Inflation, Primordial Spectrum and Cosmological Parameter Estimation

Arman Shafieloo
Institute for the Early Universe

Meeting on primordial spectrum and non Gaussianities
December 2010, HRI, Allahabad

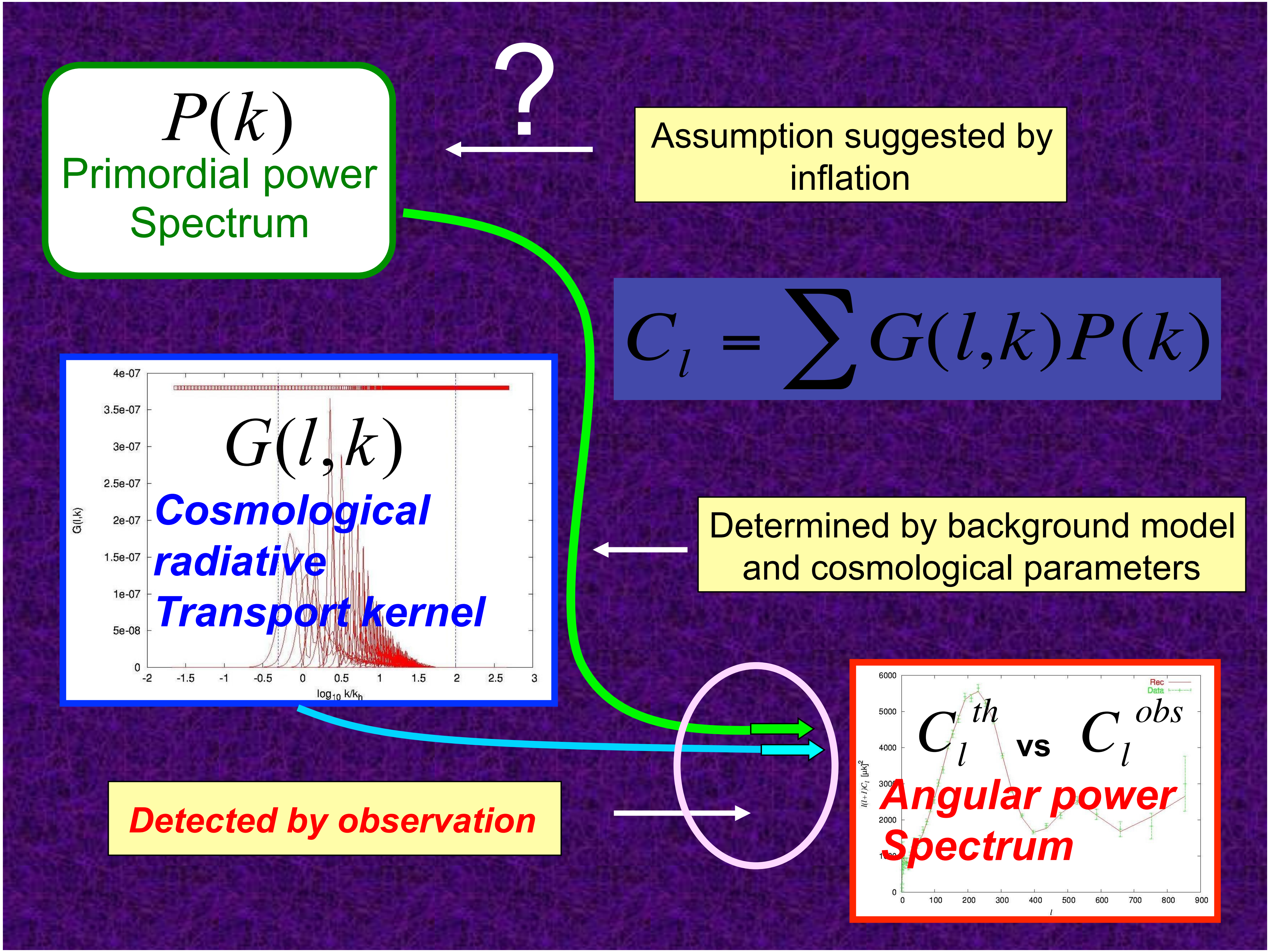
Inflation

- 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.

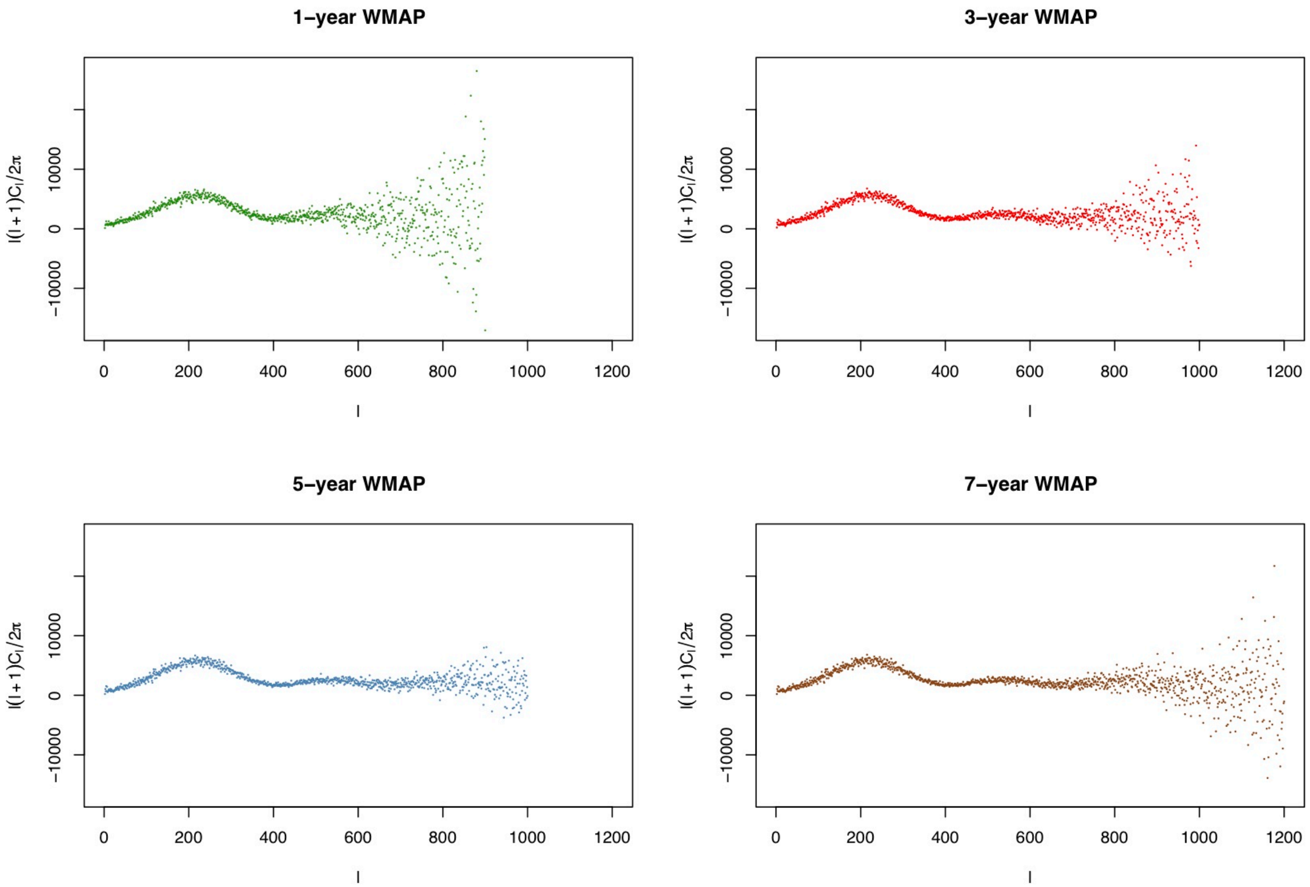
Constraints on inflationary scenarios from cosmological observations:

- 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)



P(k)
Primordial power Spectrum
?
Assumption suggested by inflation
$C_l = \sum G(l,k)P(k)$
G(l,k)
Cosmological radiative Transport kernel
Determined by background model and cosmological parameters
log10 k/kh
G(l,k)
C_l^{th} vs C_l^{obs}
Angular power Spectrum
Rec
Data
Detected by observation

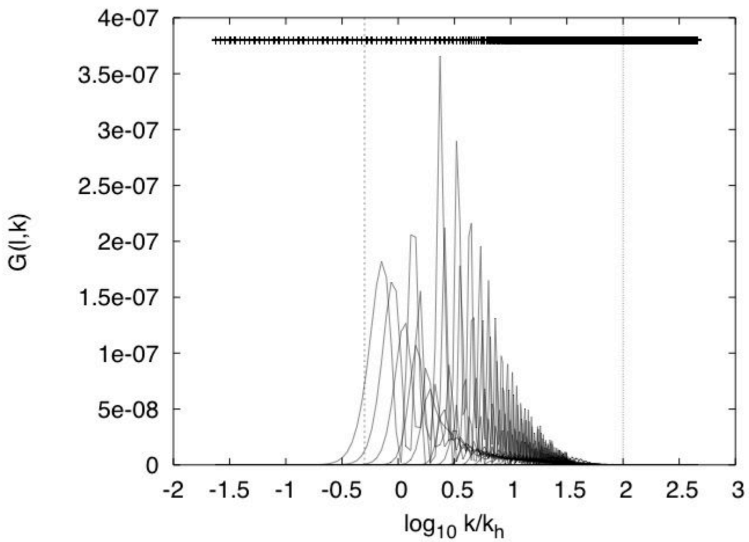


Observed angular power spectrum from WMAP

Shafieloo & Souradeep 2004

Plot from Aghamousa, Mihir and Souradeep

Shape of the transfer kernel, G(l,k)



Standard Model of Cosmology- *Vanilla Model*

- 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

Cosmological Parameters from WMAP

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

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

Table from LAMBDA website

Parameter estimation within a cosmological framework

Harisson-Zel'dovich (HZ)

WMAP Cosmological Parameters Model: lcdm+ns=1 Data: wmap	
$10^2\Omega_b h^2$	$2.405^{+0.046}_{-0.047}$
$\Delta^2_{\mathcal{R}}(k=0.002/\mathrm{Mpc})$	$(23.1 \pm 1.2) \times 10^{-10}$
h	0.778 ± 0.032
H_0	77.8 ± 3.2 km/s/Mpc
$\Omega_b h^2$	$0.02405^{+0.00046}_{-0.00047}$
Ω_Λ	0.788 ± 0.031
Ω_m	0.212 ± 0.031
$\Omega_m h^2$	$0.1271^{+0.0086}_{-0.0087}$
σ_8	$0.796^{+0.053}_{-0.054}$
A_{SZ}	$0.92^{+0.63}_{-0.61}$
t_0	13.353 ± 0.096 Gyr
τ	0.141 ± 0.029
θ_A	$0.5986 \pm 0.0017\,^\circ$
z_r	14.6 ± 2.0

Power-Law (PL)

WMAP Cosmological Parameters Model: lcdm Data: wmap	
$10^2\Omega_b h^2$	2.229 ± 0.073
$\Delta^2_{\mathcal{R}}(k=0.002/\mathrm{Mpc})$	$(23.5 \pm 1.3) \times 10^{-10}$
h	$0.732^{+0.031}_{-0.032}$
H_0	$73.2^{+3.1}_{-3.2}$ km/s/Mpc
$\log(10^{10} A_s)$	3.156 ± 0.056
$n_s(0.002)$	0.958 ± 0.016
$\Omega_b h^2$	0.02229 ± 0.00073
$\Omega_c h^2$	$0.1054^{+0.0078}_{-0.0077}$
Ω_Λ	0.759 ± 0.034
Ω_m	0.241 ± 0.034
$\Omega_m h^2$	$0.1277^{+0.0080}_{-0.0079}$
σ_8	$0.761^{+0.049}_{-0.048}$
τ	0.089 ± 0.030
θ_A	$0.5952 \pm 0.0021\,^\circ$
z_r	$11.0^{+2.6}_{-2.5}$

PL with Running (RN)

WMAP Cosmological Parameters Model: lcdm+run Data: wmap	
$10^2\Omega_b h^2$	2.10 ± 0.10
$\Delta^2_{\mathcal{R}}(k=0.002/\mathrm{Mpc})$	$(23.9 \pm 1.3) \times 10^{-10}$
$dn_s/d\ln k$	$-0.055^{+0.030}_{-0.031}$
h	$0.681^{+0.042}_{-0.041}$
H_0	$68.1^{+4.2}_{-4.1}$ km/s/Mpc
$n_s(0.002)$	$1.050^{+0.059}_{-0.058}$
$\Omega_b h^2$	0.0210 ± 0.0010
Ω_Λ	$0.703^{+0.056}_{-0.055}$
Ω_m	$0.297^{+0.055}_{-0.056}$
$\Omega_m h^2$	$0.1350^{+0.0099}_{-0.0097}$
σ_8	$0.771^{+0.051}_{-0.050}$
A_{SZ}	$1.06^{+0.62}_{-0.65}$
t_0	13.97 ± 0.20 Gyr
τ	0.101 ± 0.031
θ_A	$0.5940 \pm 0.0021\,^\circ$
z_r	12.8 ± 2.8

Tables from LAMBDA website

Parameter estimation within a cosmological framework

Harisson-Zel'dovich (HZ)

WMAP Cosmological Parameters
Model: lcdm+ns=1
Data: wmap

$10^2\Omega_b h^2$	$2.405^{+0.046}_{-0.047}$
$\Delta^2_{\mathcal{R}}(k = 0.002/\mathrm{Mpc})$	$(23.1 \pm 1.2) \times 10^{-10}$
h	0.778 ± 0.032
H_0	77.8 ± 3.2 km/s/Mpc
$\Omega_b h^2$	$0.02405^{+0.00046}_{-0.00047}$
Ω_Λ	0.788 ± 0.031
Ω_m	0.212 ± 0.031
$\Omega_m h^2$	$0.1271^{+0.0086}_{-0.0087}$
σ_8	$0.796^{+0.053}_{-0.054}$
A_{SZ}	$0.92^{+0.63}_{-0.61}$
t_0	13.353 ± 0.096 Gyr
τ	0.141 ± 0.029
θ_A	0.5986 ± 0.0017 °
z_r	14.6 ± 2.0

Power-Law (PL)

WMAP Cosmological Parameters
Model: lcdm
Data: wmap

$10^2\Omega_b h^2$	2.229 ± 0.073
$\Delta^2_{\mathcal{R}}(k = 0.002/\mathrm{Mpc})$	$(23.5 \pm 1.3) \times 10^{-10}$
h	$0.732^{+0.031}_{-0.032}$
H_0	$73.2^{+3.1}_{-3.2}$ km/s/Mpc
$\log(10^{10} A_s)$	3.156 ± 0.056
$n_s(0.002)$	0.958 ± 0.016
$\Omega_b h^2$	0.02229 ± 0.00073
$\Omega_c h^2$	$0.1054^{+0.0078}_{-0.0077}$
Ω_Λ	0.759 ± 0.034
Ω_m	0.241 ± 0.034
$\Omega_m h^2$	$0.1277^{+0.0080}_{-0.0079}$
σ_8	$0.761^{+0.049}_{-0.048}$
τ	0.089 ± 0.030
θ_A	0.5952 ± 0.0021 °
z_r	$11.0^{+2.6}_{-2.5}$

