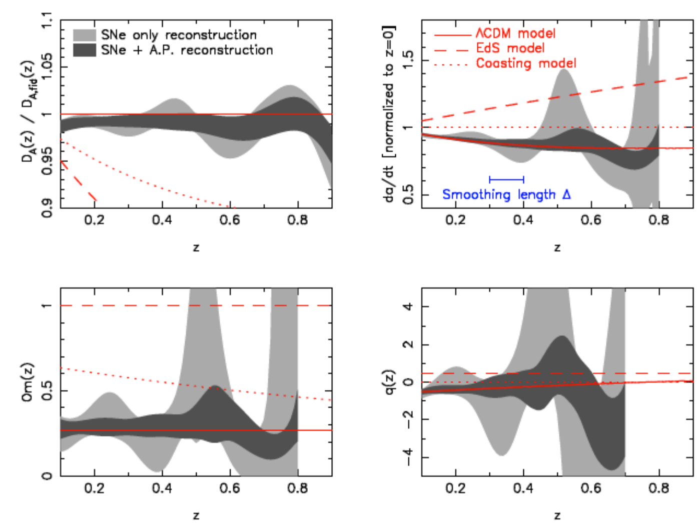


Figure 6. This Figure shows our non-parametric reconstruction of the cosmic expansion history using Alcock-Paczynski and supernovae data. The four panels of this figure display our reconstructions of the distance-redshift relation $D_A(z)$, the expansion rate $\dot{a}/H_0$, the Om(z) statistic and the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

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

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

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

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

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

Only for LCDM

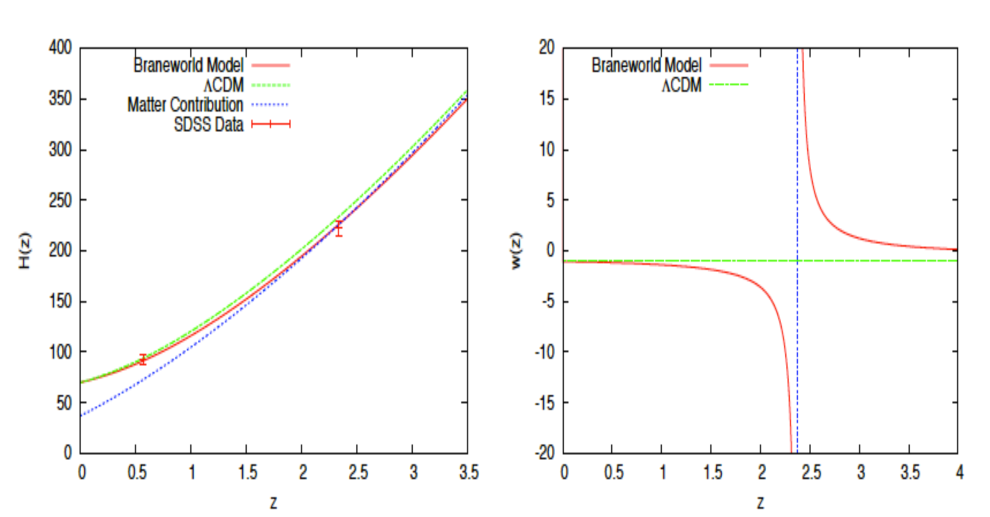
Sahni, Shafieloo, Starobinsky, ApJ Lett 2014

$$Omh^2 = 0.1426 \pm 0.0025$$

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

(Present)t

Standard Model of Cosmology

Universe is Flat

Universe is Isotropic

Universe is Homogeneous (large scales)

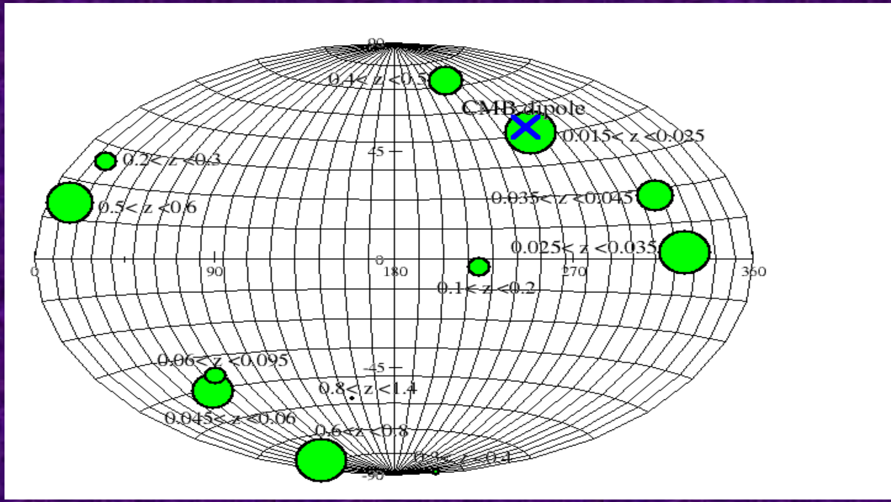
Dark Energy is Lambda (w=-1)

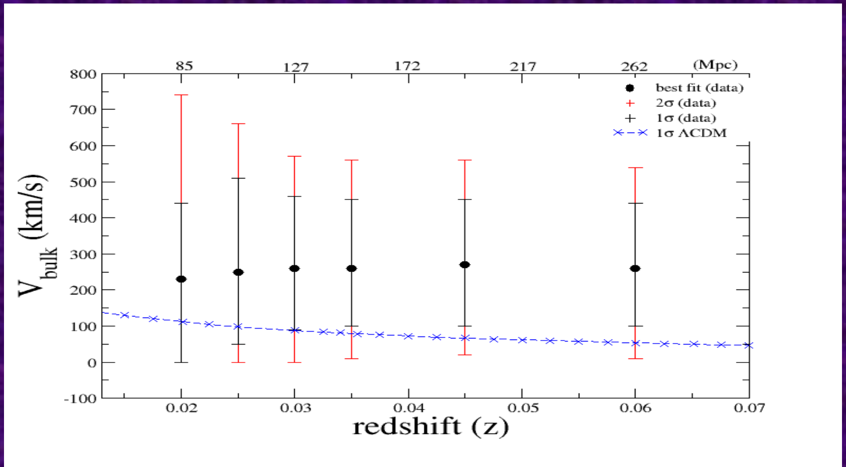
Power-Law primordial spectrum (n_s=const)

