Searching for primordial features from CMB and LSS surveys

collab. with A. Achucarro, V. Atal, P. Ortiz, J. Torrado

[PRD 89 (2014) 103006]
[PRD 90 (2014) 023511]
[PRD 91 (2015) 064039]

Bin Hu

Lorentz Institute, Leiden University

Early Universe, Cosmology and Fundamental Physics, KITPC/Beijing, Sept. 2015

Outline

1. State-of-the-art of inflation from observational point of view
2. Observational hints of oscillatory features
3. Models with a transient reduction of the speed of sound
4. Search with CMB power spectrum
5. Search with LSS survey
6. Conclusion

What do we mean by inflation from a phenomenological point of view?

A_s — the size of the primordial scalar power spectrum

n_s — the power index of the primordial scalar power spectrum

r — the primordial tensor-to-scalar ratio

f_nl — the size of 3 point function of primordial curvature fluctuations

$$P_s(k) \sim A_s \left(\frac{k}{k_0}\right)^{n_s - 1} \qquad P_t(k) \sim A_t \left(\frac{k}{k_p}\right)^{n_t} \qquad r \sim \frac{P_t(k_*)}{P_s(k_*)}$$

$$B_\Phi(k_1, k_2, k_3) = f_{\rm NL} F(k_1, k_2, k_3)\,.$$

[1] Parameter	[2] 2013N(DS)	[6] 2015F(CHM) (Plik)	$([2]-[6])/\sigma_{[6]}$
$100\theta_{MC}$	1.04131 ± 0.00063	1.04086 ± 0.00048	0.71
$\Omega_b h^2$	0.02205 ± 0.00028	0.02222 ± 0.00023	−0.61
$\Omega_c h^2$	0.1199 ± 0.0027	0.1199 ± 0.0022	0.00
H_0	67.3 ± 1.2	67.26 ± 0.98	0.03
n_s	0.9603 ± 0.0073	0.9652 ± 0.0062	−0.67
Ω_m	0.315 ± 0.017	0.316 ± 0.014	−0.06
σ_8	0.829 ± 0.012	0.830 ± 0.015	−0.08
τ	0.089 ± 0.013	0.078 ± 0.019	0.85
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.881 ± 0.014	−3.46

Planck2013 TT
+WMAP low-ell
polarization

Planck2015 TT
+Planck2015 low-ell
polarization

Tension
between
2013 and 2015

A_s ~ 4E-9

$r < 0.12$ at 95%

BKP

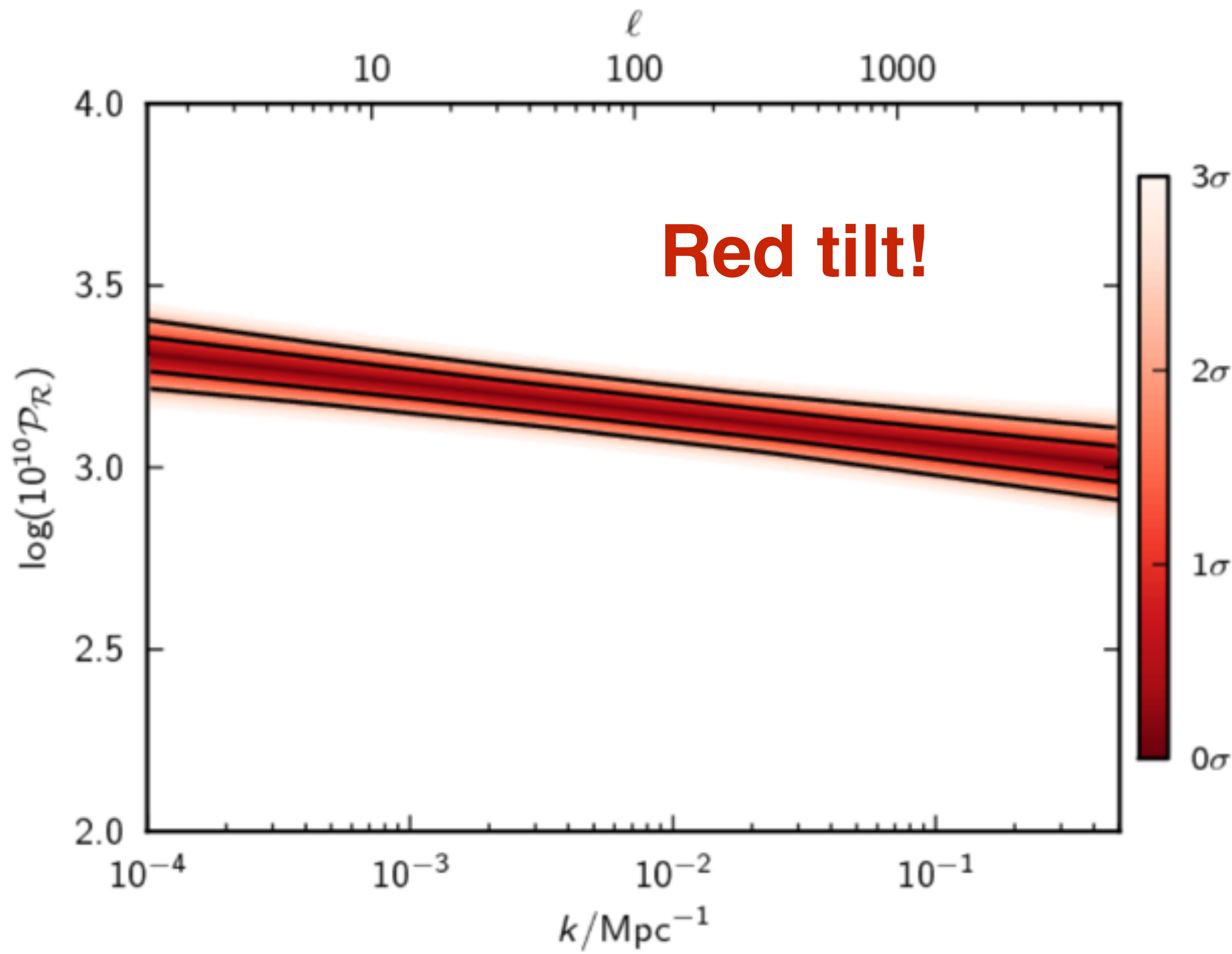
All primordial type
f_nl are consistent with 0