PL with Running (RN)

WMAP Cosmological Parameters
Model: lcdm+run
Data: wmap

$10^2\Omega_b h^2$	2.10 ± 0.10
$\Delta^2_{\mathcal{R}}(k = 0.002/\mathrm{Mpc})$	$(23.9 \pm 1.3) \times 10^{-10}$
$dn_s/d\ln k$	$-0.055^{+0.030}_{-0.031}$
h	$0.681^{+0.042}_{-0.041}$
H_0	$68.1^{+4.2}_{-4.1}$ km/s/Mpc
$n_s(0.002)$	$1.050^{+0.059}_{-0.058}$
$\Omega_b h^2$	0.0210 ± 0.0010
Ω_Λ	$0.703^{+0.056}_{-0.055}$
Ω_m	$0.297^{+0.055}_{-0.056}$
$\Omega_m h^2$	$0.1350^{+0.0099}_{-0.0097}$
σ_8	$0.771^{+0.051}_{-0.050}$
A_{SZ}	$1.06^{+0.62}_{-0.65}$
t_0	13.97 ± 0.20 Gyr
τ	0.101 ± 0.031
θ_A	0.5940 ± 0.0021 °
z_r	12.8 ± 2.8

Tables from LAMBDA website

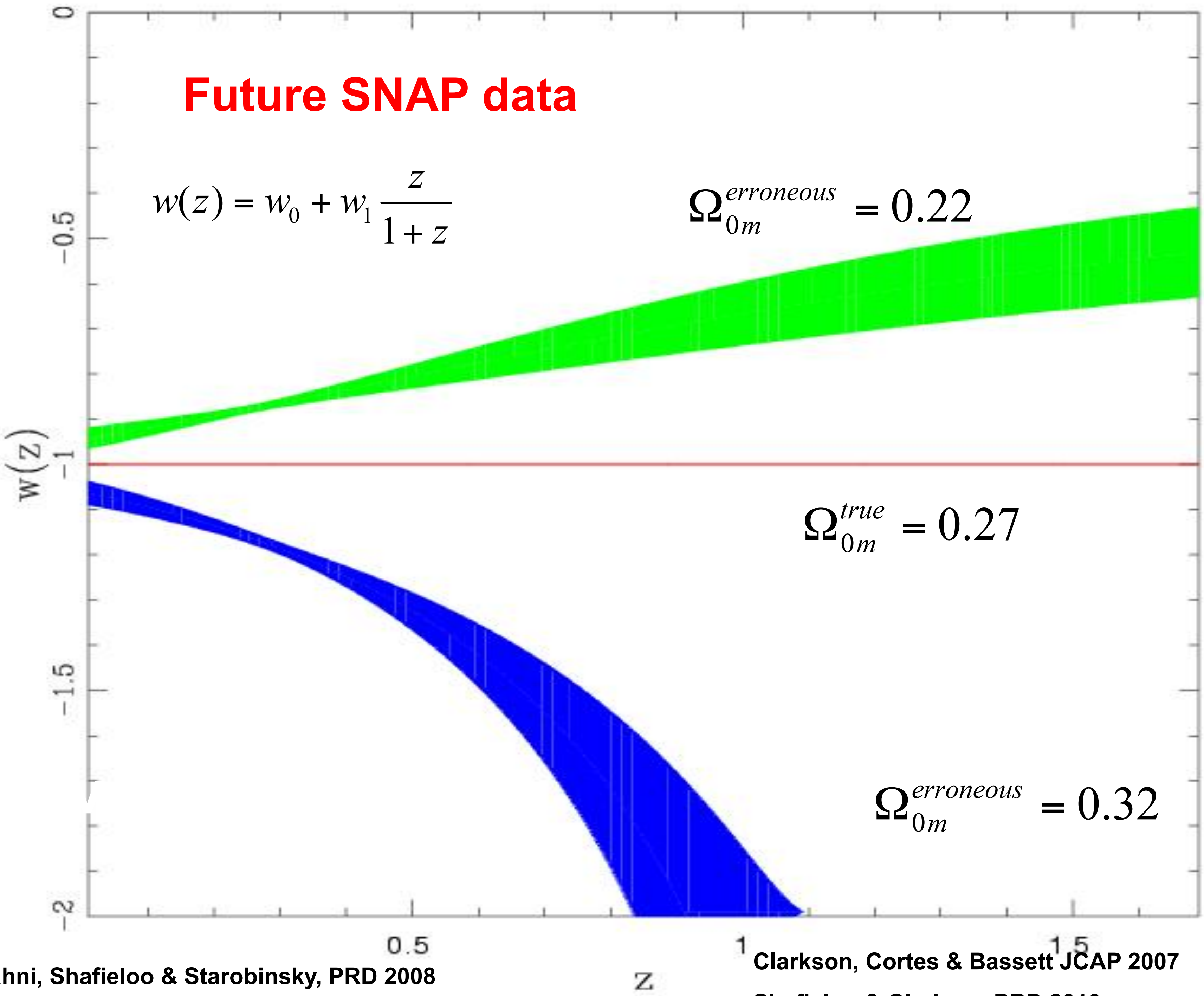
Dark Energy Reconstruction

- Any uncertainties in matter density is bound to affect the reconstructed w(z).

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

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

Shafieloo et al, MNRAS 2006 ; Shafieloo MNRAS 2007



Sahni, Shafieloo & Starobinsky, PRD 2008

Clarkson, Cortes & Bassett JCAP 2007

Shafieloo & Clarkson PRD 2010

Model Independent Estimation of Primordial Spectrum

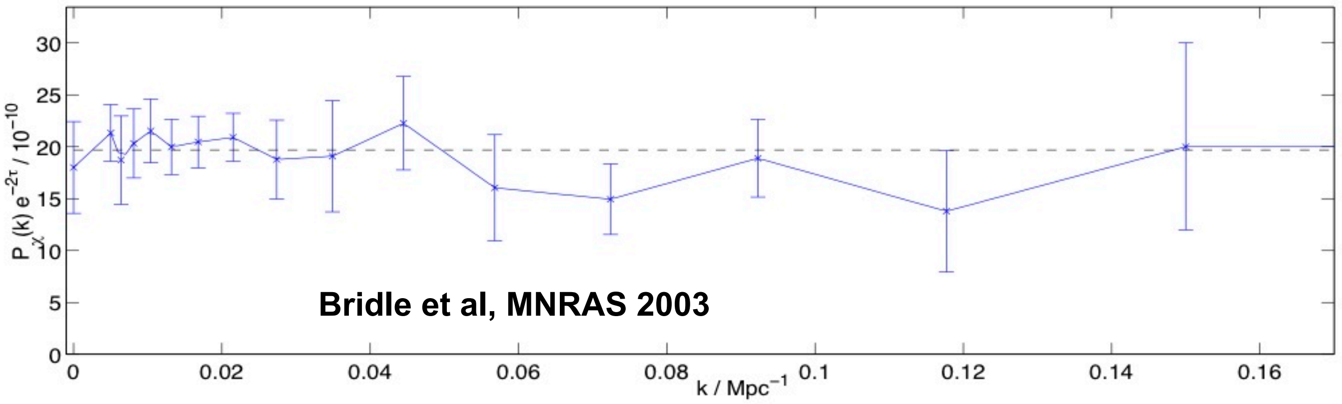
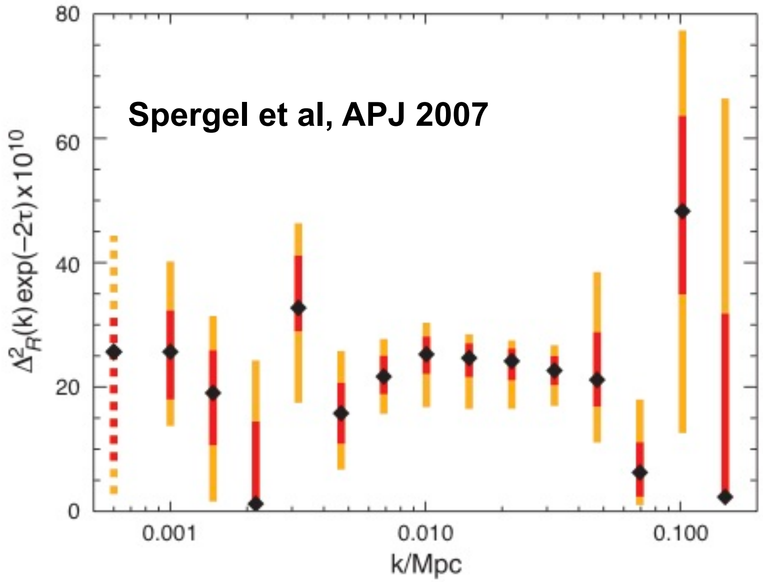


Figure 4. Reconstruction of the shape of the primordial power spectrum in 16 bands after marginalising over the Hubble constant, baryon and dark matter densities, and the redshift of reionization.

Binning Primordial Spectrum

➔ Paniez talk on optimal binning of the primordial spectrum

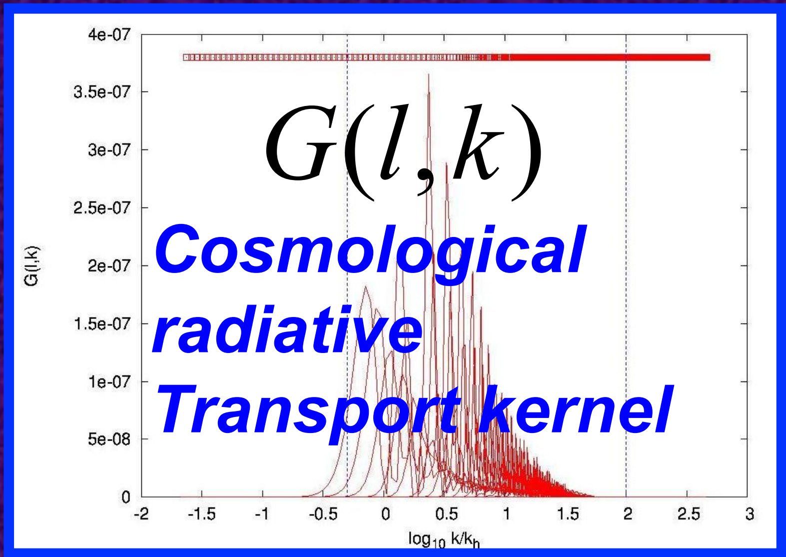


$$P(k)$$

Primordial power Spectrum

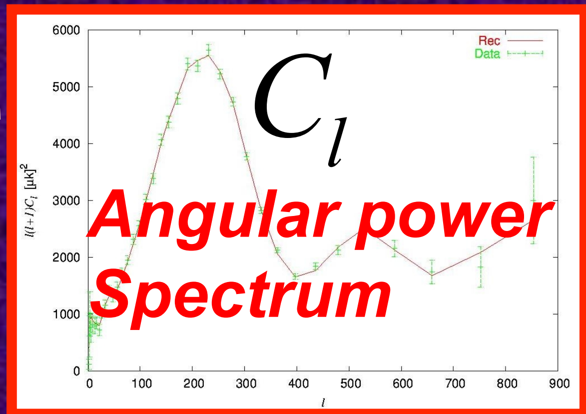
DIRECT RECONSTRUCTION

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



Determined by cosmological parameters

Detected by observation



Richardson-Lucy Deconvolution

Method: 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]

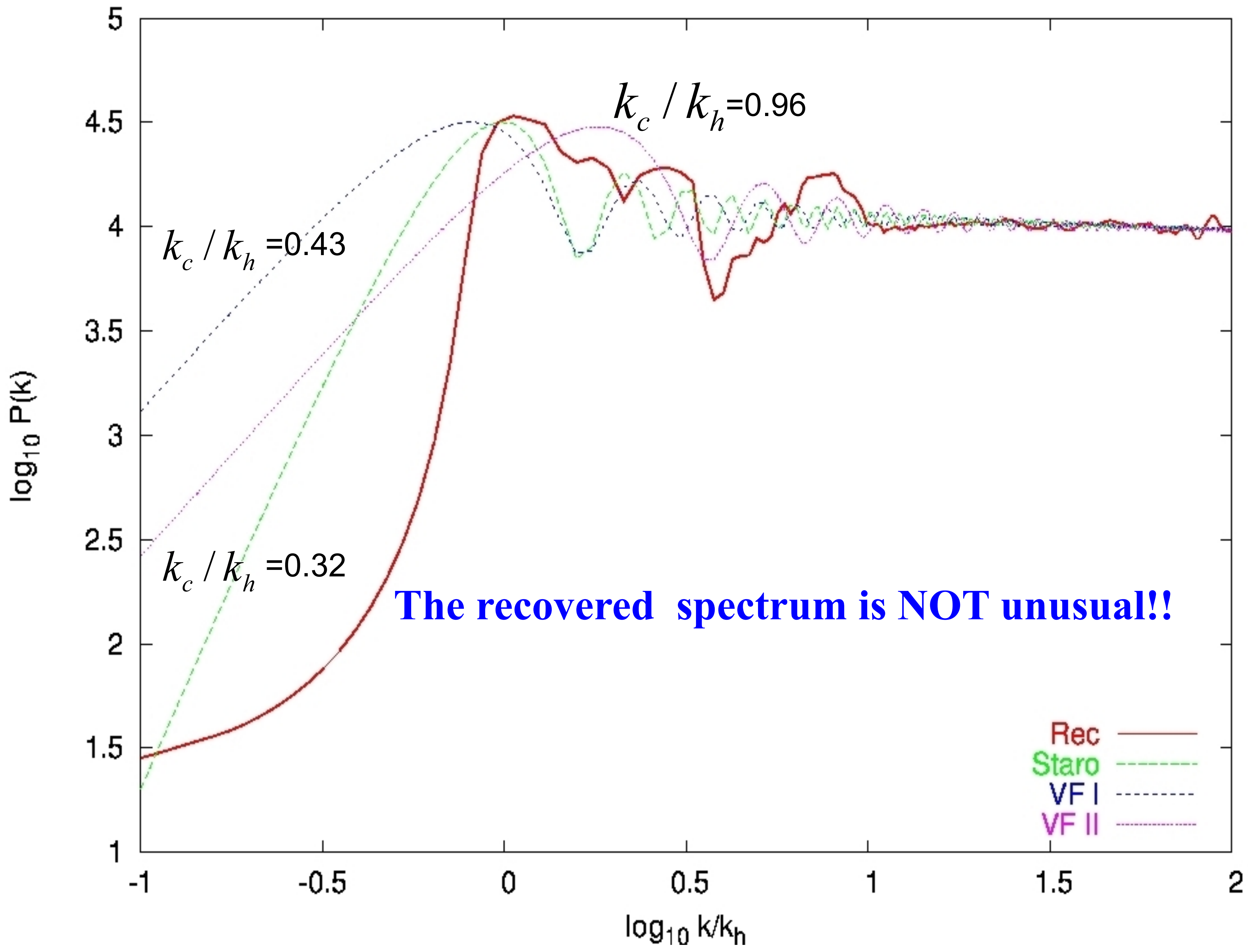
$$C_l^{(i)} = \sum_l G(l,k) P^{(i)}(k)$$

$$P^{(i+1)}(k) - P^{(i)}(k) = P^{(i)}(k) \sum_l G(l,k) \frac{C_l^D - C_l^{(i)}}{C_l^{(i)}} \tanh^2 \frac{(C_l^D - C_l^{(i)})^2}{\sigma_l^2}$$

C_l^D has some finite error bars.