Dark Matter is cold

All within framework of FLRW

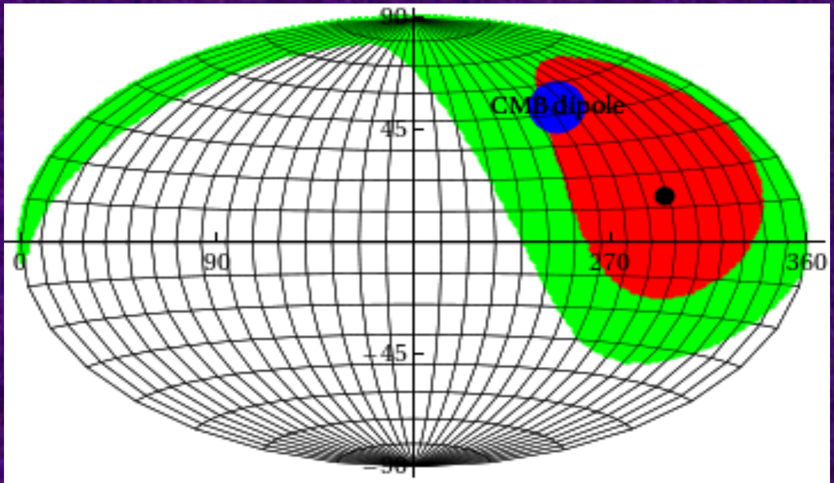
Falsification: Is Universe Isotropic?





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 doubling 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

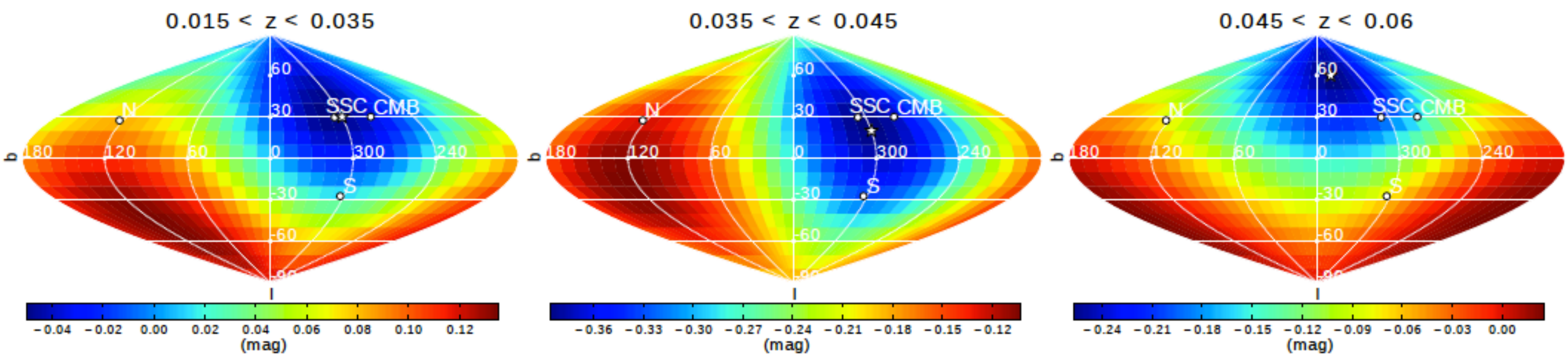
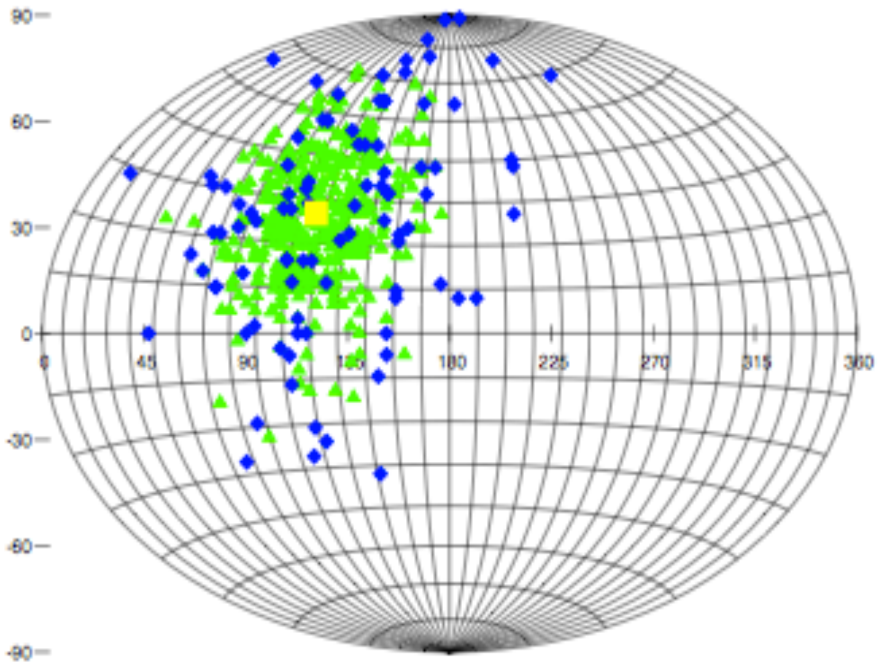
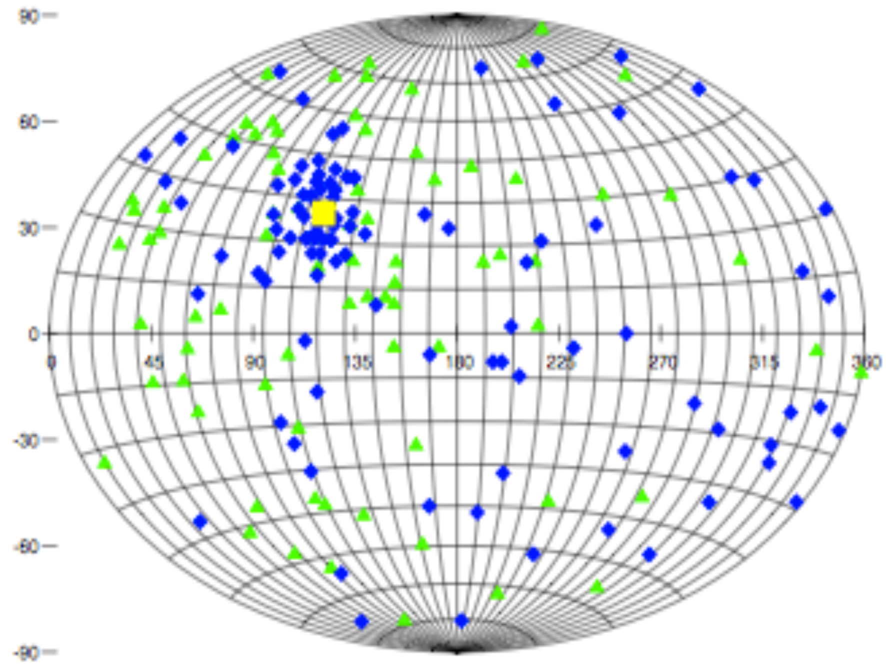