n_s

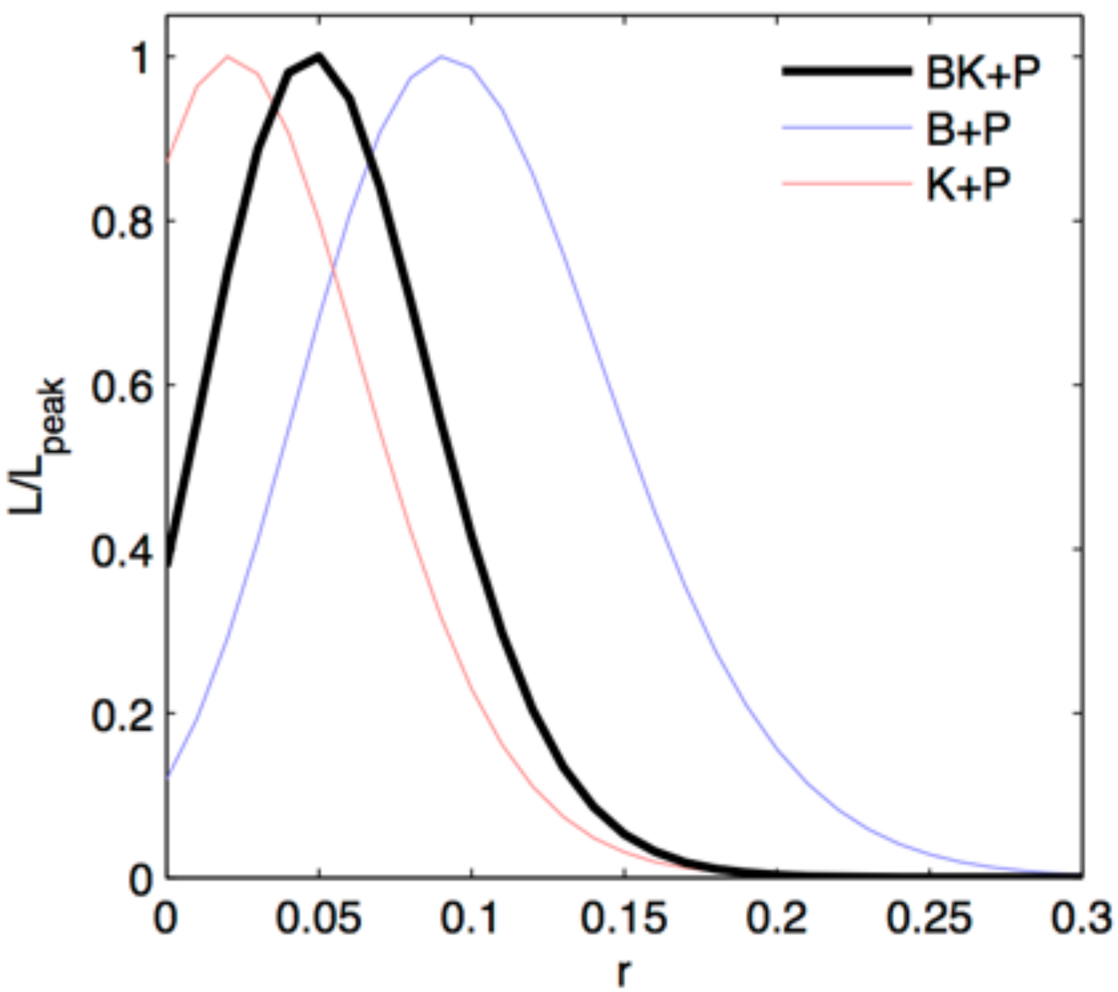
$$P_s(k) \sim A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