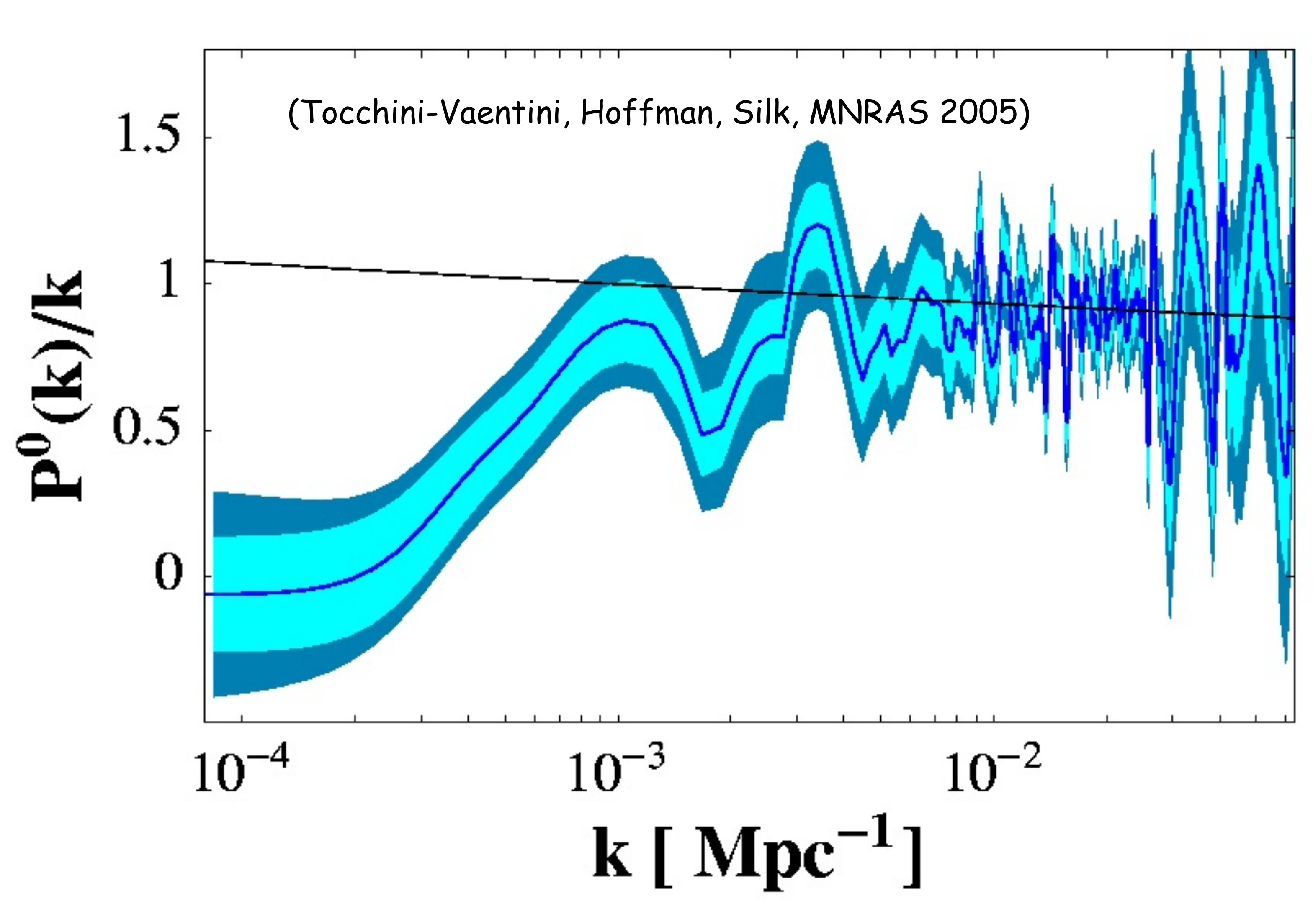
Regularizing function

Shafieloo & Souradeep PRD 2004 ;
Shafieloo et al, PRD 2007;
Shafieloo & Souradeep 2008;
Nicholson & Contaldi JCAP 2009



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

Regularized Least Square Method



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.

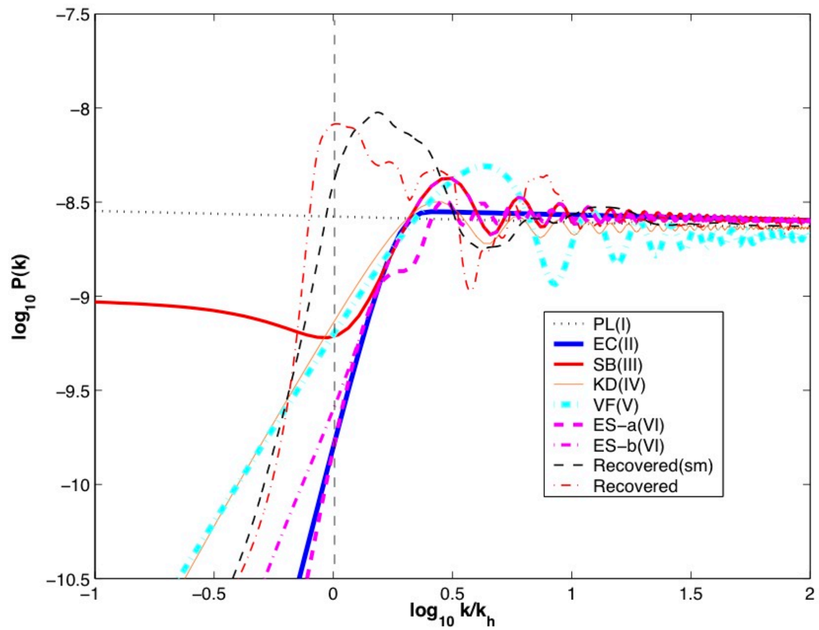
$$P(k) = P_0(k)D(k,k_c,r) = A_s k^{1-n_s}[1-3(r-1)\frac{1}{y}((1-\frac{1}{y^2})\sin 2y + \frac{2}{y}\cos 2y + \frac{9}{2}(r-1)^2\frac{1}{y^2}((1+\frac{1}{y^2})\cos 2y - \frac{2}{y}\sin 2y)]$$

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



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 (2004)

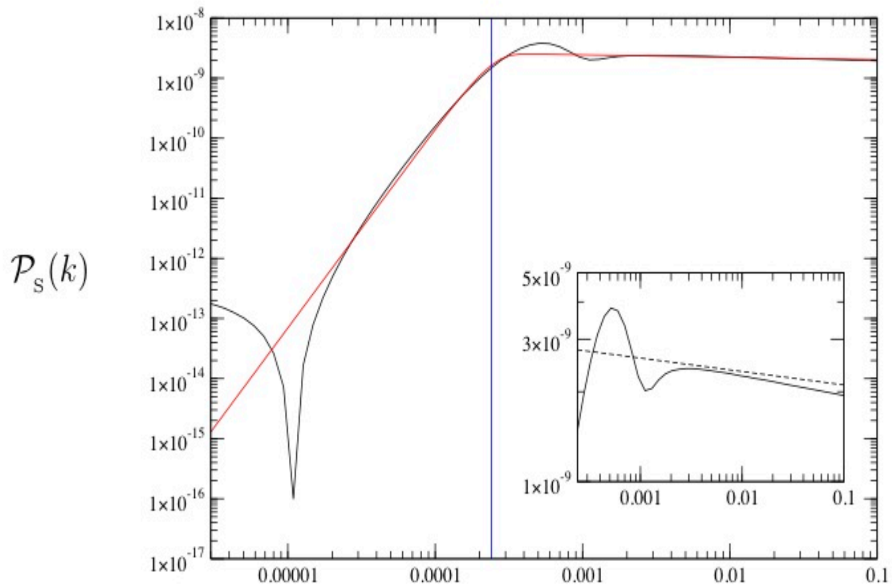
Direct Reconstruction

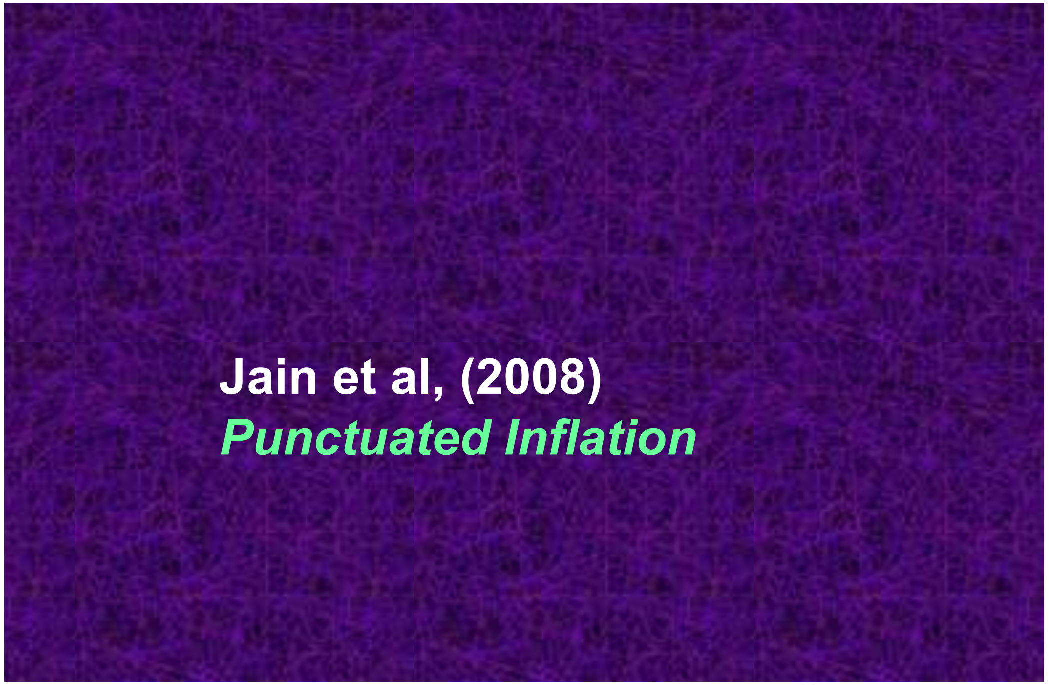
LCDM Model

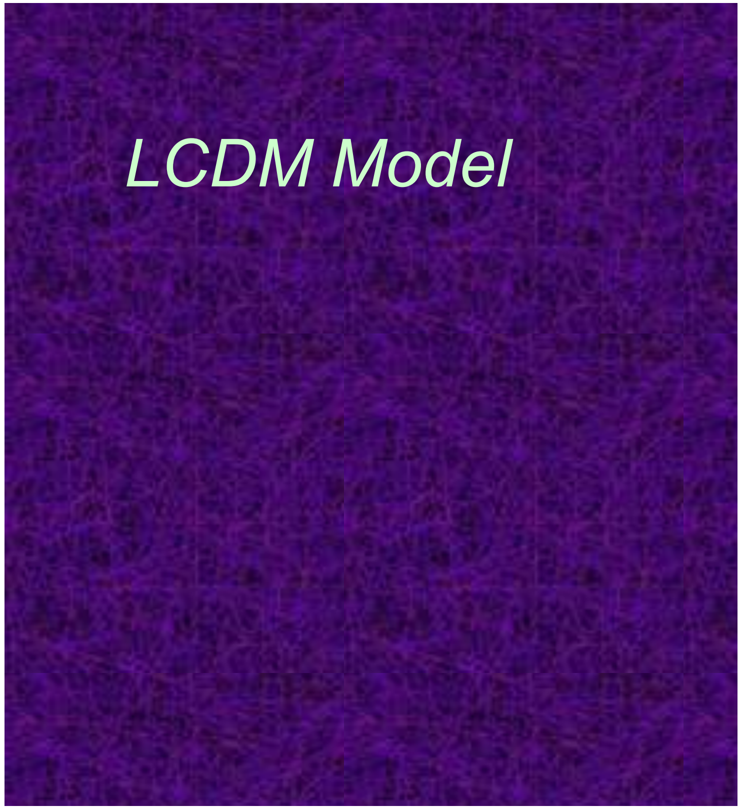
Sinha & Souradeep PRD 2005

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).