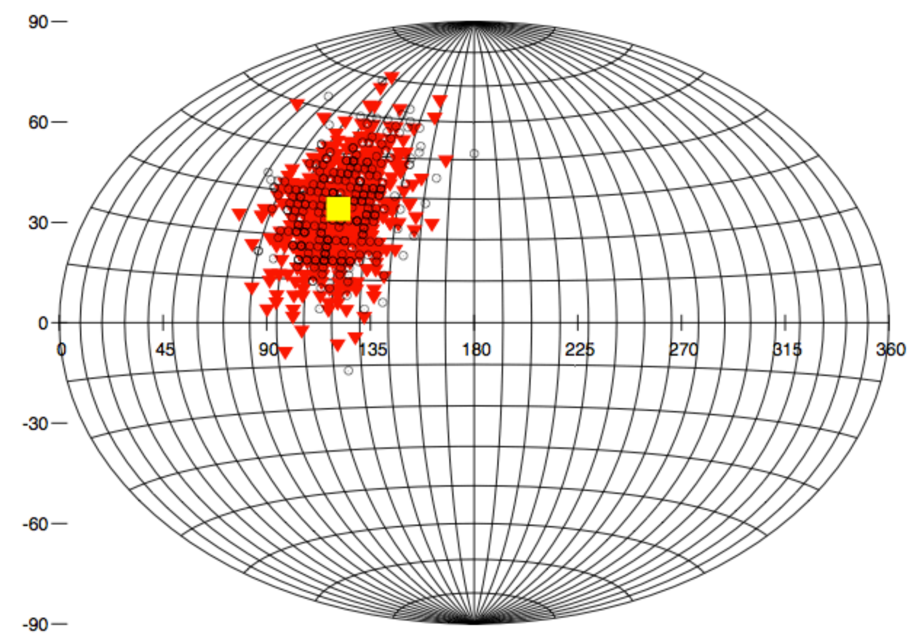
Fig. 3. Magnitude residuals of SNe Ia from the combined Union2 and SNFACTORY dataset as a function of galactic coordinates (l, b) after smoothing with a Gaussian window function of width $\delta = \frac{\pi}{2}$ in the redshift range $0.015 < z < 0.035$ (left), $0.035 < z < 0.045$ (middle) and $0.045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





Distribution	$N_{\rm exc}$ (method A)	$N_{\rm exc}$ (method B)
Isotropic	404	406
Anisotropic I	239	212
Anisotropic II	838	189

Appleby & Shafieloo, JCAP 2014



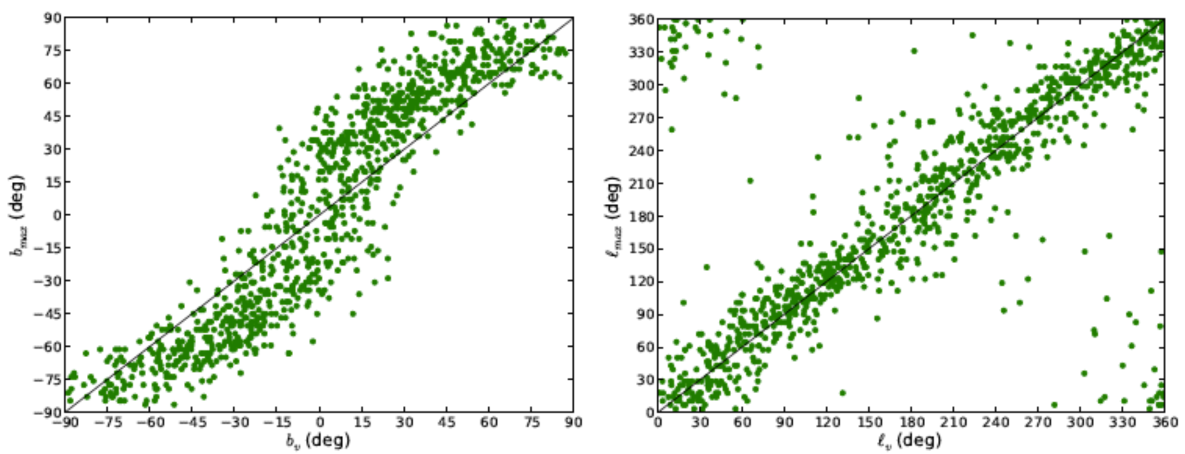
Catalog	$0.015 \le z < 0.025$	$0.025 \le z < 0.035$	$0.035 \le z < 0.045$	$0.045 \le z < 0.06$	$0.06 \le z < 0.1$
Union 2.1	61	51	15	17	19
Constitution	53	40	11	12	8
LOSS	76	64	23	17	19
Combined	98	67	22	27	12