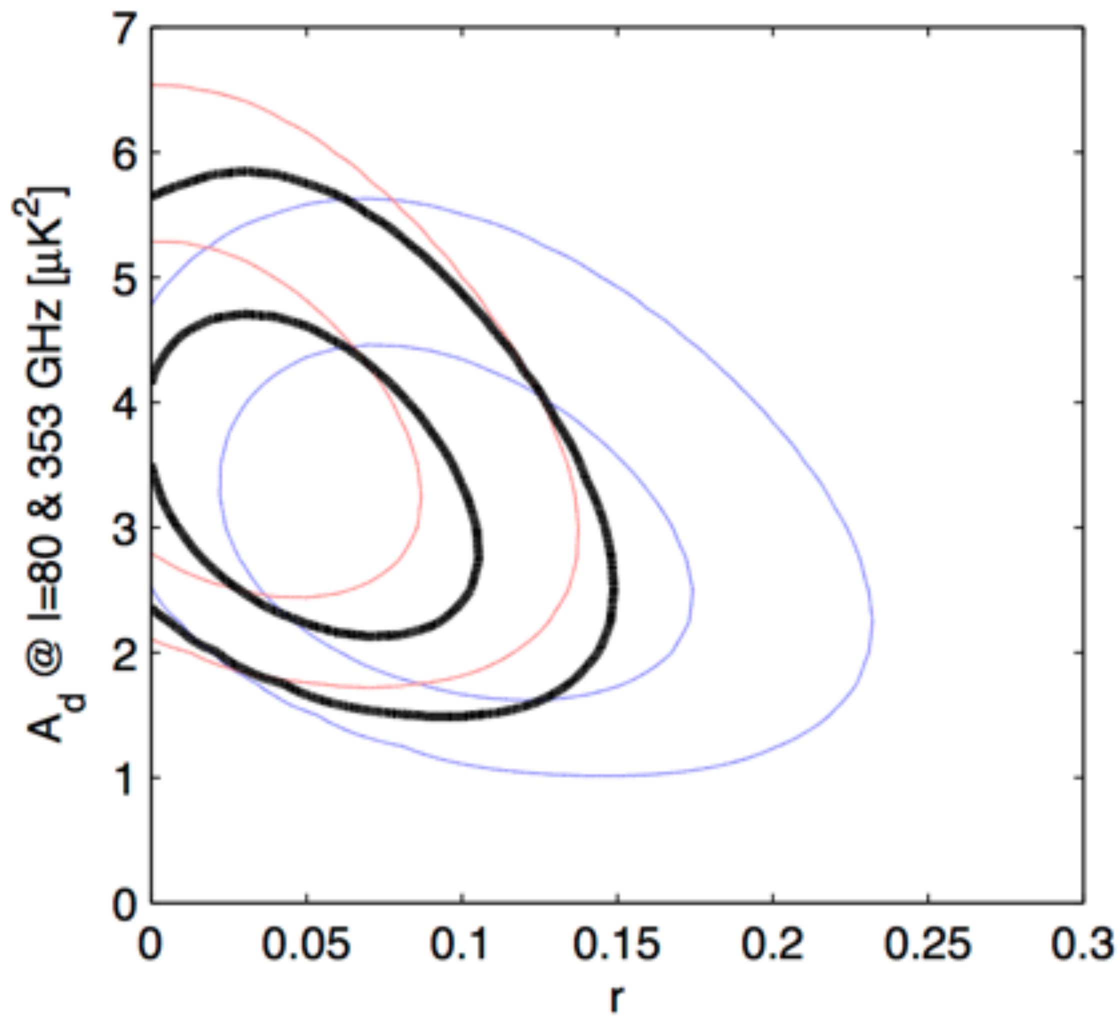
0.9645 ± 0.0049

Power spectrum is larger on low-k, smaller on high-k



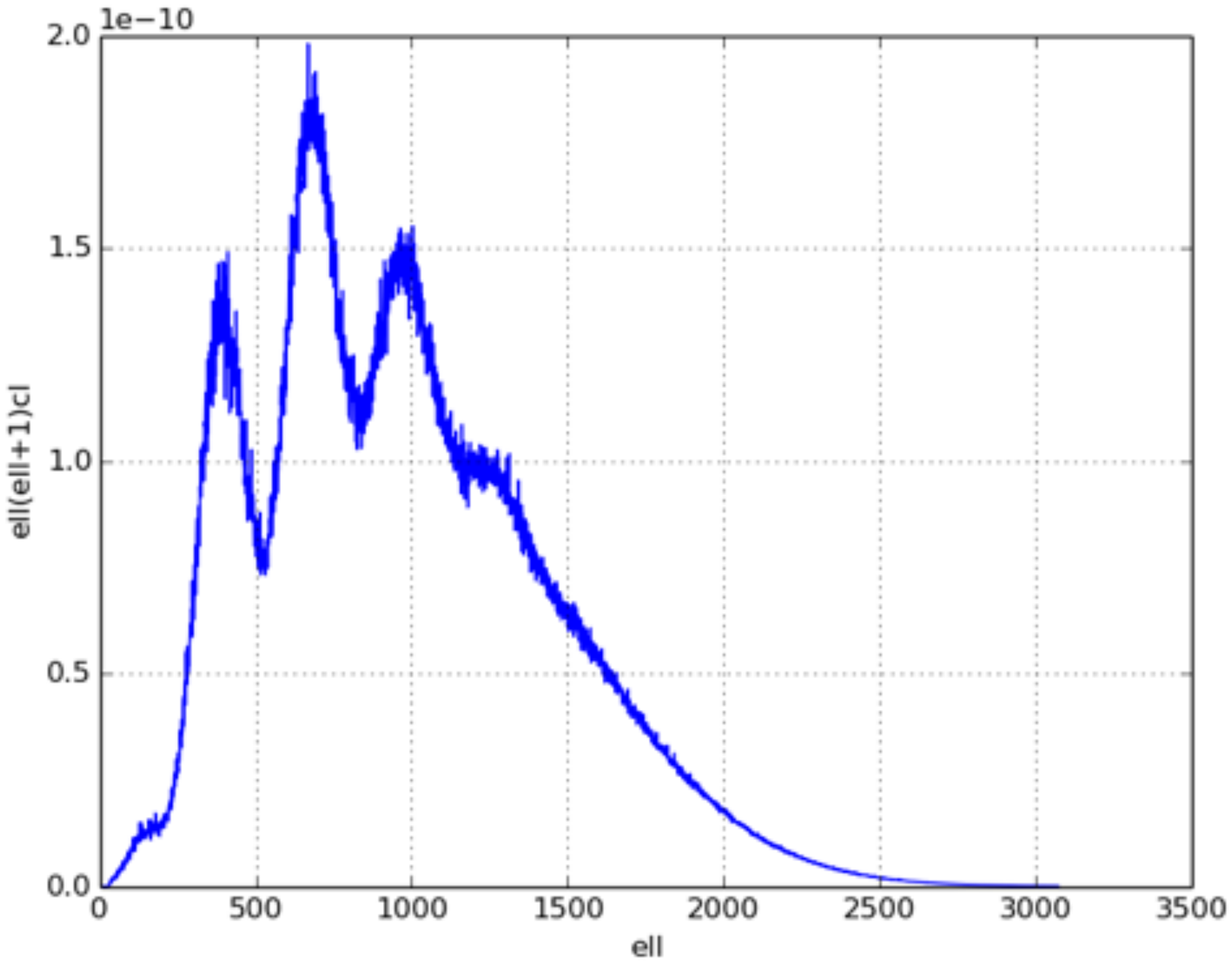
r

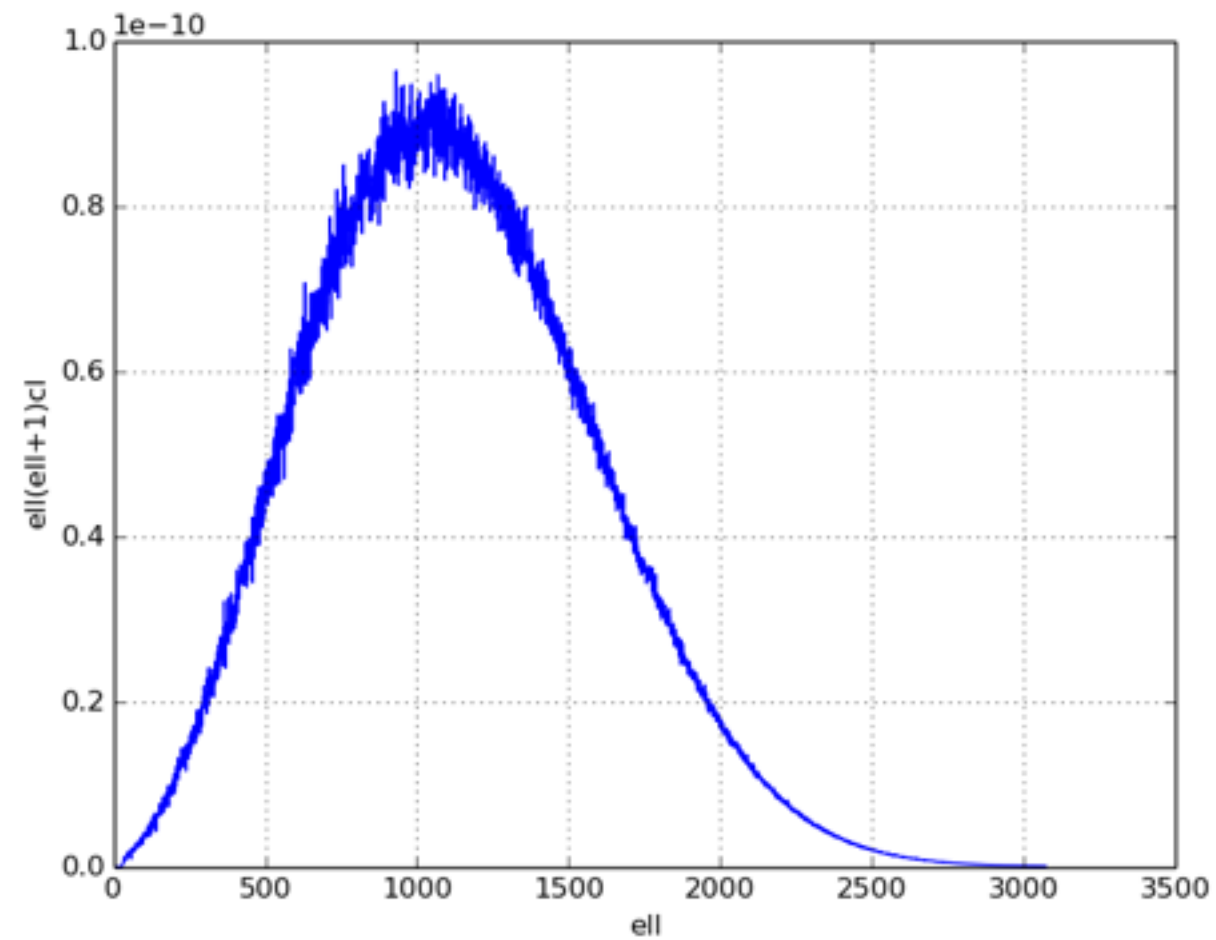




BICEP-II: NO detection of primordial B-mode!