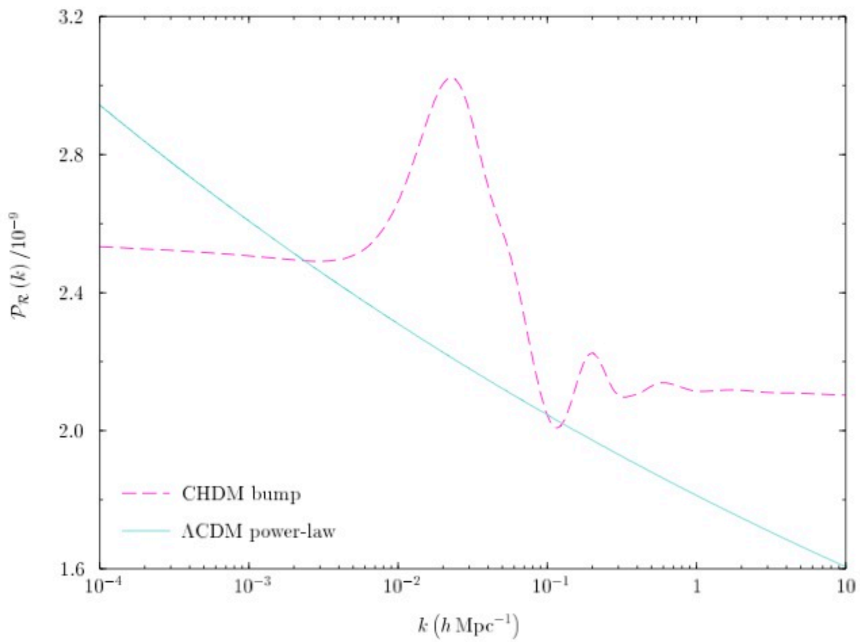
Parameter	Expo-cutoff EC(II)	Starobinsky SB(III)	Kin. Dom. KD(IV)	VF VF(V)	**Expo-staro(a)**[†] ES-a(VI)	Expo-staro(b)[‡] ES-b(VI)	Power Law PL(I)
$k_*(\times 10^{-4})\mathrm{Mpc}^{-1}$	$3.0^{+4.8}_{-2.9}$	$3.1^{+5.8}_{-2.8}$	$3.5^{+3.0}_{-3.3}$	$0.4^{+0.7}_{-0.3}$	$\mathbf{3.0^{+0.5}_{-2.0}}$	$3.1^{+5.8}_{-2.1}$	–
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
$\chi^2_{\mathrm{eff}} \equiv -2\ln\mathcal{L}$	969.78	969.78	970.36	972.92	**966.88**	968.90	972.56
d.o.f.	891	891	892	892	**890**	890	893







Parameter	Reference model	Our model
$\Omega_b h^2$	$0.02242^{+0.00155}_{-0.00127}$	$0.02146^{+0.00142}_{-0.00108}$
$\Omega_c h^2$	$0.1075^{+0.0169}_{-0.0126}$	$0.12051^{+0.02311}_{-0.02387}$
θ	$1.0395^{+0.0075}_{-0.0076}$	$1.03877^{+0.00979}_{-0.00931}$
τ	$0.08695^{+0.04375}_{-0.03923}$	$0.07220^{+0.04264}_{-0.02201}$
$\log\,[10^{10}\,A_S]$	$3.0456^{+0.1093}_{-0.1073}$	—
n_S	$0.9555^{+0.0394}_{-0.0305}$	—
$\log\,[10^{10}\,m^2]$	—	$-8.3509^{+0.1509}_{-0.1473}$
ϕ_0	—	$1.9594^{+0.00290}_{-0.00096}$
a_0	—	$0.31439^{+0.02599}_{-0.02105}$



Hunt & Sarkar, (2008)

Bump model

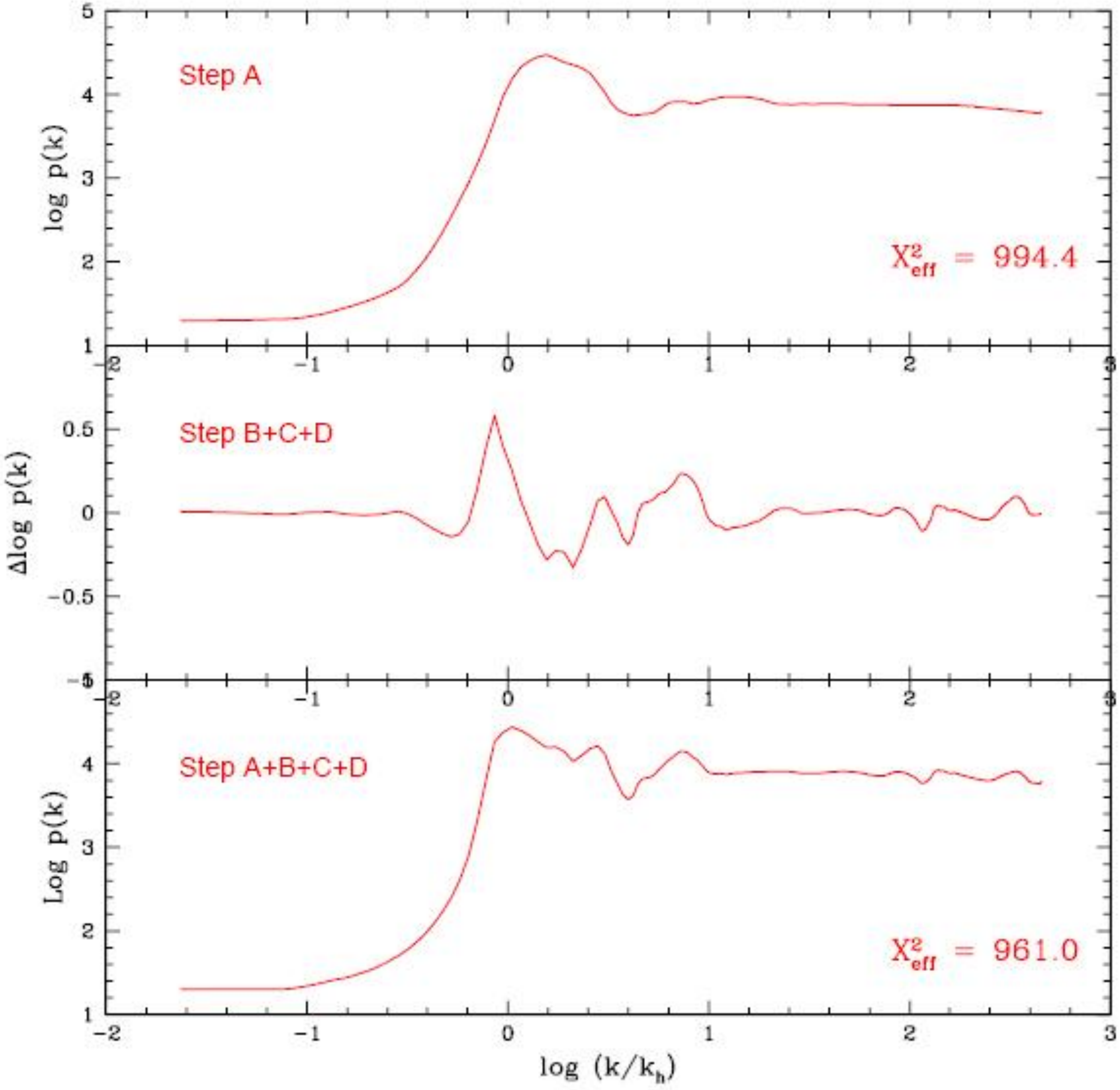
CHDM Model

Hunt & Sarkar, PRD 2008

	WMAP	+*SDSS*	+LRG	+*SDSS*+LRG
$\Omega_b h^2$	$0.01748^{+0.00073}_{-0.00071}$	$0.01762^{+0.00080}_{-0.00078}$	$0.01692^{+0.00047}_{-0.00047}$	$0.01688^{+0.00044}_{-0.00045}$
θ	$1.0365^{+0.0051}_{-0.0051}$	$1.0378^{+0.0049}_{-0.0049}$	$1.0300^{+0.0040}_{-0.0040}$	$1.0300^{+0.0039}_{-0.0039}$
τ	$0.078^{+0.012}_{-0.011}$	$0.079^{+0.012}_{-0.012}$	$0.071^{+0.011}_{-0.011}$	$0.071^{+0.012}_{-0.011}$
f_ν	$0.096^{+0.017}_{-0.023}$	$0.103^{+0.011}_{-0.011}$	$0.1360^{+0.0092}_{-0.0092}$	$0.1353^{+0.0075}_{-0.0067}$
$10^4 k_1/\mathrm{Mpc}^{-1}$	86^{+15}_{-13}	$82^{+11}_{-9.8}$	77^{+12}_{-10}	$77^{+11}_{-9.5}$
$10^4 k_2/\mathrm{Mpc}^{-1}$	527^{+78}_{-78}	539^{+84}_{-82}	380^{+24}_{-24}	379^{+22}_{-22}
$\ln\left(10^{10}\mathcal{P}_{\mathcal{R}}{}^{(0)}\right)$	$3.282^{+0.047}_{-0.047}$	$3.276^{+0.045}_{-0.046}$	$3.270^{+0.046}_{-0.046}$	$3.270^{+0.046}_{-0.047}$
b_{LRG}			$2.99^{+0.16}_{-0.16}$	$2.99^{+0.16}_{-0.16}$
$\Omega_c h^2$	$0.155^{+0.012}_{-0.011}$	$0.1539^{+0.0084}_{-0.0083}$	$0.1387^{+0.0041}_{-0.0044}$	$0.1387^{+0.0037}_{-0.0036}$
$\Omega_d h^2$	$0.1712^{+0.0063}_{-0.0062}$	$0.1715^{+0.0061}_{-0.0059}$	$0.1605^{+0.0030}_{-0.0031}$	$0.1604^{+0.0030}_{-0.0030}$
Age/GYr	$15.01^{+0.27}_{-0.27}$	$14.99^{+0.26}_{-0.27}$	$15.48^{+0.14}_{-0.14}$	$15.48^{+0.14}_{-0.14}$
σ_8	$0.668^{+0.093}_{-0.089}$	$0.648^{+0.053}_{-0.054}$	$0.565^{+0.032}_{-0.033}$	$0.565^{+0.029}_{-0.028}$
z_{reion}	$13.6^{+3.1}_{-3.1}$	$13.6^{+3.0}_{-3.1}$	$12.7^{+3.1}_{-3.1}$	$12.7^{+3.1}_{-3.2}$
h	$0.4344^{+0.0078}_{-0.0077}$	$0.4348^{+0.0079}_{-0.0076}$	$0.4212^{+0.0037}_{-0.0038}$	$0.4211^{+0.0038}_{-0.0038}$
Δm_1^2	$0.07476^{+0.00070}_{-0.00071}$	$0.07468^{+0.00068}_{-0.00069}$	$0.07459^{+0.00068}_{-0.00069}$	$0.07459^{+0.00068}_{-0.00070}$
Δm_2^2	$0.1510^{+0.0013}_{-0.0013}$	$0.1508^{+0.0012}_{-0.0013}$	$0.1507^{+0.0012}_{-0.0013}$	$0.1507^{+0.0012}_{-0.0013}$
$\widetilde{t}_2 - \widetilde{t}_1$	$1.82^{+0.16}_{-0.18}$	$1.89^{+0.15}_{-0.19}$	$1.62^{+0.12}_{-0.17}$	$1.62^{+0.11}_{-0.17}$
χ^2	11247	11265	11297	11315
Δ_{AIC}	0	0	28	29

Wavelet analysis of the recovered features

Shafieloo et al, PRD 2007



Combining different CMB data sets

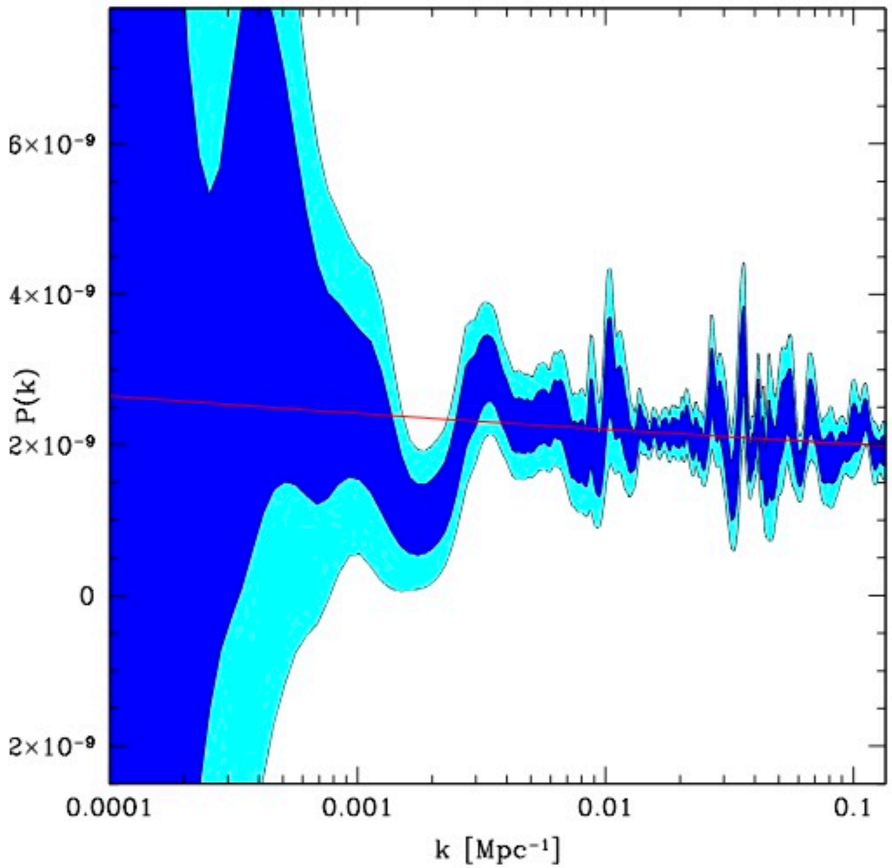


FIG. 3: Current limits from a combination of CMB data sets (WMAP, ACBAR, QUaD, BOOMERanG and CBI). There is some evidence of a dip in power at around $k \approx 0.002$ below the best fit power law model. Shaded regions are defined as in Fig. 2.

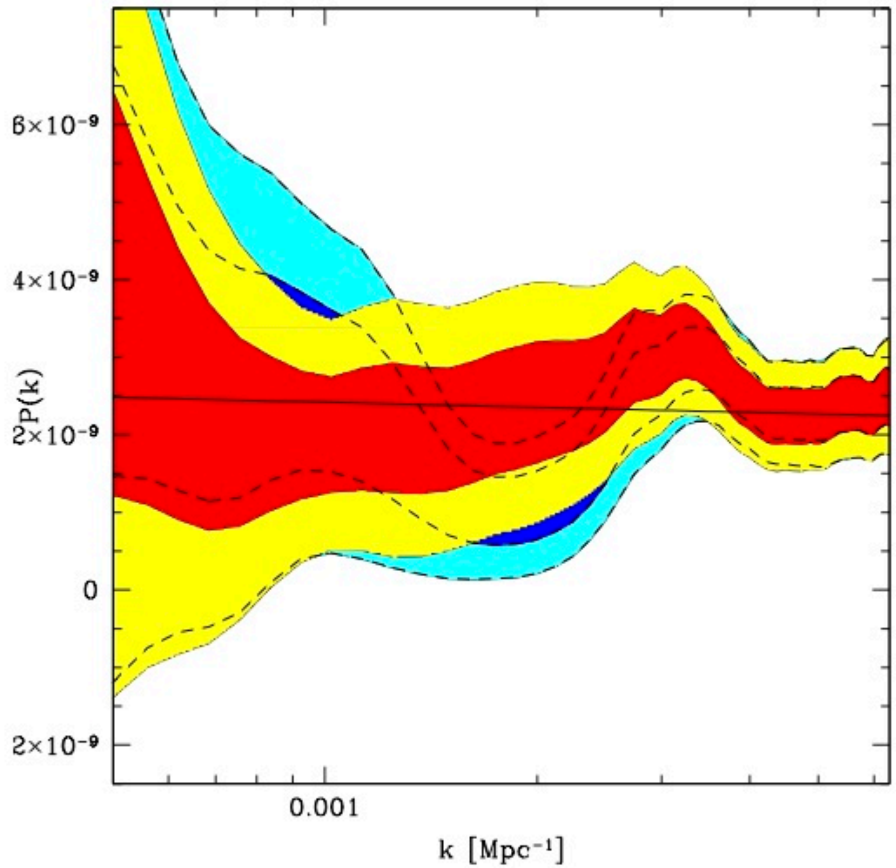


FIG. 4: As an indication of the origin of the dip at $k \approx 0.002$ Mpc^{-1} we remove the data between $\ell = 18$ and $\ell = 26$ and re-run the estimator. The red/yellow contours show the effect of the removal over the original estimate (blue/cyan).