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

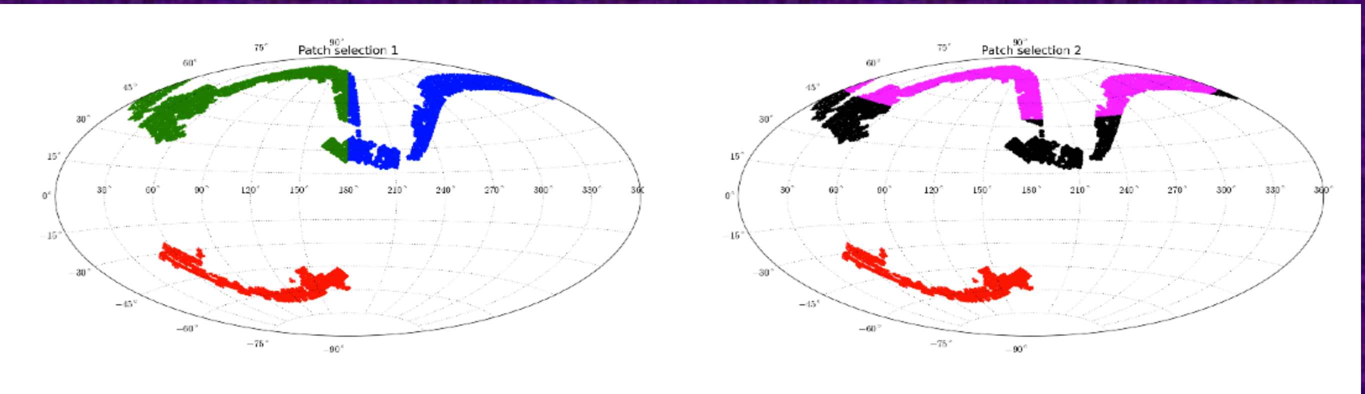


Bias in the Sky

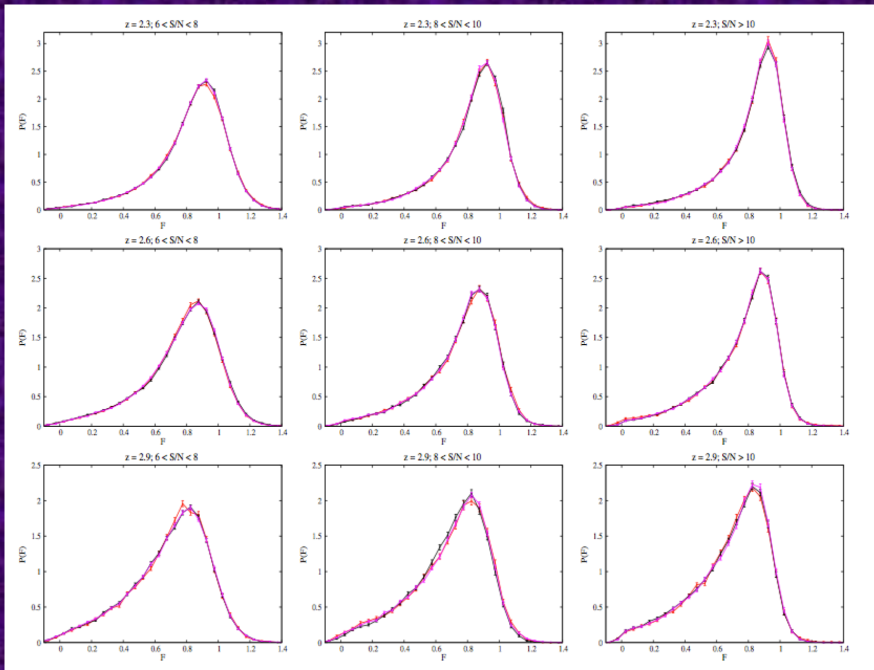
	North ($b_v > 20°$)		South ($b_v < -20°$)	
$V_{\rm bulk}({\rm kms}^{-1})$	$(\Delta b, \Delta\ell)$	$(\delta b, \delta\ell)$	$(\Delta b, \Delta\ell)$	$(\delta b, \delta\ell)$
400	$(13°, -3°)$	$(14°, 28°)$	$(-12°, 2°)$	$(14°, 29°)$
800	$(15°, -4°)$	$(9°, 22°)$	$(-13°, 2°)$	$(9°, 21°)$

Appleby, Shafieloo, 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, arXiv:1506.03926