Dust contamination!


1e−10
2.0
1.5
1.0
0.5
0.0
ell(ell+1)cl
0
500
1000
1500
2000
2500
3000
3500
ell


1e−10
1.0
0.8
0.6
0.4
0.2
0.0
ell(ell+1)cl
0
500
1000
1500
2000
2500
3000
3500
ell

Say CMB died ONCE MORE!

$\ell(\ell+1)C_\ell^{\mathrm{BB}}/(2\pi)$ $(\mu\mathrm{K}^2)$

A Instrumental specifications

Experiments	$f_{sky}[\%]$	$\nu[GHz]$	$\theta_{FWHW}[']$	$\delta P[\mu K']$
AdvACT	50	90	2.2	7.8
	50	150	1.3	6.9
	50	230	0.9	25
CLASS	70	38	90	39
	70	93	40	13
	70	148	24	15
	70	217	18	43
Keck/BICEP3	1	95	30	9.0
	1	150	30	2.3
	1	220	30	10
Simons Array	20	90	5.2	15.2
	20	150	3.5	12.3
	20	220	2.7	23.6
SPT-3G	6	95	1	6.0
	6	150	1	3.5
	6	220	1	6.0
EBEX	1	150	8	5.8
	1	250	8	17
	1	410	8	150
Spider	7.5	94	49	17.8
	7.5	150	30	13.6
	7.5	280	17	52.6
CMBPol	70	30	26	19.2
	70	45	17	8.3
	70	70	11	4.2
	70	100	8	3.2
	70	150	5	3.1
	70	220	3.5	4.8
	70	340	2.3	21.6
COrE	70	45	23	9.1
	70	75	14	4.7
	70	105	10	4.6
	70	135	7.8	4.6
	70	165	6.4	4.6
	70	195	5.4	4.5
	70	225	4.7	4.6
	70	255	4.1	10.5
	70	285	3.7	17.4
	70	315	3.3	46.6
	70	375	2.8	119
LiteBIRD	70	60	32	10.3
	70	78	58	6.5
	70	100	45	4.7
	70	140	32	3.7
	70	195	24	3.1
	70	280	16	3.8

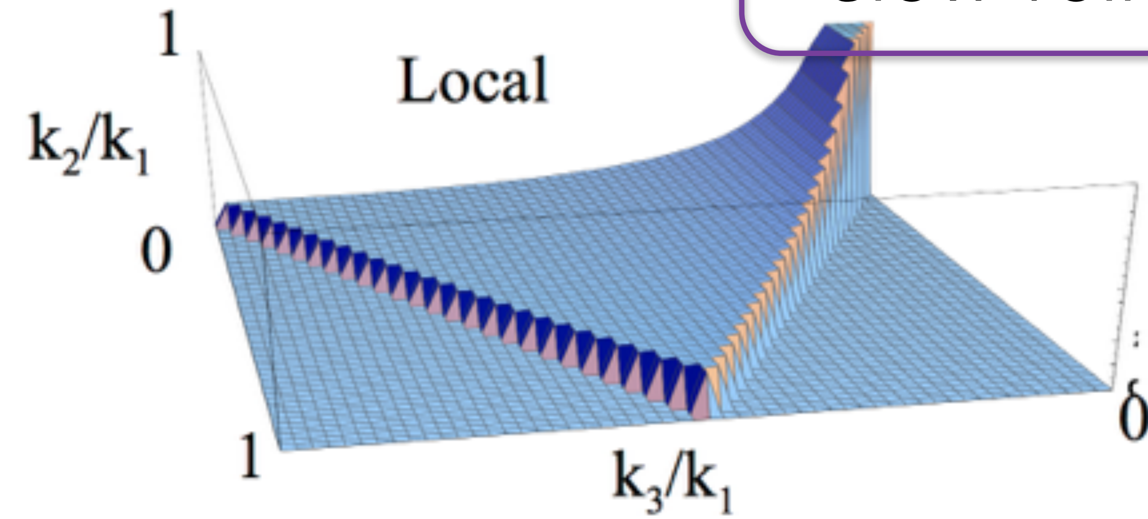
[Huang et.al. 1509.02676]

f_nl

2013

Shape & Method	f_{NL}(KSW) Independent	ISW-lensing subtracted
SMICA		
Local	9.8 ± 5.8	**2.7 ± 5.8**
Equilateral	−37 ± 75	**−42 ± 75**
Orthogonal	−46 ± 39	**−25 ± 39**