Nicholson & Contaldi, JCAP 2009

Model A: SDSS

Model B: 2df

Model C: BAO

Model D: SN +BAO

Model E: WMAP1

Model F: SCDM

Model G: PL

Shafieloo & Souradeep, PRD 2008

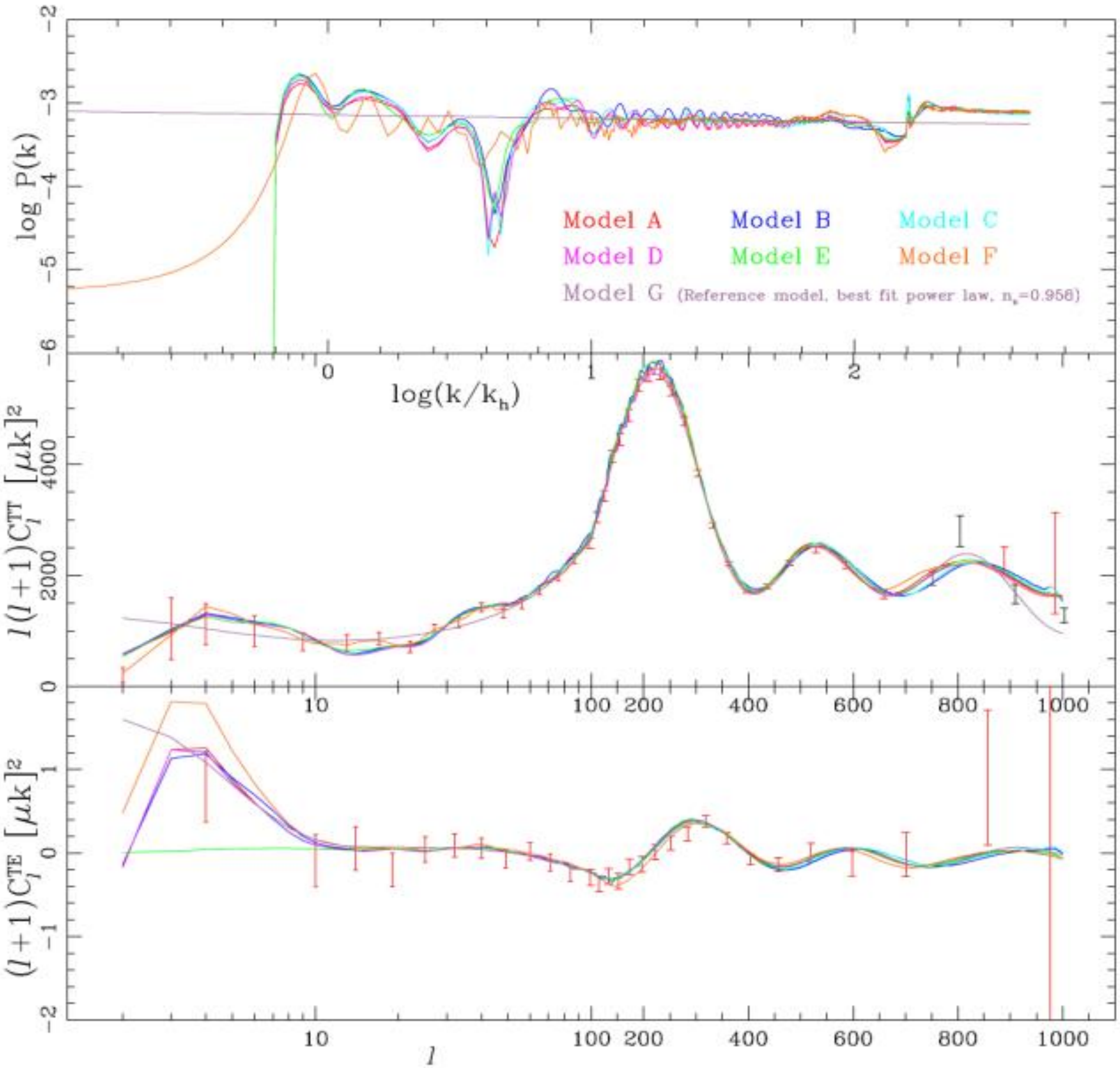
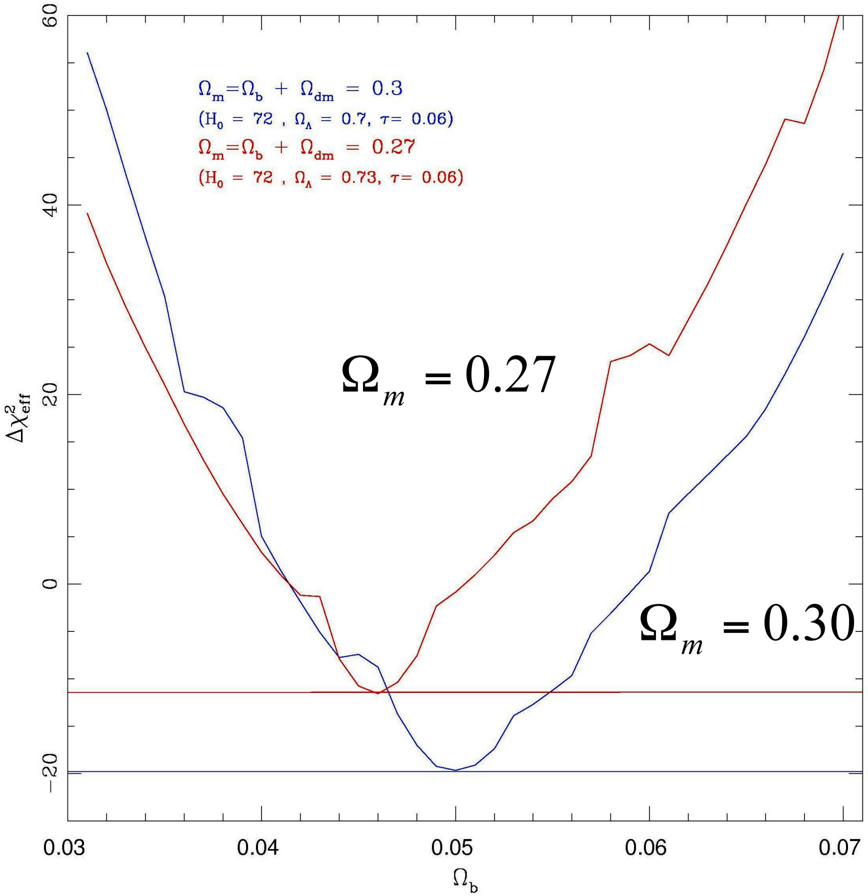


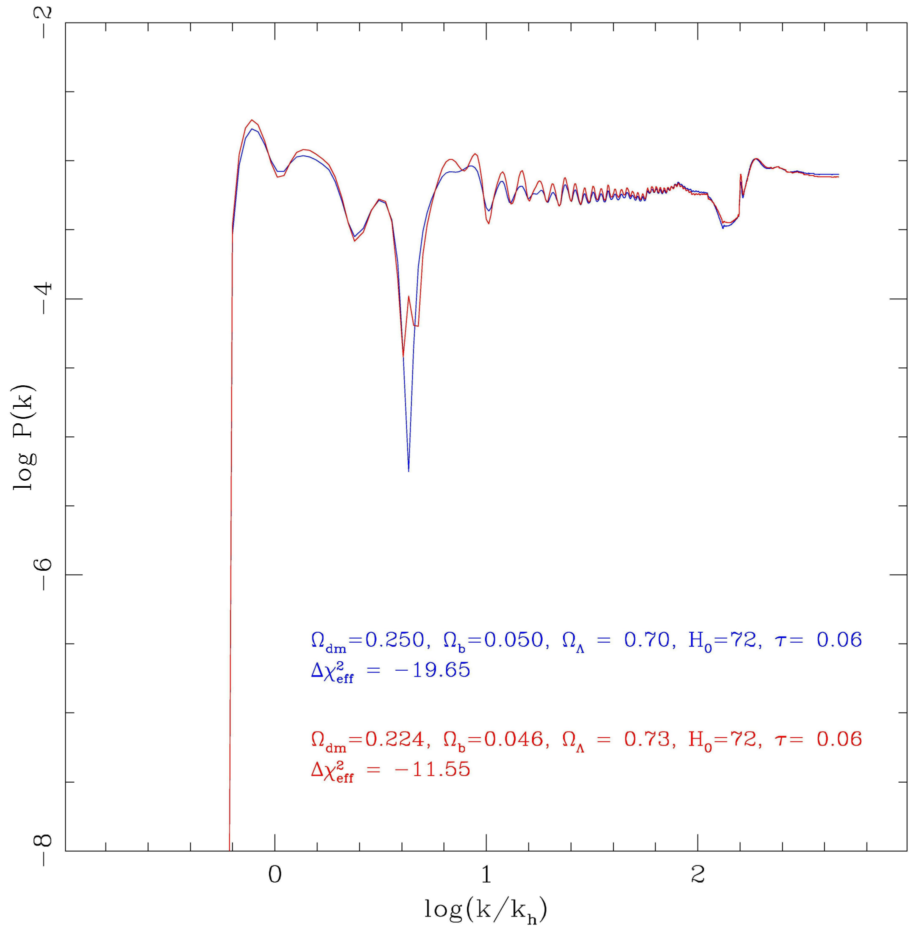
TABLE I: Different points in the parameter space and their resultant effective likelihood from the reconstructed primordial spectrum using WMAP 3 year data. The $\Delta\chi^2_{\rm eff}$ is with respect to the best driven result in the whole parameter space by assuming scale invariant form of the primordial spectrum.

Model	H_0	Ω_{dm}	Ω_{bm}	Ω_Λ	τ	$\Delta\chi^2_{\rm eff}$
Model A (compatible with SDSS)	72.0	0.246	0.050	0.704	0.06	-18.76
Model B (compatible with 2df)	63.0	0.251	0.041	0.708	0.06	-4.38
Model C (compatible with BAO)	68.0	0.229	0.052	0.719	0.06	-2.93
Model D (compatible with SN Ia + BAO)	72.0	0.229	0.046	0.725	0.06	-14.52
Model E (compare to WMAP1)	71.0	0.226	0.044	0.730	0.0	-13.40
Model F (compatible with flat CDM)	50.0	0.904	0.096	0.0	0.06	-26.70