Falsification: Test of Statistical Isotropy in CMB

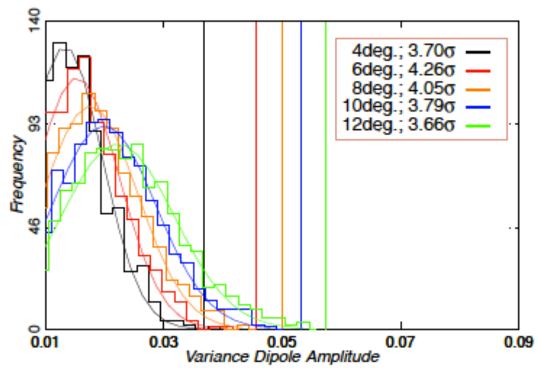


FIG. 3.— Histograms of the local-variance dipole amplitudes from the 1000 FFP6 simulations for disk radii 4°, 6°, 8°, 10° and 12°, together with the best-fit Gaussian distributions in all cases. Vertical lines indicate the corresponding amplitudes measured from the Planck data. The legend shows the rough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

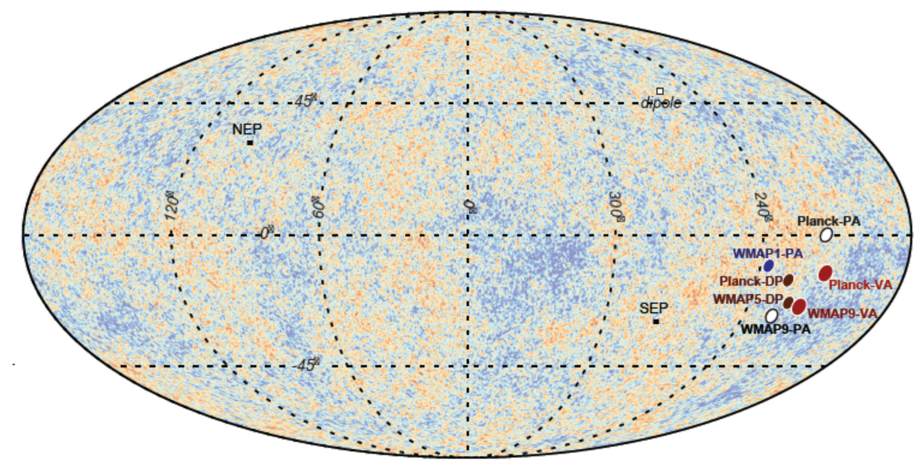


FIG. 6.— Asymmetry directions found in this work by analyzing the local variance of the WMAP 9-year and Planck 2013 data [denoted by *WMAP9-VA* and *Planck-VA*], as well as the directions found previously from the latest likelihood analyses of the dipole modulation model [denoted by *WMAP5-DP* (Hoftuft *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