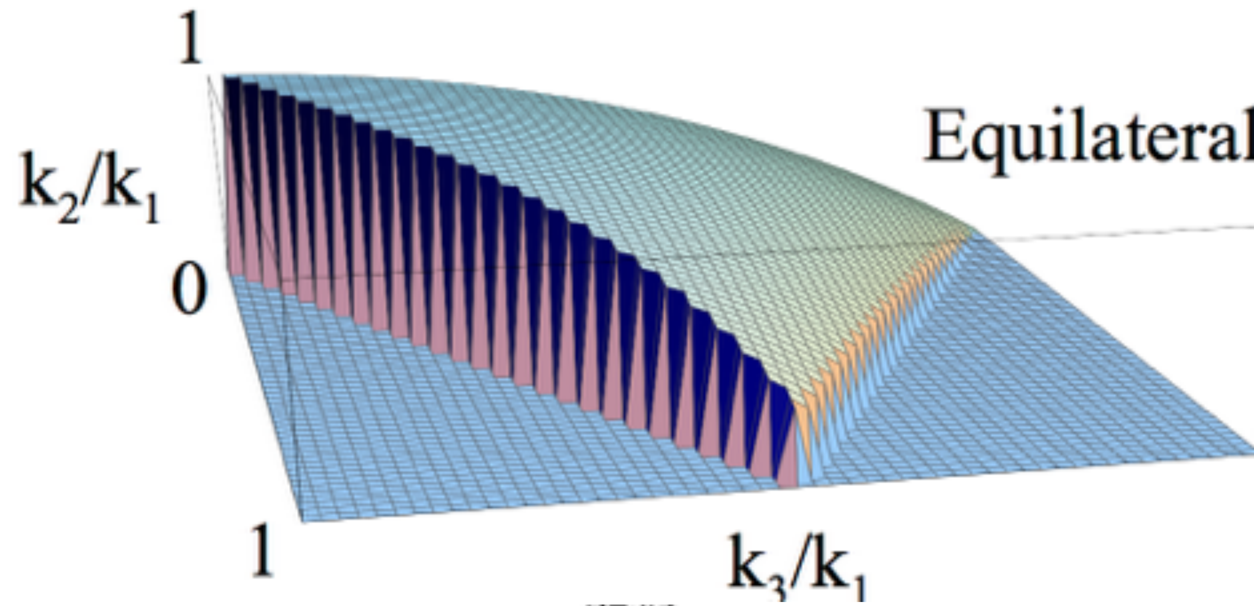
single field slow-roll

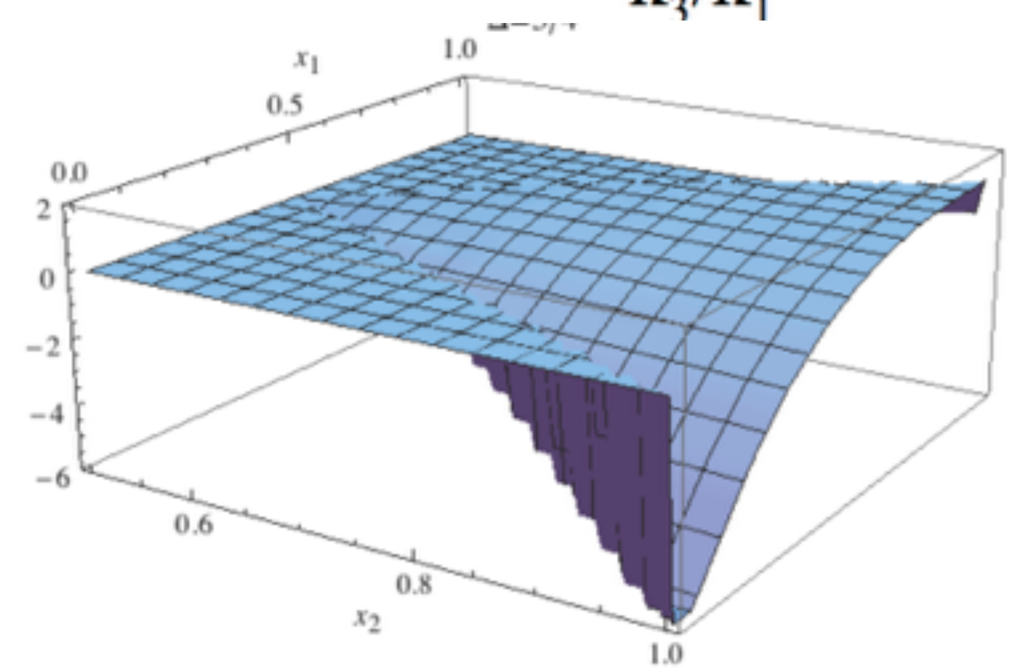


2015

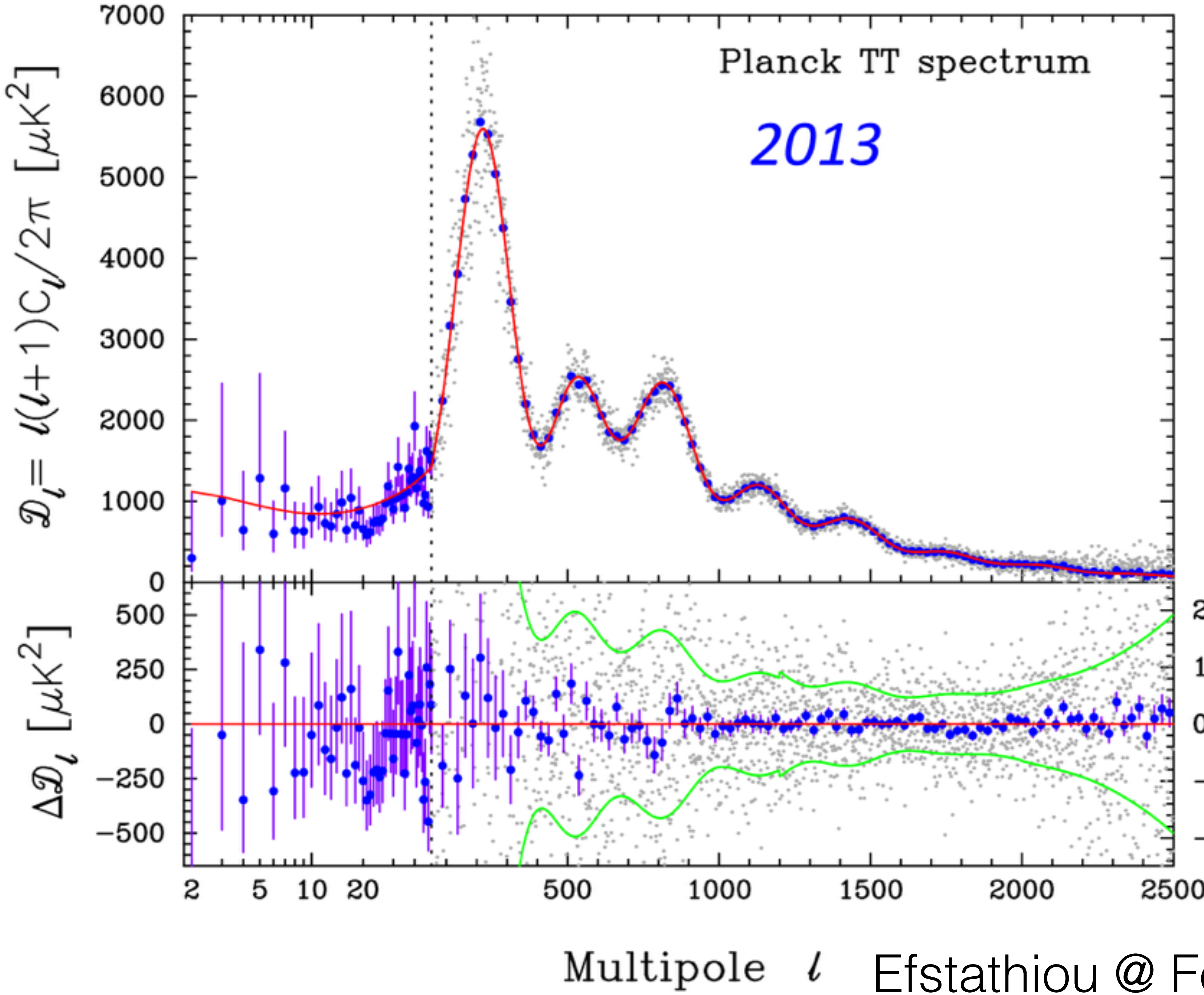
non-canonical kinetic, e.g. DBI

Shape and method	f_{NL}(KSW) Independent	ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