Shafieloo & Souradeep, PRD 2008

Towards Cosmological Parameter Estimation





Shafieloo & Souradeep, PRD 2008

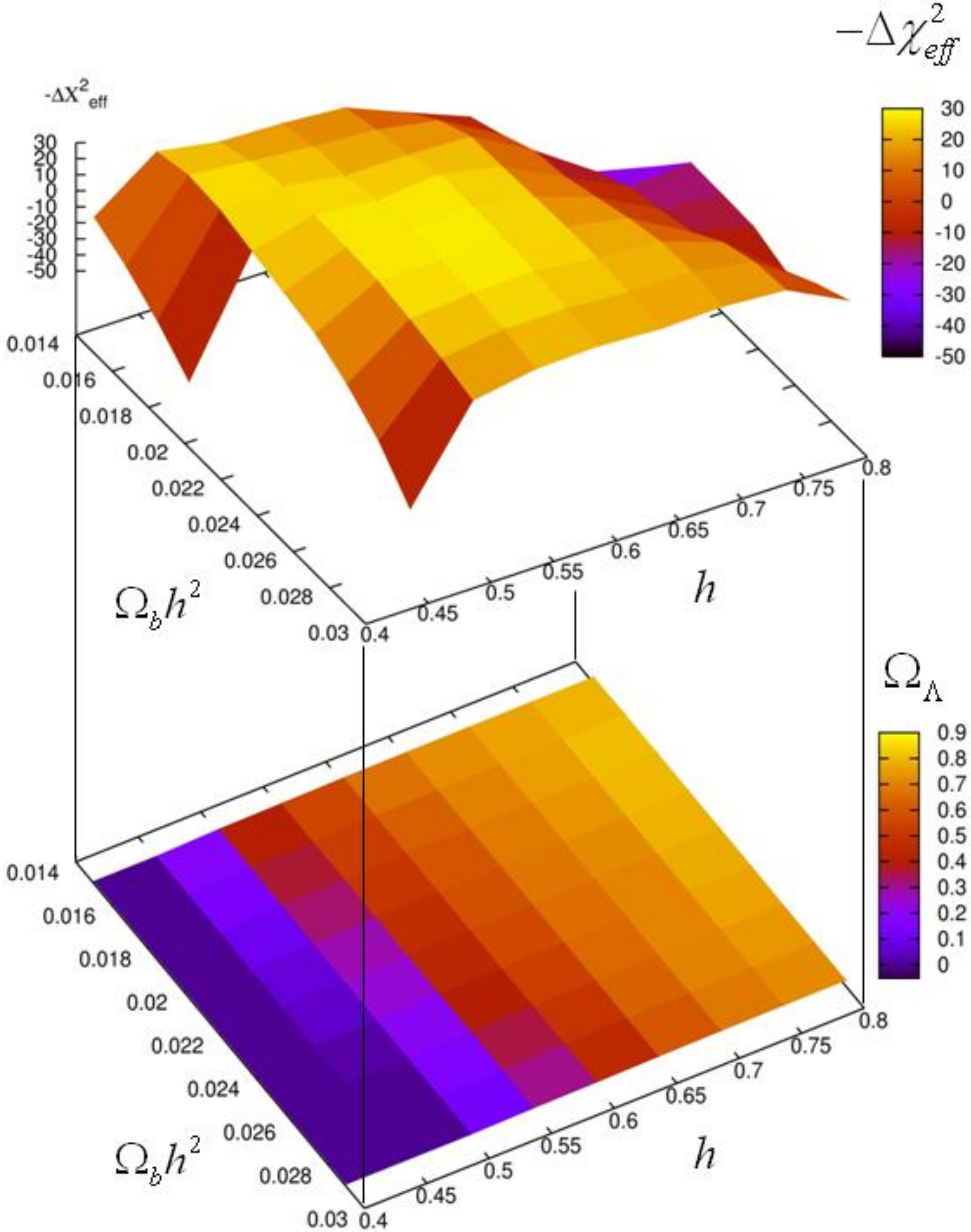
$\Omega_b = 0.058$

$\Omega_c = 0.416$

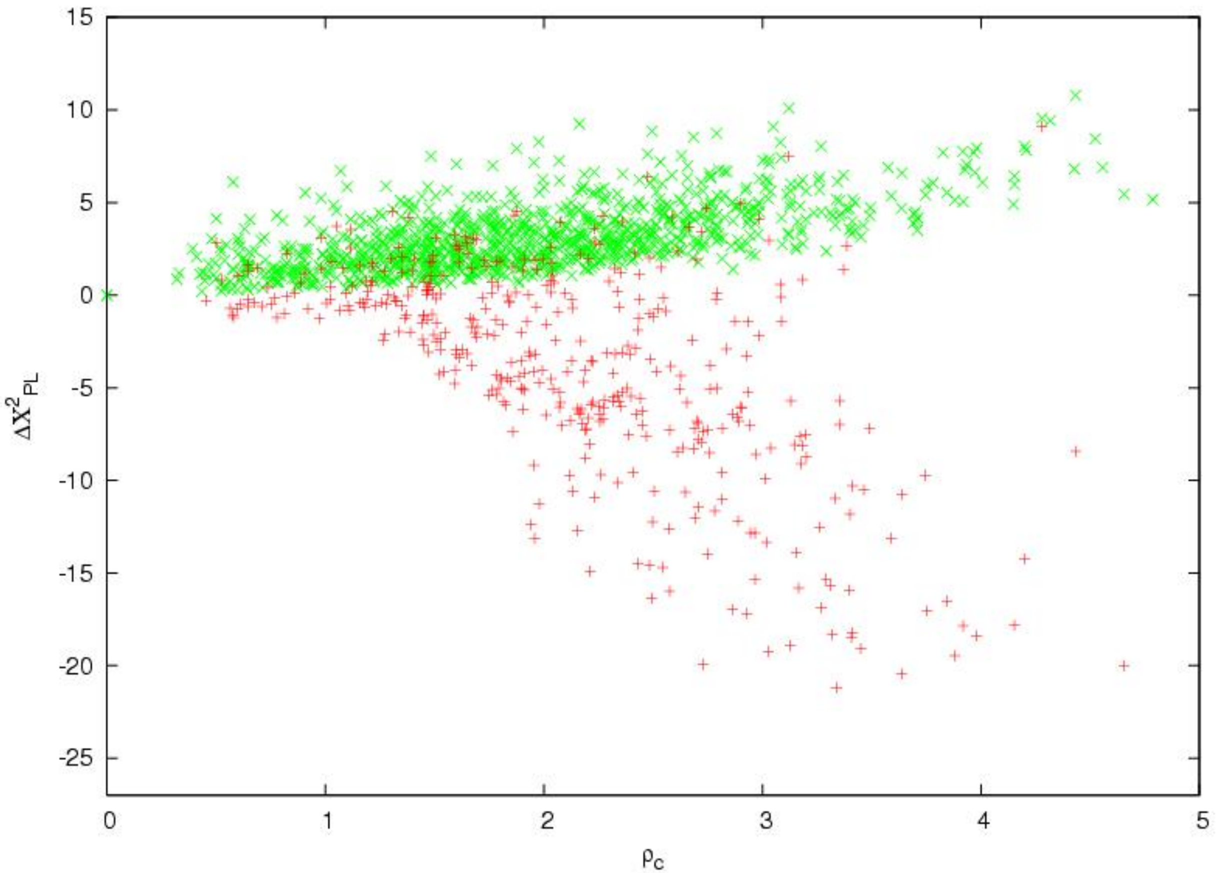
$\Omega_\Lambda = 0.526$

$H_0 = 60$

$\Delta\chi^2 = -29.014$



A. Shafieloo & T. Souradeep
PRD 2008



$$\rho(a,b) = \sqrt{\sum_i \frac{(P_i^a - P_i^b)^2}{(\sigma_i^b)^2}}$$

$$\rho(a,b) \neq \rho(b,a)$$

$\Omega_b h^2$ h

$\Omega_{0m} h^2$ τ

$\rho(HZ, PL) = 6.89$

$\rho(RN, PL) = 4.85$

$\rho(HZ, RN) = 11.09$

$\rho(PL, RN) = 2.44$

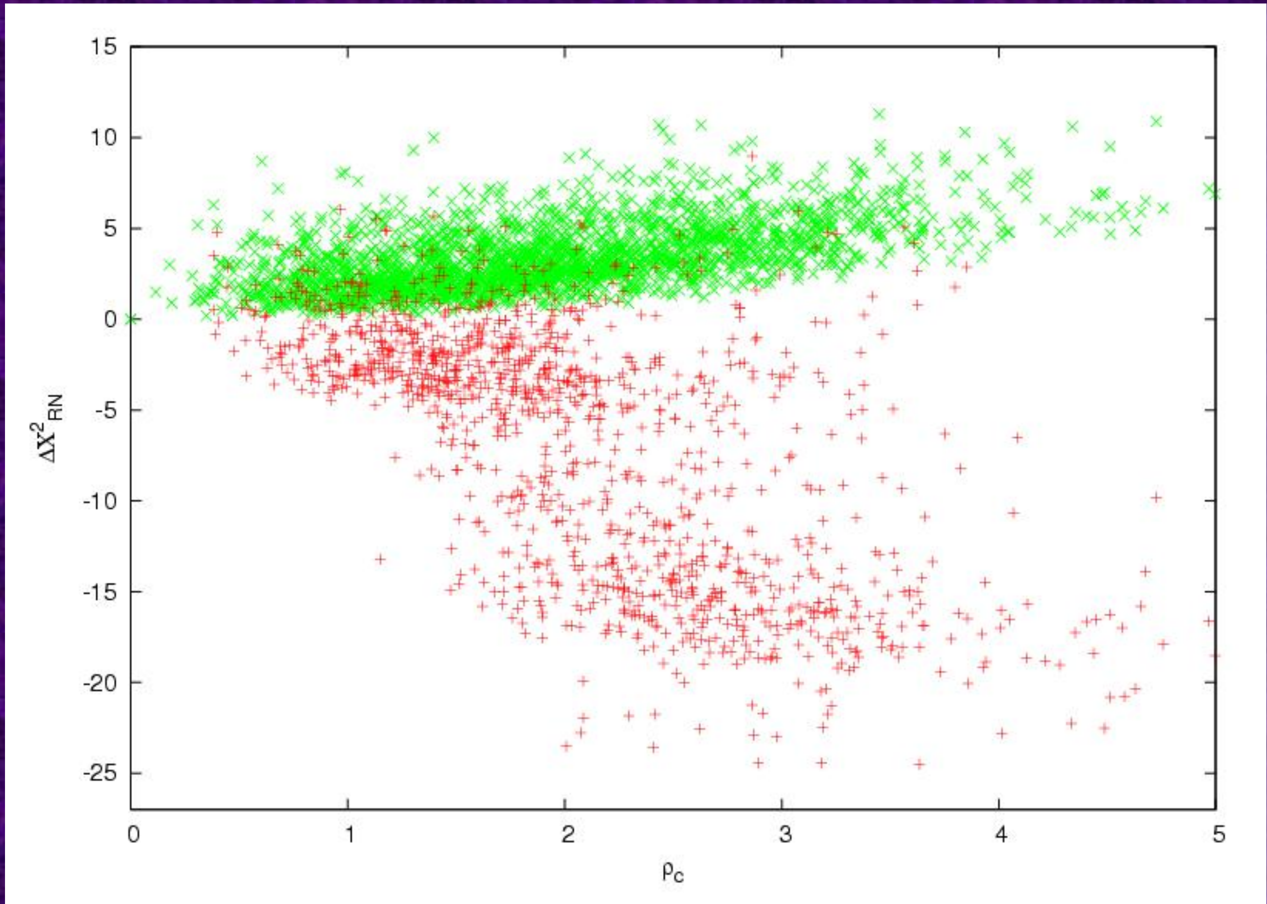
$\rho(PL, HZ) = 14.56$

$\rho(RN, HZ) = 43.79$

Power Law Assumption

Optimized over Primordial Spectrum

Shafieloo & Souradeep, 2009



$$\rho(a,b) = \sqrt{\sum_i \frac{(P_i^a - P_i^b)^2}{(\sigma_i^b)^2}}$$

$$\rho(a,b) \neq \rho(b,a)$$

$\Omega_b h^2$ h

$\Omega_{0m} h^2$ τ

$\rho(HZ, PL) = 6.89$

$\rho(RN, PL) = 4.85$

$\rho(HZ, RN) = 11.09$

$\rho(PL, RN) = 2.44$

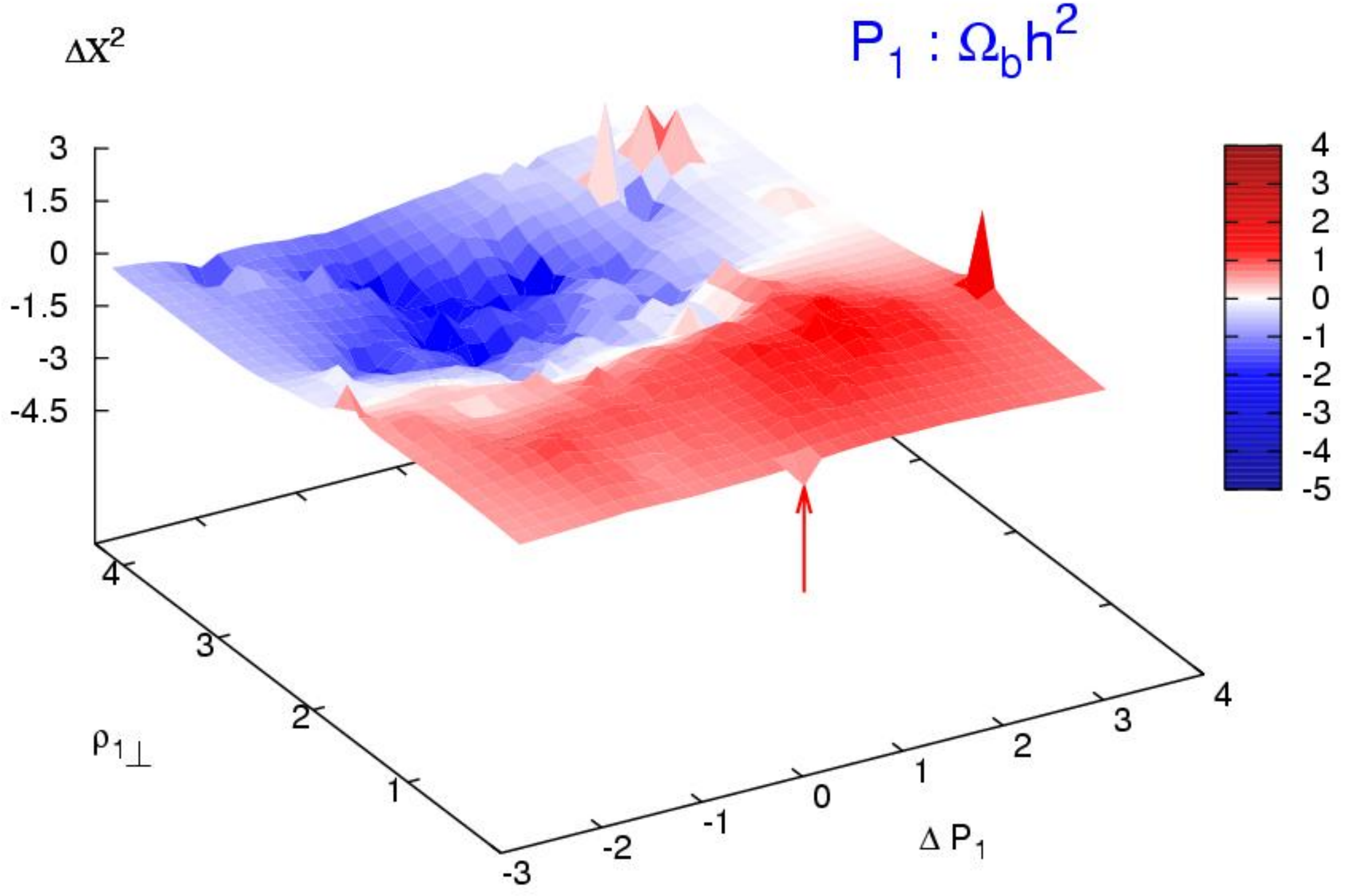
$\rho(PL, HZ) = 14.56$

$\rho(RN, HZ) = 43.79$

Power Law with Running Assumption

Optimized over Primordial Spectrum

Shafieloo & Souradeep, arXiv:0901.0716

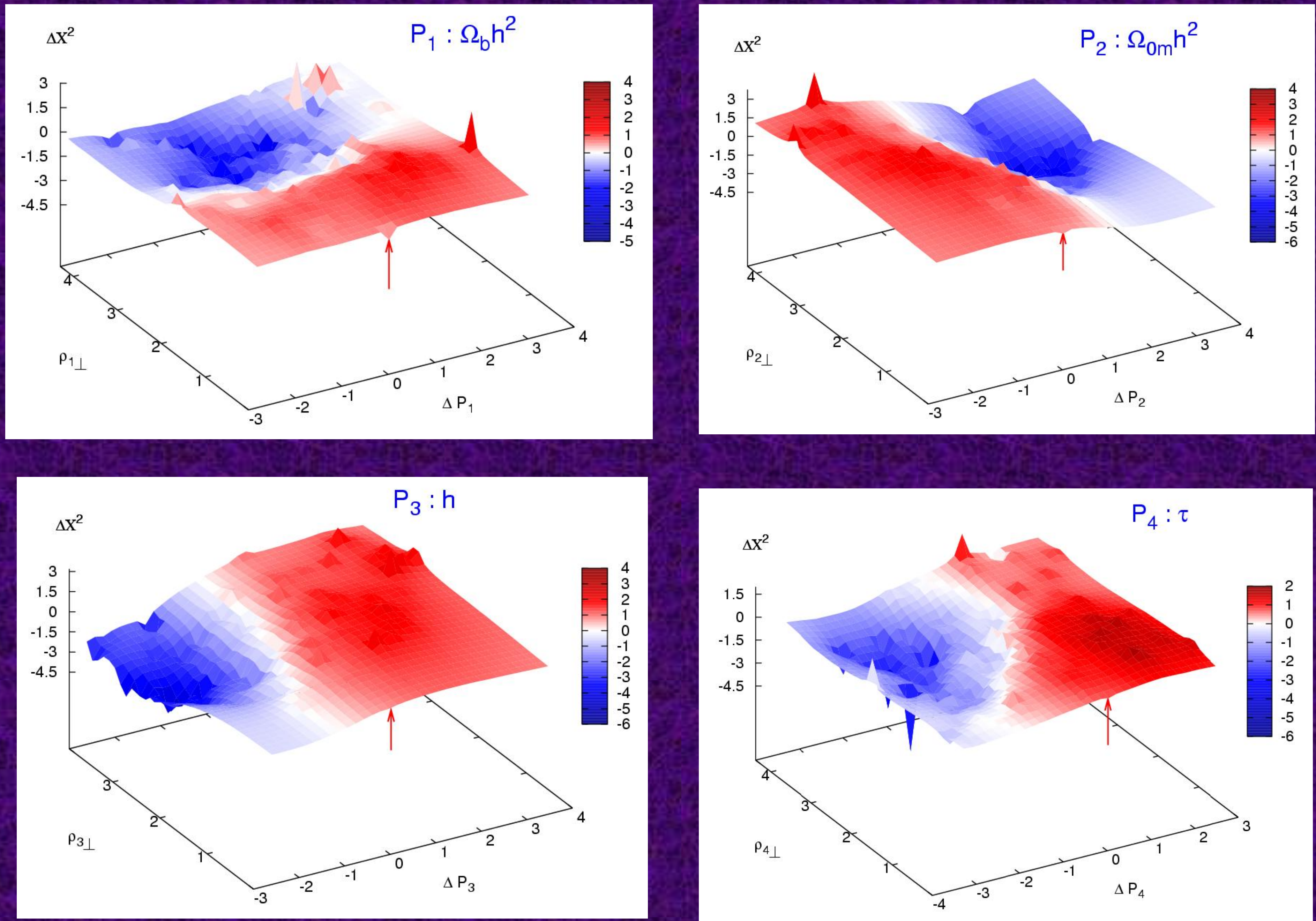


Using Power Law Sample

Shafieloo & Souradeep, arXiv:0901.0716

$$\Delta P_i = \frac{P_i^a - P_i^b}{\sigma_i^b}$$

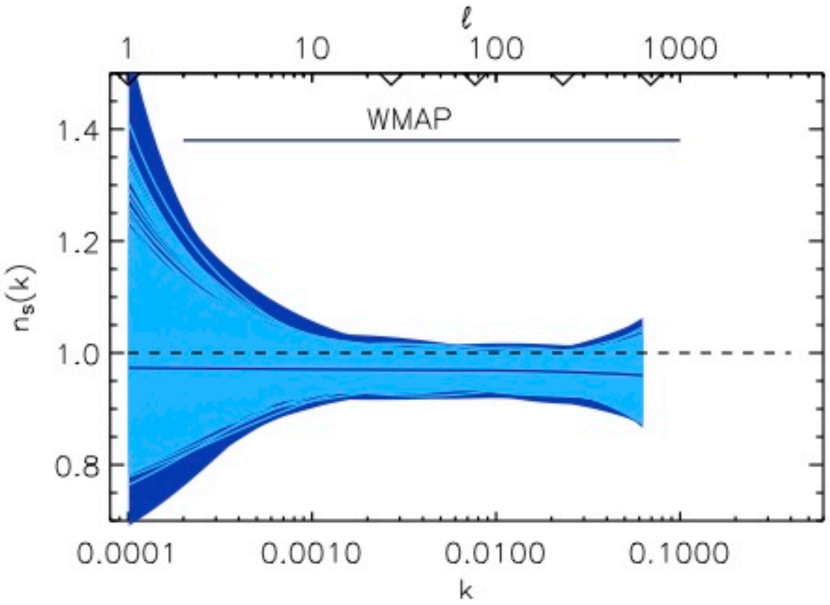
$$\rho_{i\perp} = \sqrt{\sum_{j \neq i} \frac{(P_j^a - P_j^b)^2}{(\sigma_j^b)^2}}$$

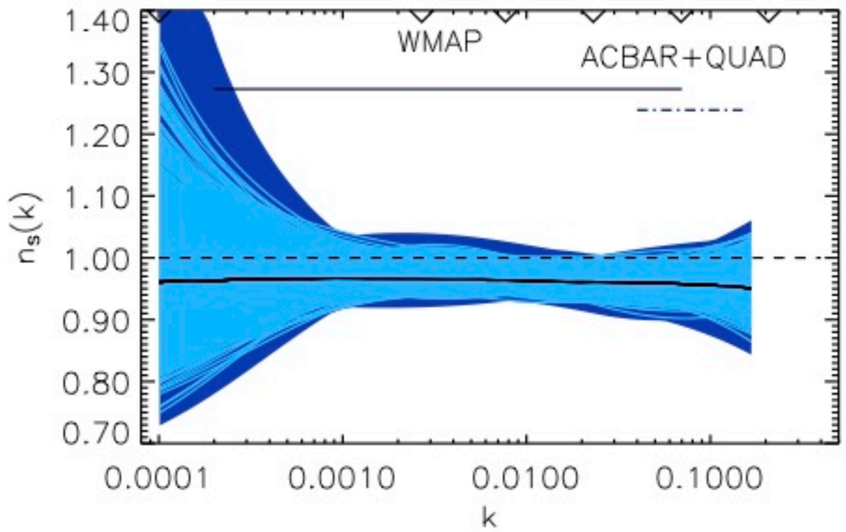


Shafieloo & Souradeep, arXiv:0901.0716

Testing the Standard Power-Law form of PPS

Smoothing Spline Method
along with Cross Validation

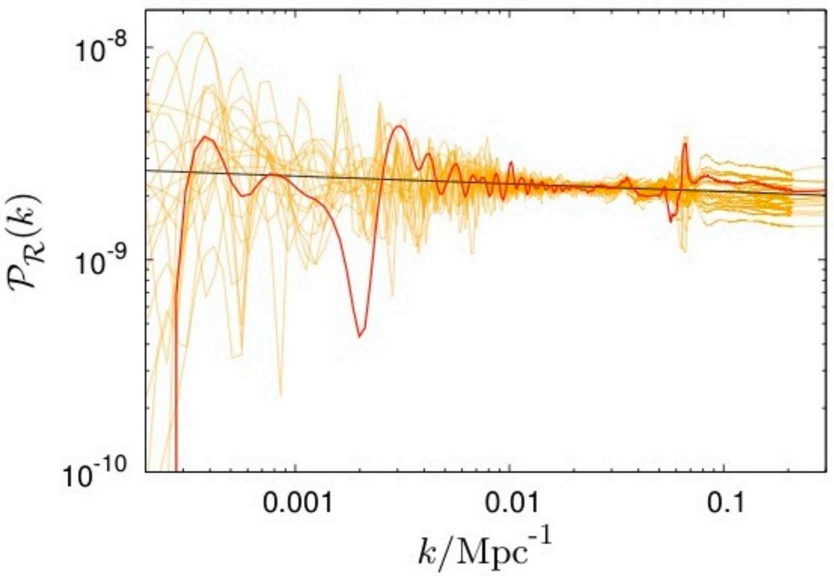




Peiris & Verde, PRD 2010