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

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

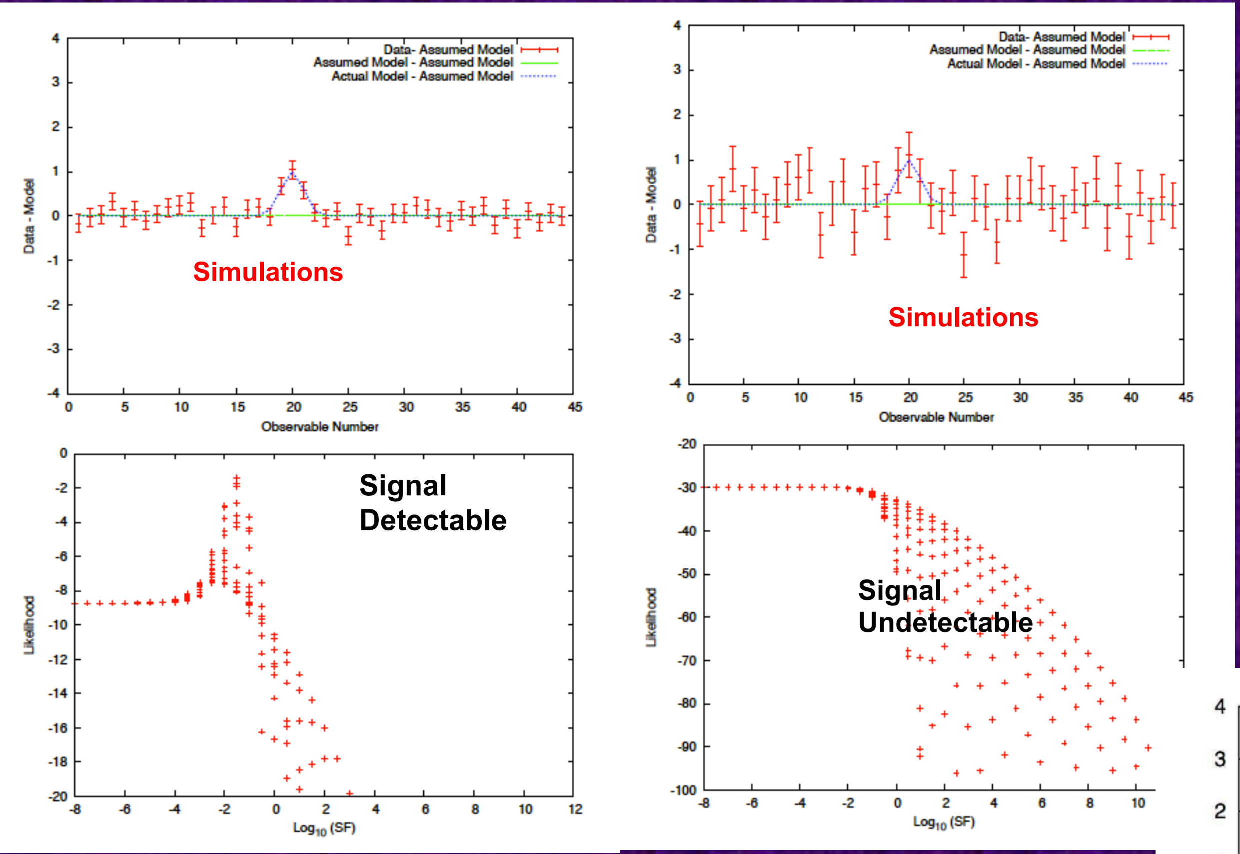
GP Hyper-parameters

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

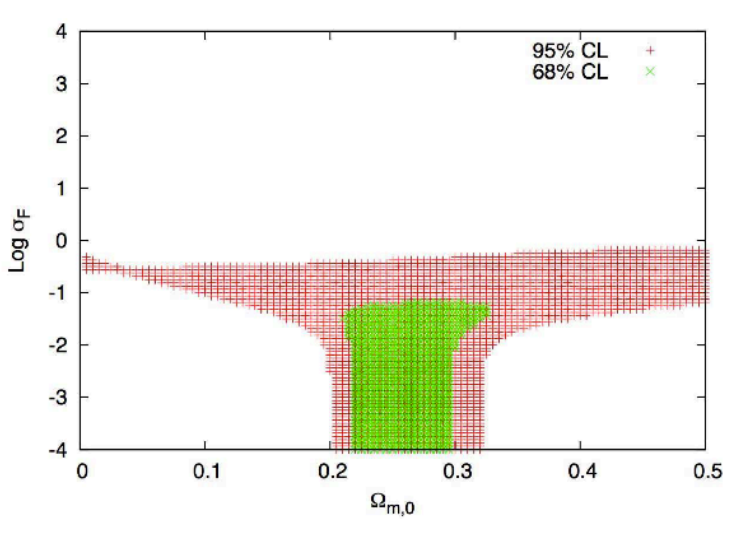
$$2\ln p(y|f) = -y^T \Sigma_{00}(Z,Z)^{-1} y - \ln\det\Sigma_{00}(Z,Z) - n\ln(2\pi),$$

GP Likelihood

Detection of the features in the residuals



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

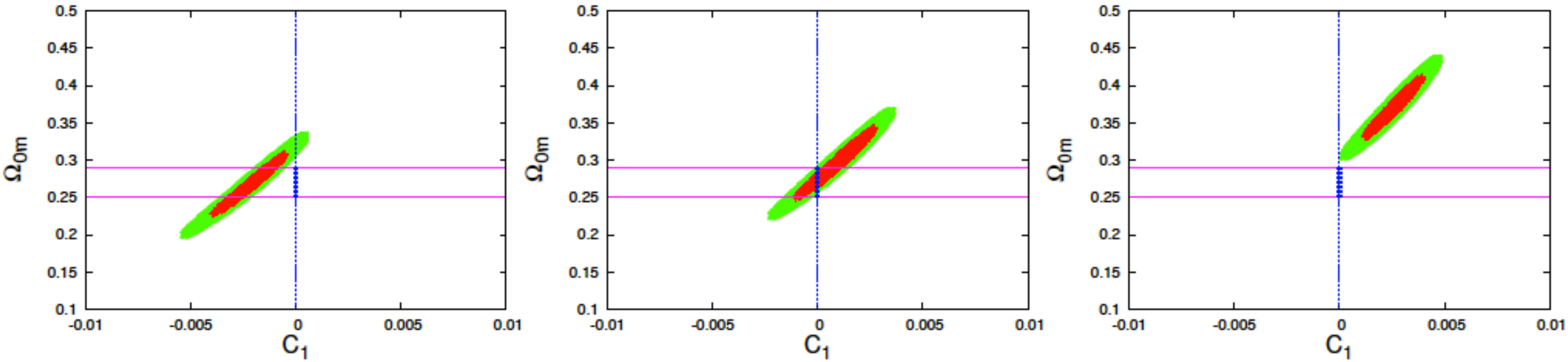


Crossing Statistic (Bayesian Interpretation)

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



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

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

Chebishev Polynomials as Crossing Functions

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

Crossing Statistic (Bayesian Interpretation)