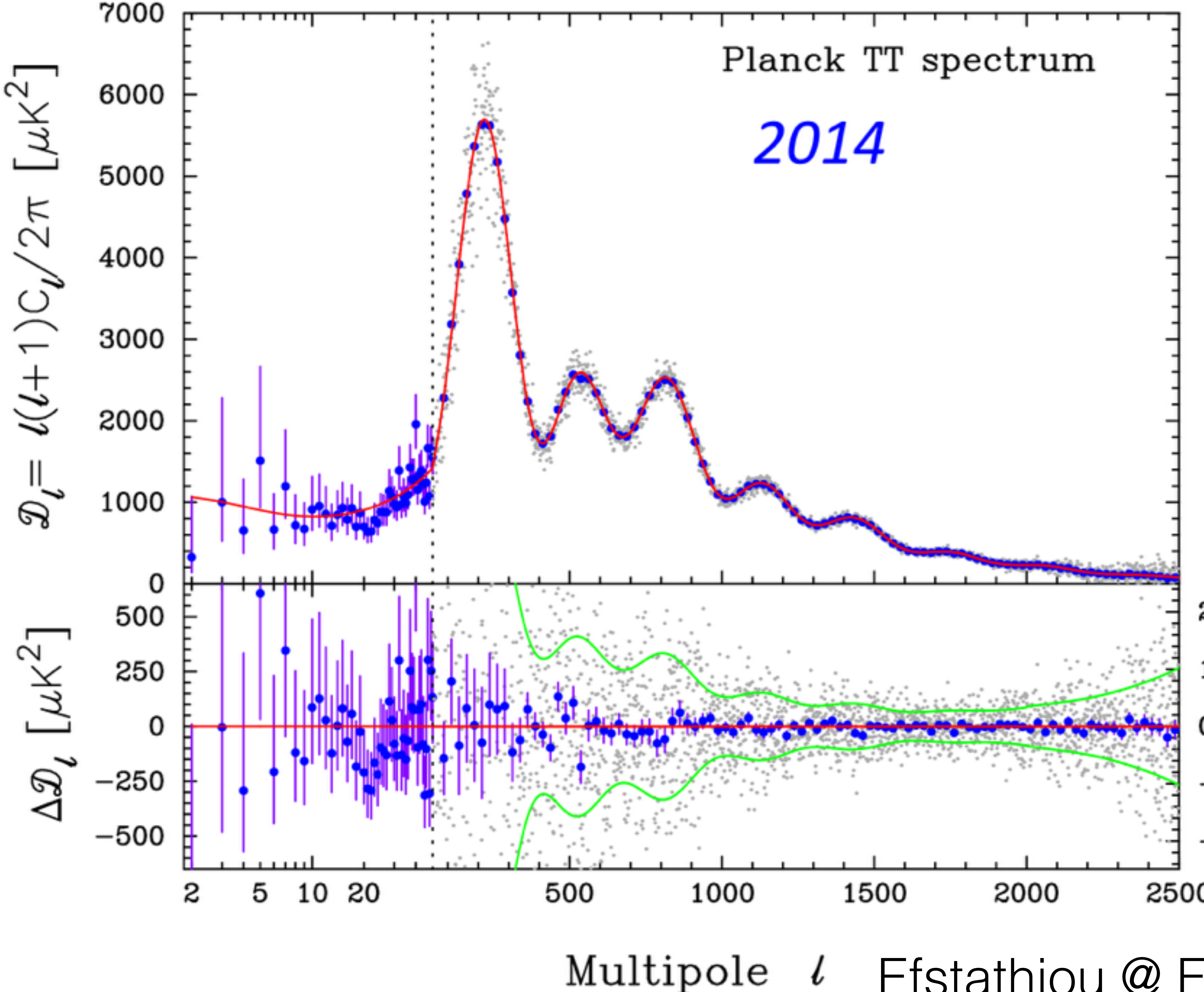




A_s



Efstathiou @ Ferrara



Efstathiou @ Ferrara

preliminary

1. As and tau

Absolute calibration:

1. Both 2013 and 2015 TT Planck likelihood code is composed by data from 100, 143, 217 GHz channels.

2. 2013 TT pipeline only calibrate 100 and 217 GHz relatively to 143 GHz channel, but fix the absolute amplitude in 143 GHz channel.

3. In 2015 pipeline, they do the same as 2013 for 100 and 217 GHz channel, but marginalise the absolute amplitude (y_p) in 143 GHz. This overall calibration uncertainty is then propagated to As*Exp(-2\tau), effective amplitude of TT spectrum.

$$C_\ell^{TT} \sim \boxed{A_s e^{-2\tau}} \int |\Delta_\ell(k)|^2 k^{n_s-1} d\log k$$

low tau: seems good news for warm DM. (have more time to form the structures before the formation of the star)

2013

$$\tau = 0.089 \pm 0.032 \quad (68\%; \textit{Planck}+\text{lensing}).$$

$$\tau = 0.078^{+0.019}_{-0.019}, \; z_{\rm re} = 9.9^{+1.8}_{-1.6}, \; \textit{Planck}\ \text{TT+lowP}; \tag{17a}$$

$$\tau = 0.070^{+0.024}_{-0.024}, \; z_{\rm re} = 9.0^{+2.5}_{-2.1}, \; \textit{Planck}\ \text{TT+lensing}; \tag{17b}$$

$$\tau = 0.066^{+0.016}_{-0.016}, \; z_{\rm re} = 8.8^{+1.7}_{-1.4}, \; \textit{Planck}\ \text{TT+lowP+lensing}; \tag{17c}$$

$$\tau = 0.067^{+0.016}_{-0.016}, \; z_{\rm re} = 8.9^{+1.7}_{-1.4}, \; \textit{Planck}\ \text{TT+lensing+BAO}; \tag{17d}$$

$$\tau = 0.066^{+0.013}_{-0.013}, \; z_{\rm re} = 8.8^{+1.3}_{-1.2}, \; \textit{Planck}\ \text{TT+lowP+lensing+BAO}. \tag{17e}$$