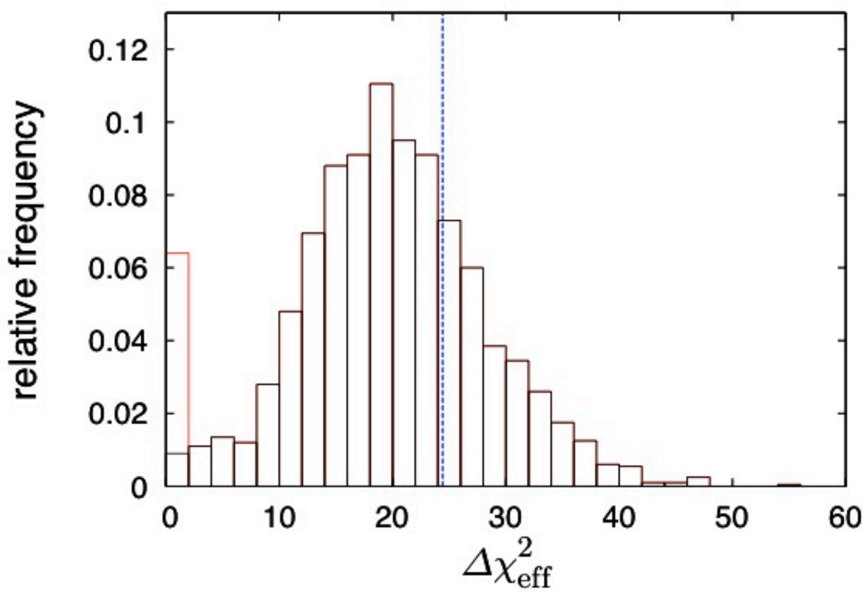
Testing the Standard Power-Law form of PPS

Frequentist test using IRL deconvolution method



It is evident that the spectrum reconstructed from real data does not have an unusual amount of features. The apparent feature at 0.05 Mpc < k < 0:07 Mpc is caused by the noise term becoming dominant at the corresponding multipoles in the WMAP data.

P-value = 26%



Hamann, Shafieloo & Souradeep,
JCAP 2010

Full picture

$$C_\ell^{TT} = \int \frac{dk}{k} P(k) \quad G_\ell^{TT}(k)$$

$$C_\ell^{EE} = \int \frac{dk}{k} P(k) \quad G_\ell^{EE}(k)$$

$$C_\ell^{BB} = \int \frac{dk}{k} P(k) \quad G_\ell^{BB}(k)$$

$$C_\ell^{TE} = \int \frac{dk}{k} P(k) \quad G_\ell^{TE}(k)$$

$$P_S(k), P_T(k), P_{iso}(k)$$

Primordial power spectra from Early universe

$$G_\ell^{TT}(k), G_\ell^{EE}(k), G_\ell^{BB}(k), G_\ell^{TE}(k)$$

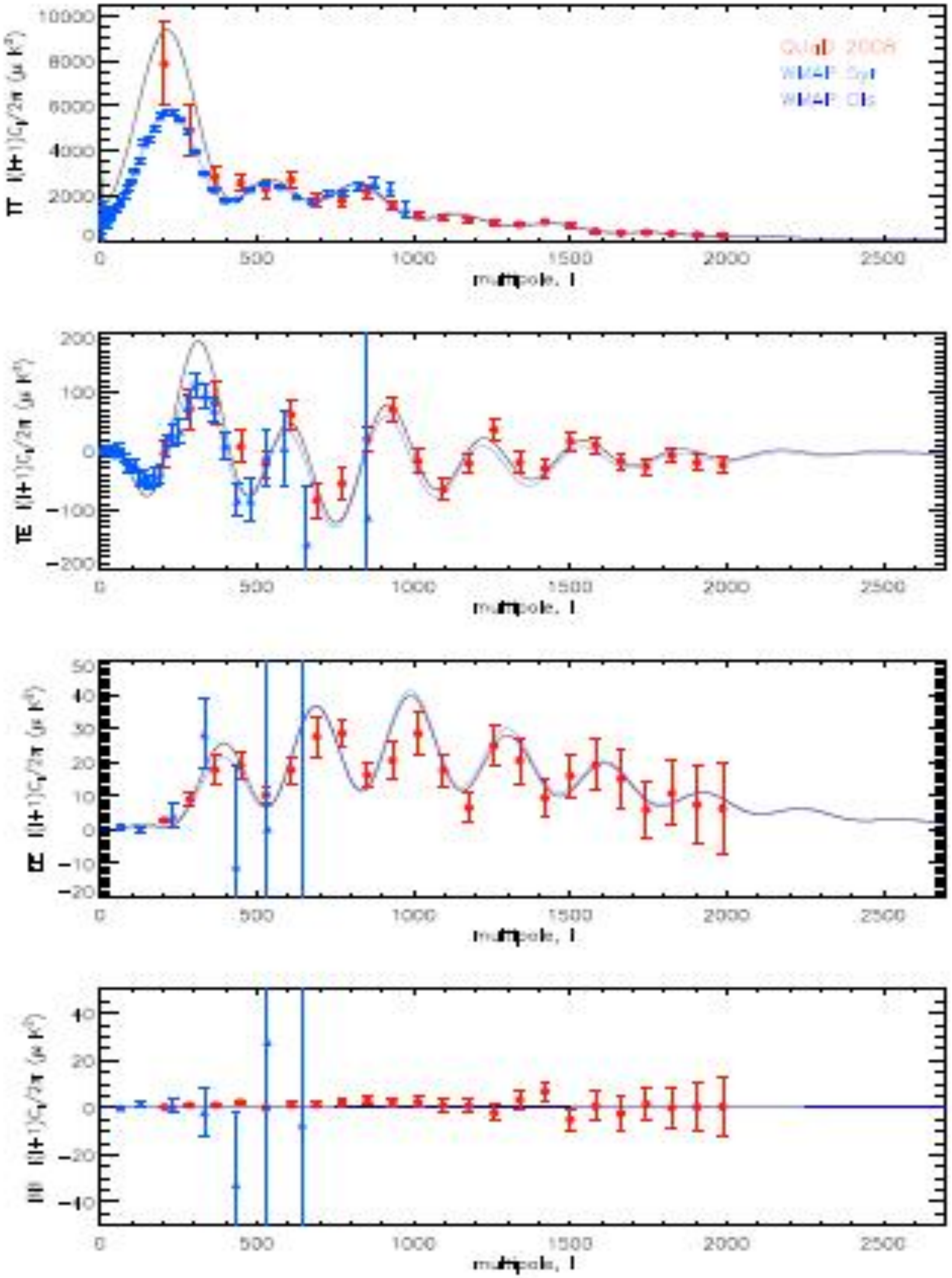
Post recombination Radiative transport kernels in a **given** cosmology

Summary

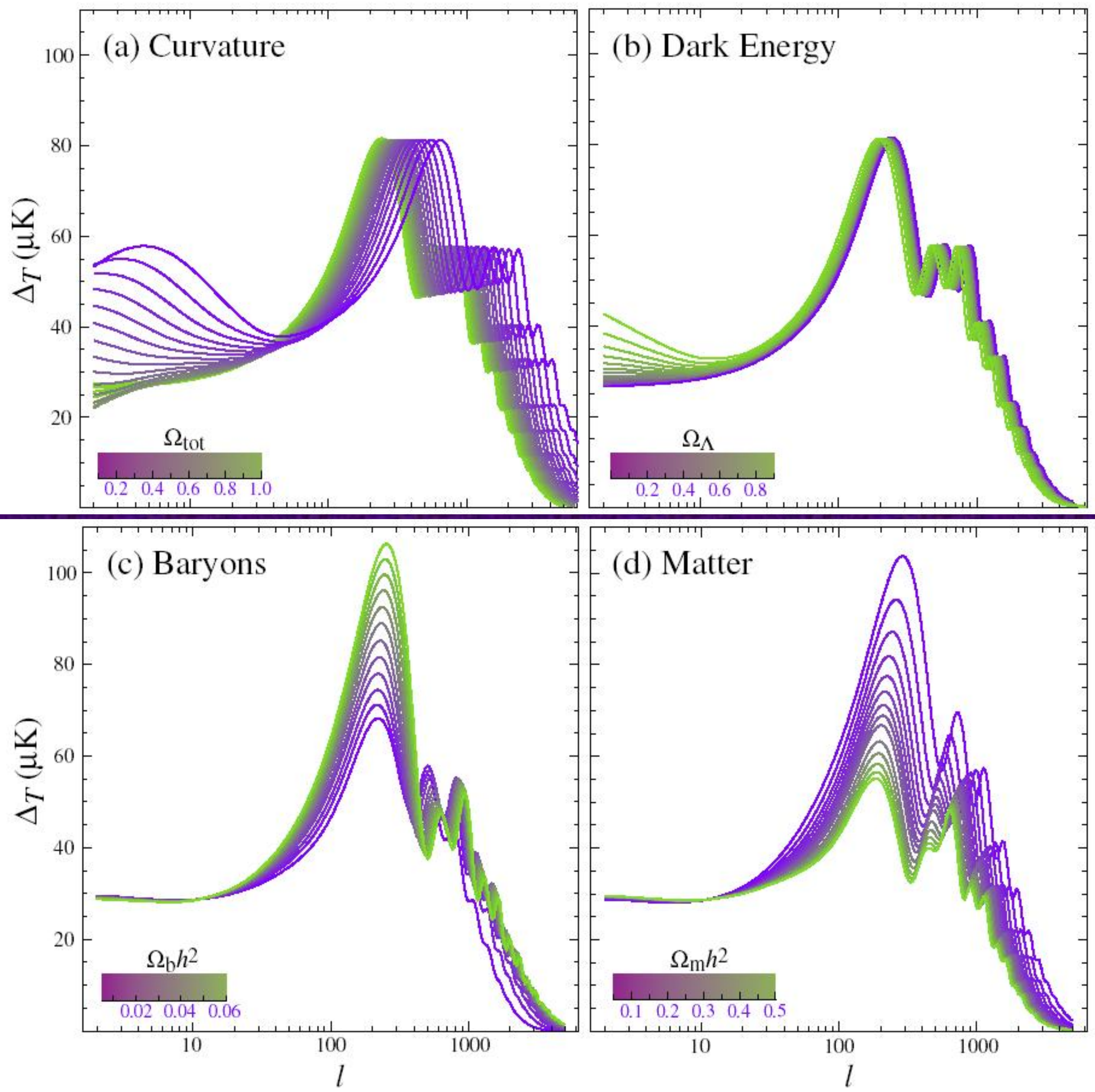
- By assuming any form of PPS, we in fact find a region in the parameter space which prefers these specific forms.
- The regions where considerably better likelihoods are obtained allowing free PPS lie outside these basins.
- The current cosmological parameters estimates are strongly prejudiced by the assumed form of PPS.
- Our results strongly motivate approaches toward simultaneous estimation of the cosmological parameters and the shape of primordial spectrum from upcoming cosmological data.
- Though standard power-law form of the PPS is very well consistent to the data, It is also important to keep an open mind towards early universe scenarios that produce features in the PPS.