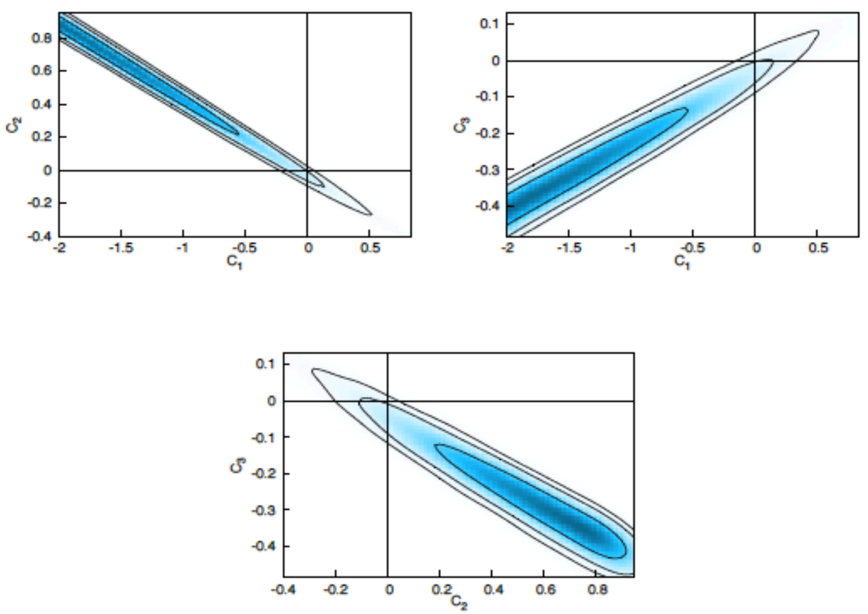
Theoretical model — Crossing function

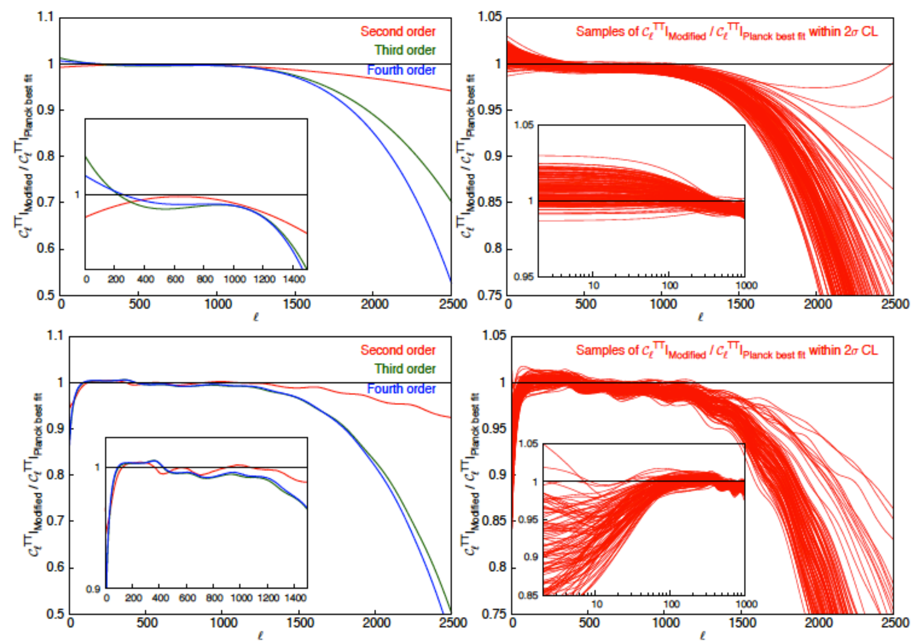
$$\mathcal{C}_\ell^{\rm TT}\,\Big|^{N}_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\,\Big|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H_0},\tau,{\rm A_S},{\rm n_S},\ell} \times T_i(C_0, C_1, C_2, ..., C_N, \ell).$$