Thank you

Polarization Data



QUaD Collaboration 2009



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

Total density

Dark Energy

Baryon density

Matter density.

From Hu & Dodelson, 2002

Beyond the Standard Model of Cosmology

- The universe may be more complicated than its current standard model (Vanilla Model).
- There might be some extensions to the standard model in defining the cosmological quantities.
- This needs proper investigation, using advanced statistical methods, high performance computational facilities and high quality observational data.

(Present)t

Standard Model of Cosmology

Universe is Flat

Universe is Isotropic

Universe is Homogeneous (large scales)

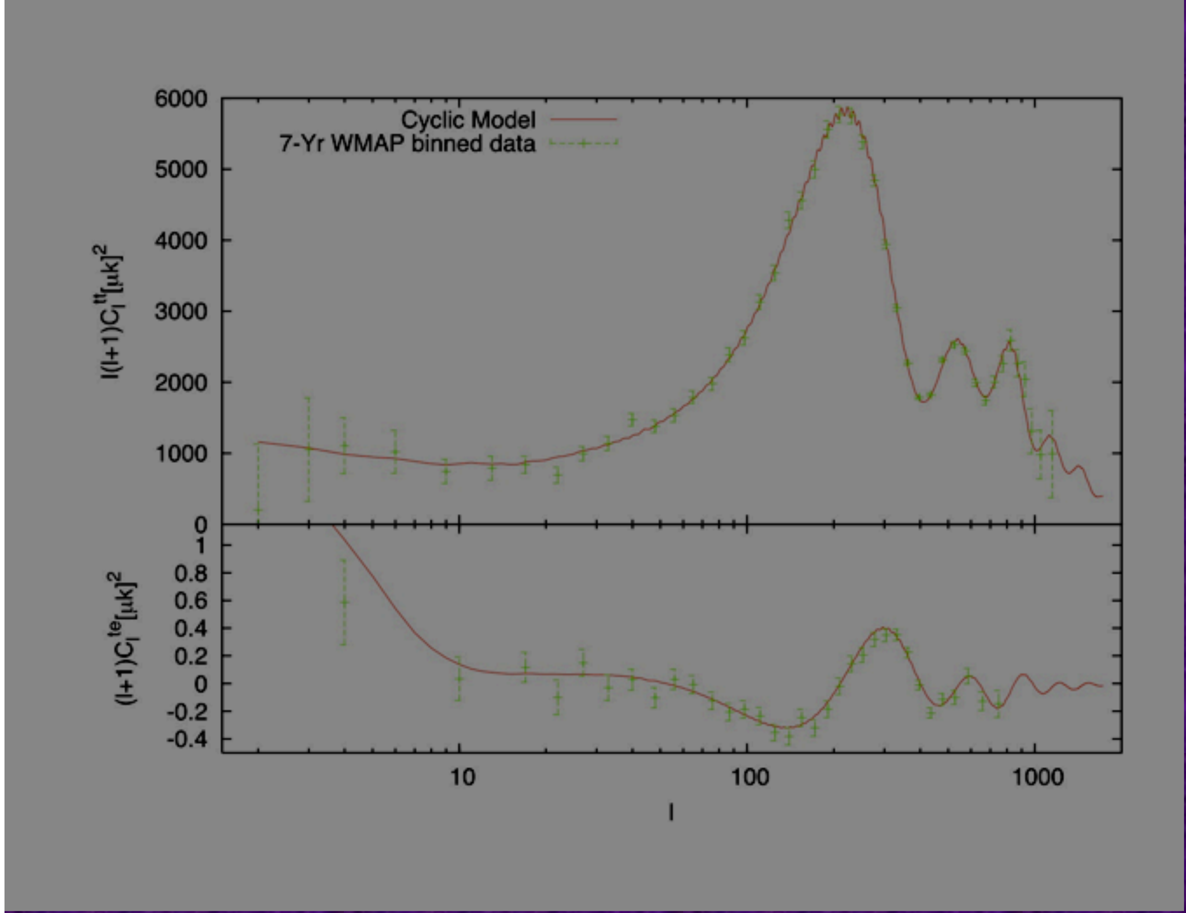
Dark Energy is Lambda (w=-1)

Power-Law primordial spectrum (n_s=const)

Dark Matter is cold

All within framework of FLRW

Insensitivity of the Data to Various Models

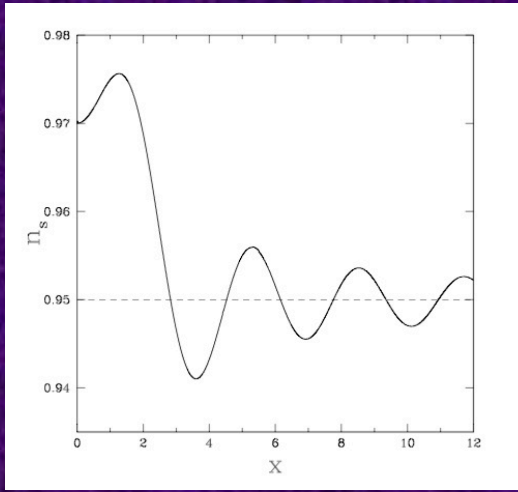


Power spectrum from non-singular cyclic inflation

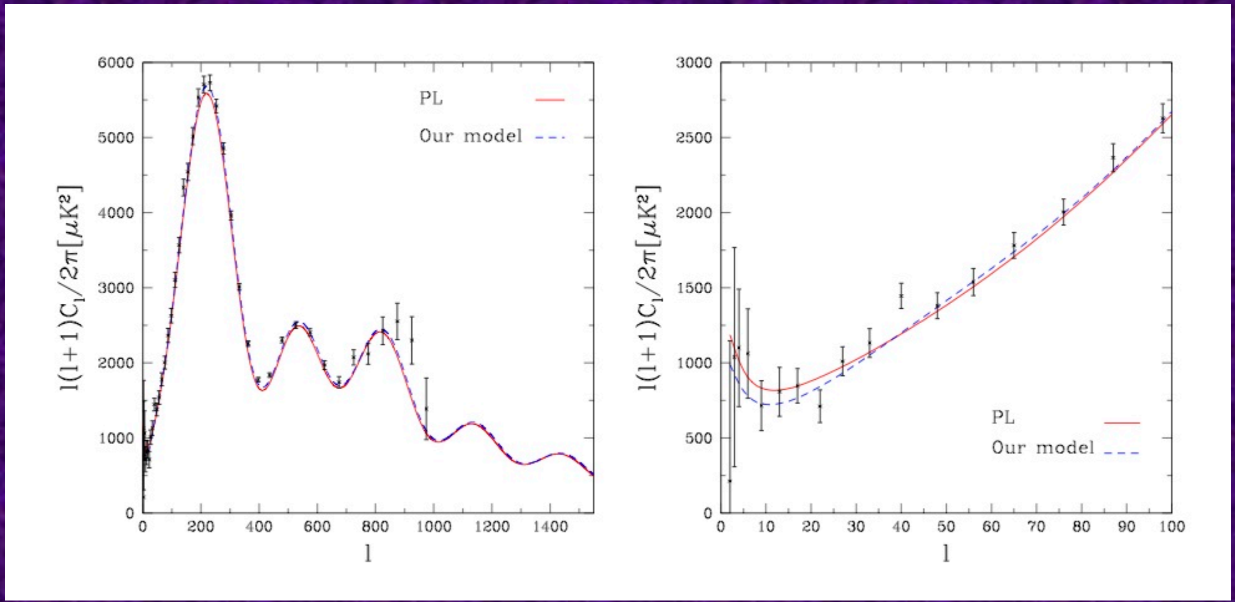
-2ln(L)=-7470.5 to WMAP 7 data

Biswas, Mazumdar & Shafieloo, 2010

Insensitivity of the Data to Various Models



step in the second derivative of the inflaton potential leads to a step in the spectral index



Joy, Shafieloo, Sahni, Starobinsky JCAP 2009

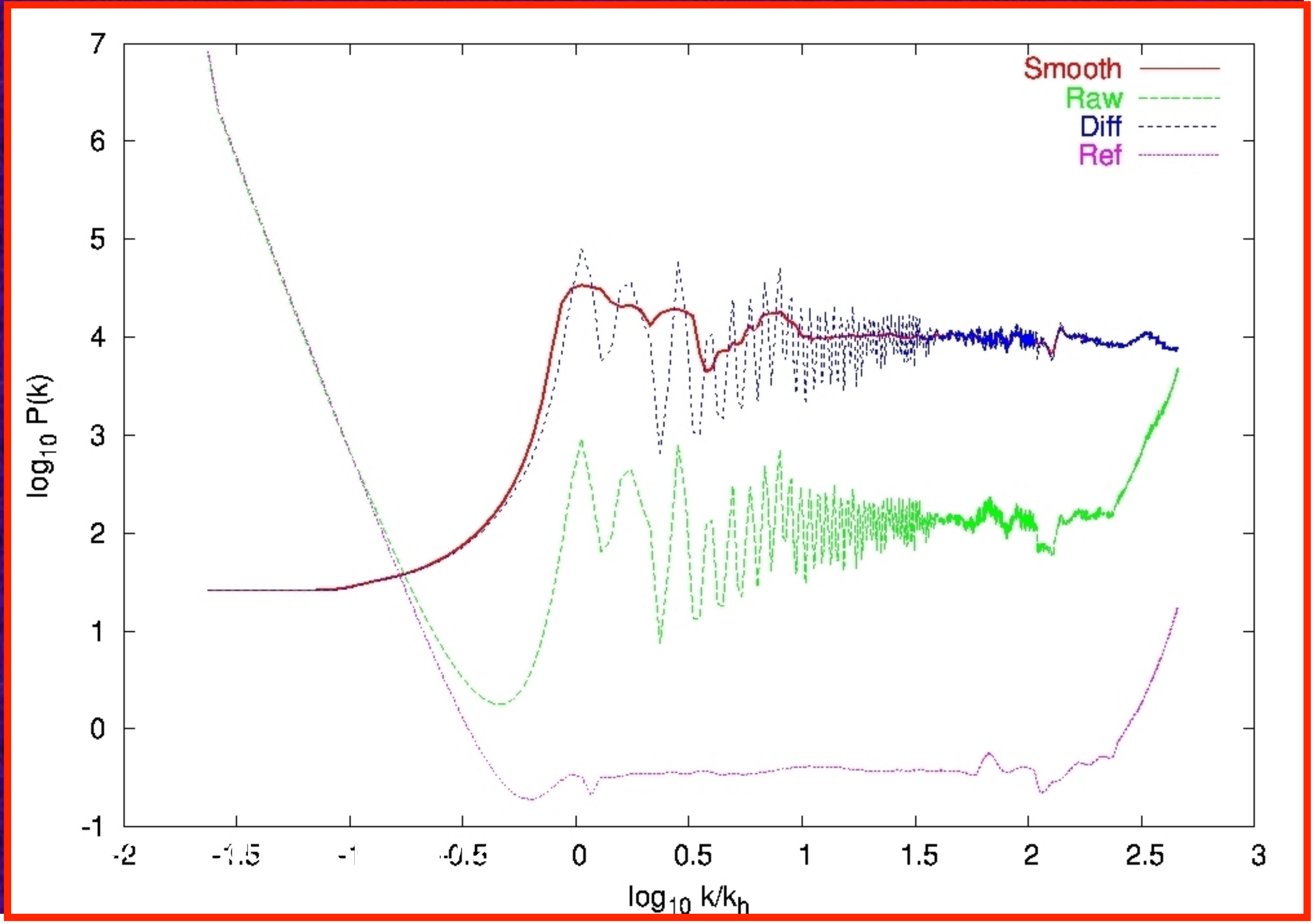
THE RECOVERED SPECTRUM

$$\tau = 0.0$$

$$h = 0.71$$

$$\Omega_\Lambda = 0.73$$

$$\Omega_b h^2 = 0.0224$$



Power spectrum	$\chi^2_{\rm eff} \equiv -2 \ln \mathcal{L}$	$k_c/k_h{}^a$ $(k_h = 4.5 \times 10^{-4}{\rm Mpc.}^{-1})$
Direct Recovered	956.76	0.71
Flat Harrison Zeldovich	1007.28	–
Power Law $(n_s = 0.95)$	978.60	–
Exponential cutoff $(n_s = 0.95,\ \alpha = 3.35)$	978.08	0.64
Exponential cutoff $(n_s = 0.95,\ \alpha = 10)$	977.84	0.64
Starobinsky break $(n_s = 0.95,\ r = 0.01)$	973.86	0.32
Vilenkin & Ford (VF-I) $(n_s = 0.95)$	976.88	0.43
Vilenkin & Ford (VF-II) $(n_s = 0.95)$	978.66	0.96

Shafieloo & Souradeep, PRD 2004