Confronting the concordance model of cosmology with Planck data

Hazra and Shafieloo, JCAP 2014

Consistent only at 2~3 sigma CL





Dates

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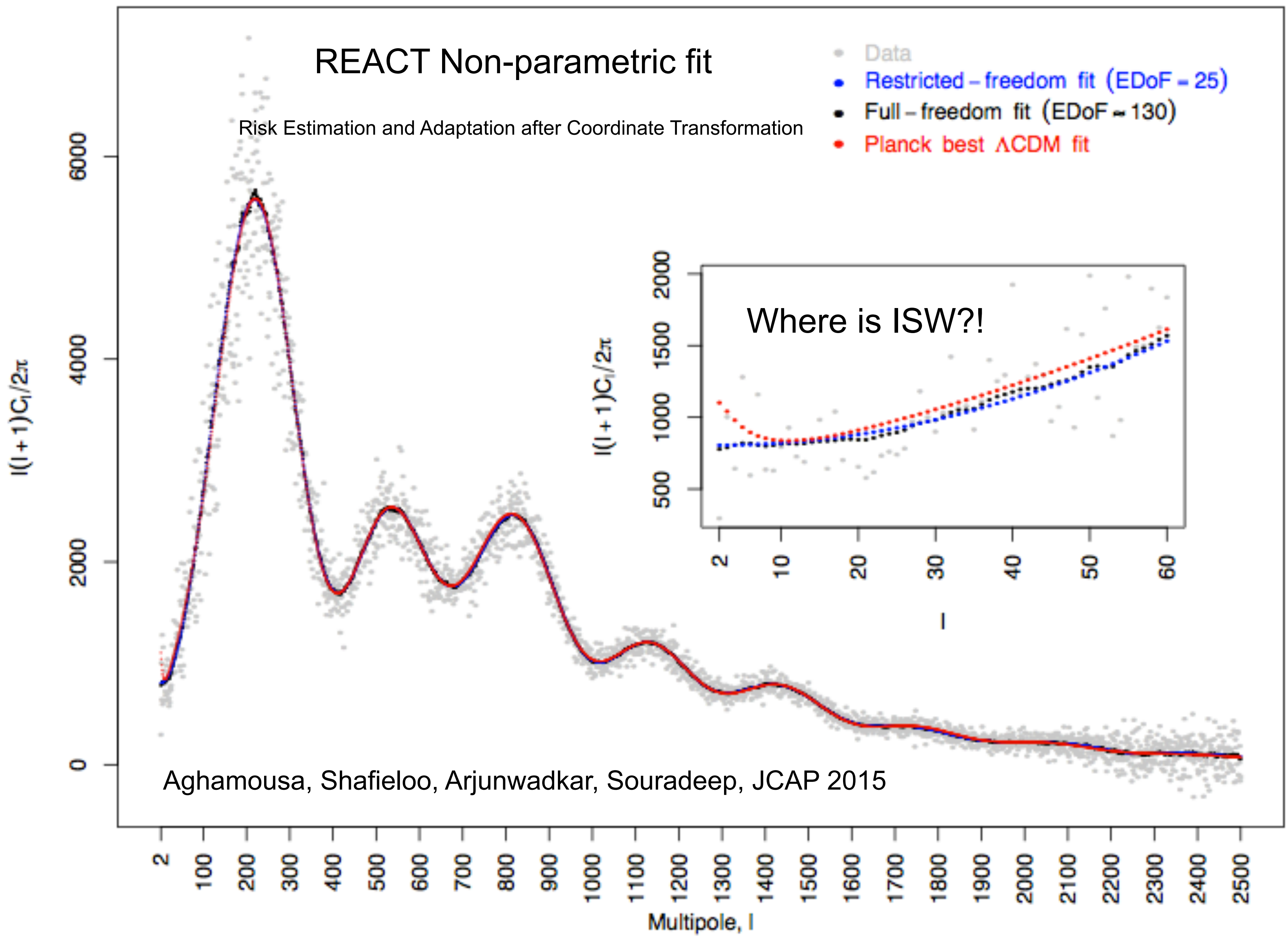
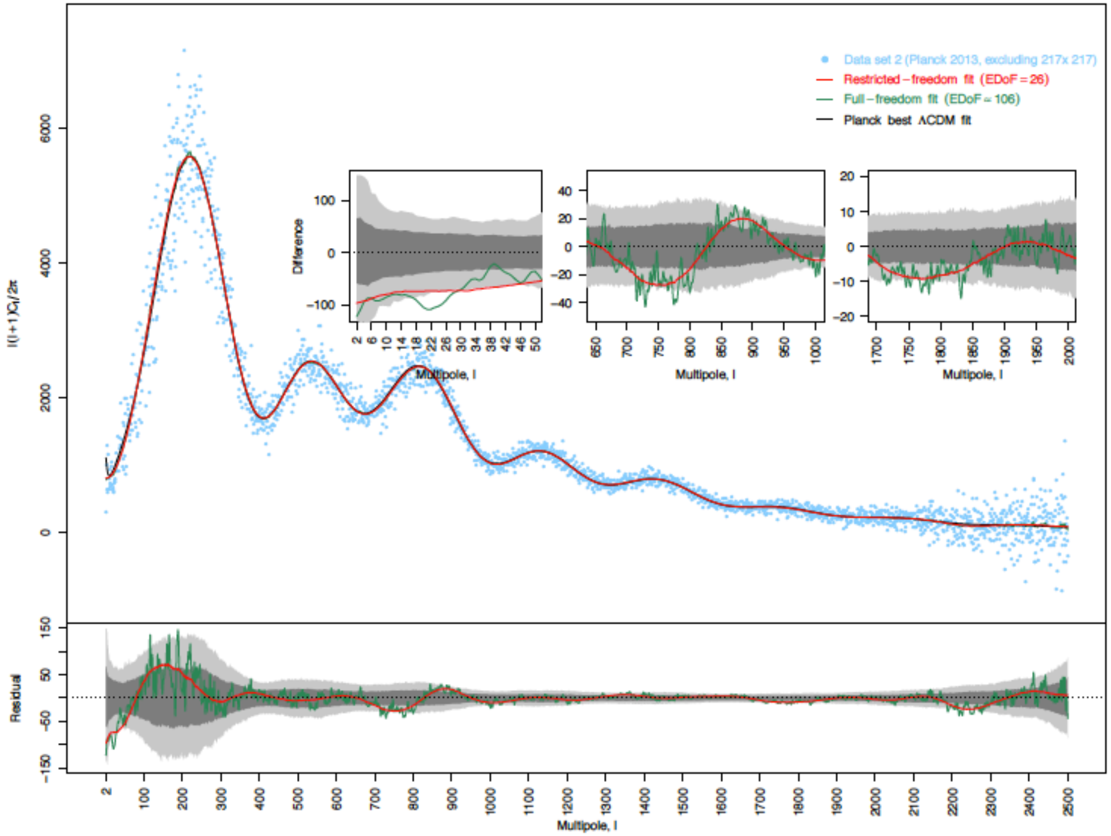
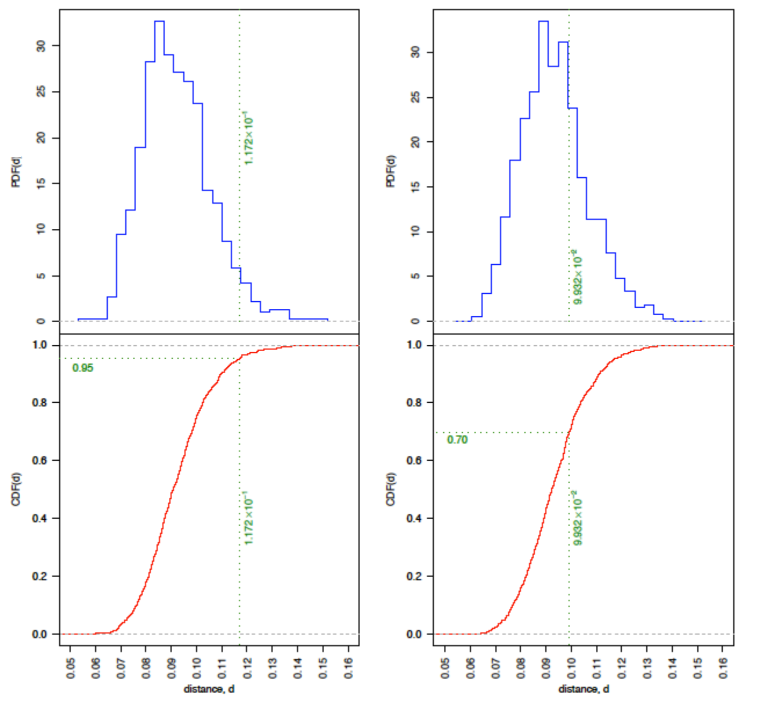


REACT Non-parametric fit
Risk Estimation and Adaptation after Coordinate Transformation
Data
Restricted – freedom fit (EDoF = 25)
Full – freedom fit (EDoF = 130)
Planck best ΛCDM fit
Where is ISW?!
l(l + 1)C_l/2π
Multipole, l
Aghamousa, Shafieloo, Arjunwadkar, Souradeep, JCAP 2015



Calibrated REACT



Aghamousa and Shafieloo, JCAP 2015

Consistent only at 2~3 sigma CL

Excluding 217 Ghz, consistent at 1~2 sigma CL

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 rigorous testing 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 falsification.