2015

Inflationary model

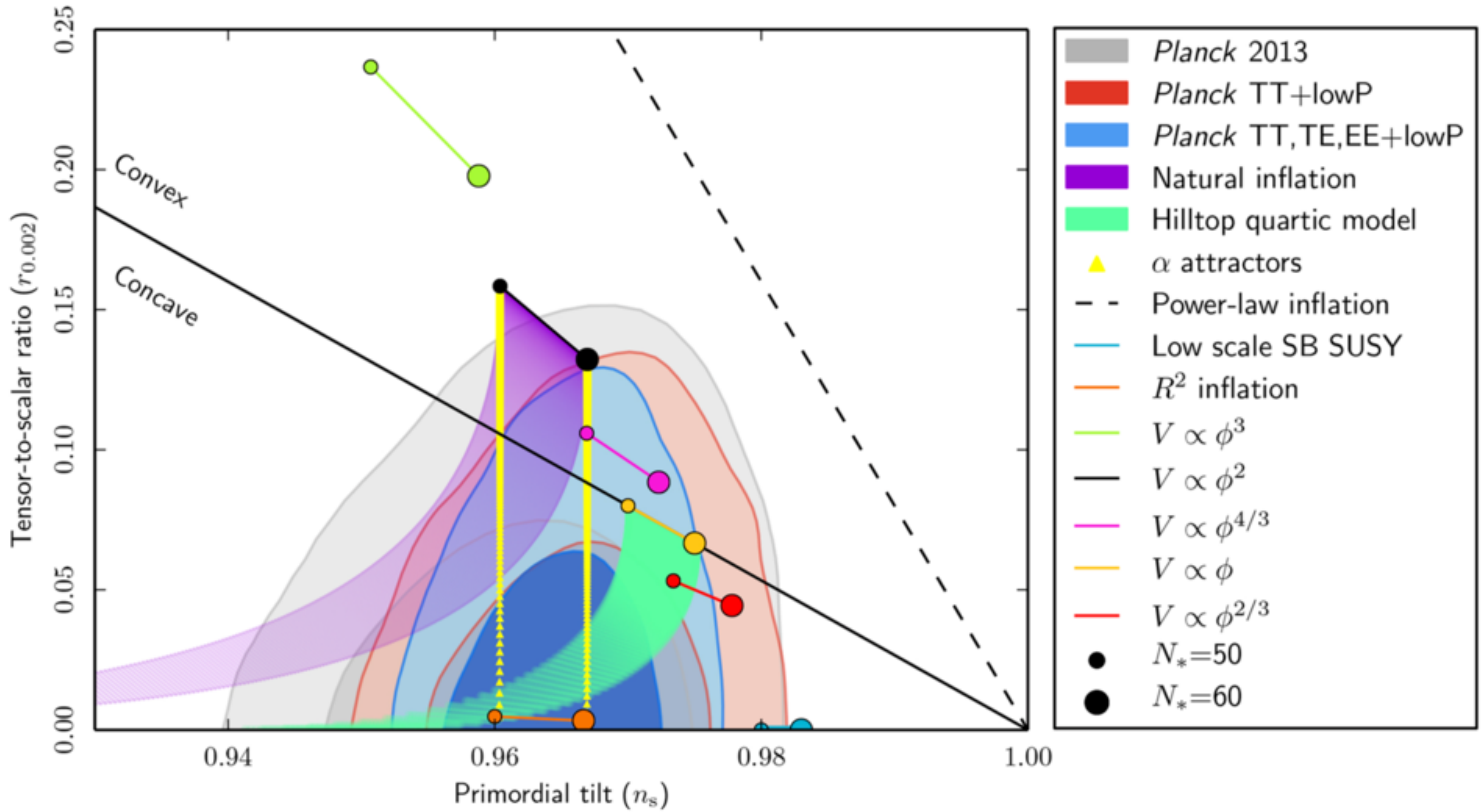


Fig. 12. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

r~16/N~0.1

Two classes of inflation

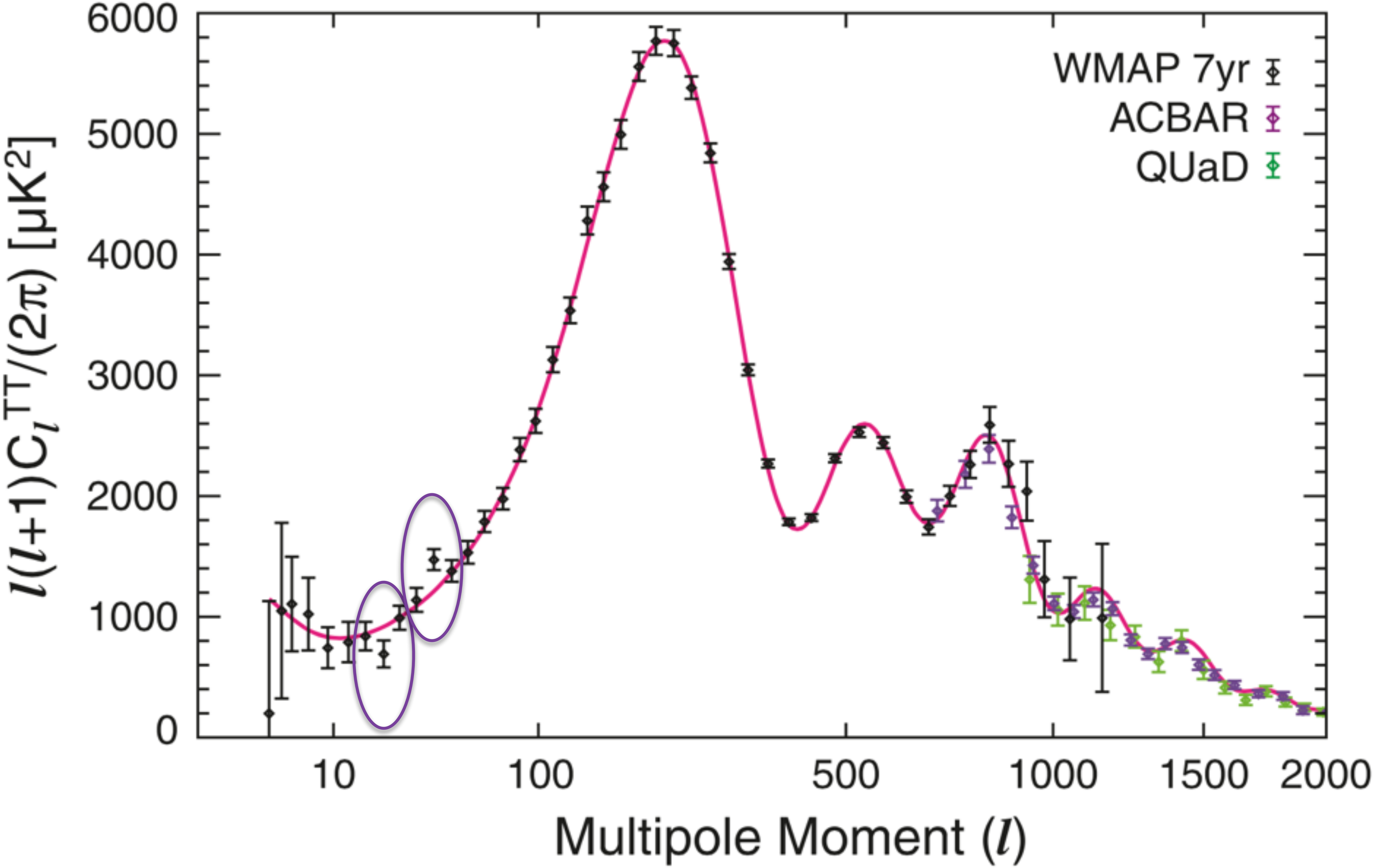
r~12/N^2~1E-3

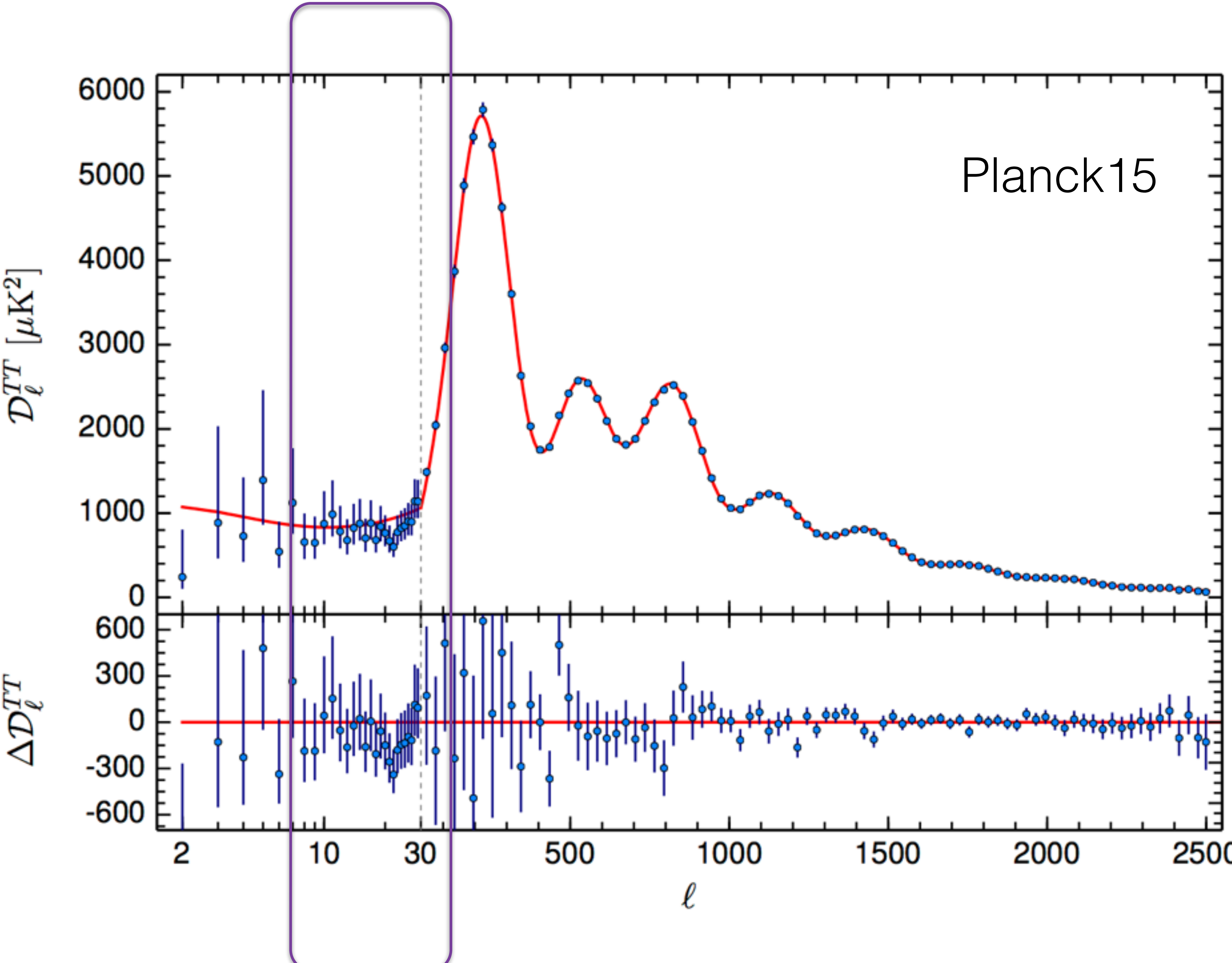
[D.Roest, JCAP 1401 (2014) 007]

Is this end of the story?

Features in Power Spectrum

low-ell anomaly

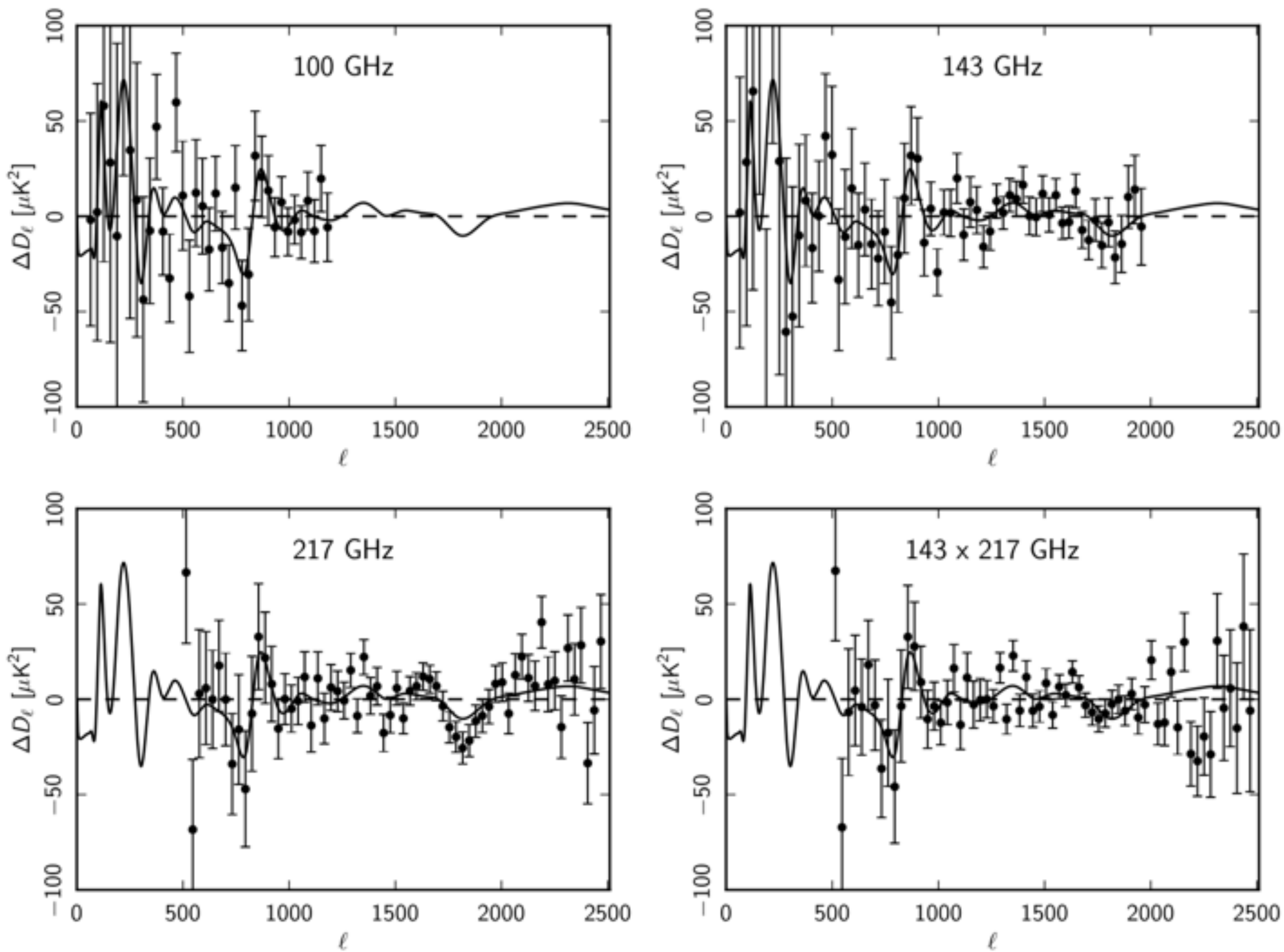

WMAP 7yr
ACBAR
QUaD
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
2000
Multipole Moment (l)
l(l+1)C_l^TT/(2π) [μK²]


Planck15
$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$
ℓ
6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500

- The low-ell anomaly, \ell~(20,40), is in the sky, not due to systematics!
- Are they primordial signal?
- But the significance is not strong enough, due to the cosmic variance.

1. Observational hints of oscillatory features

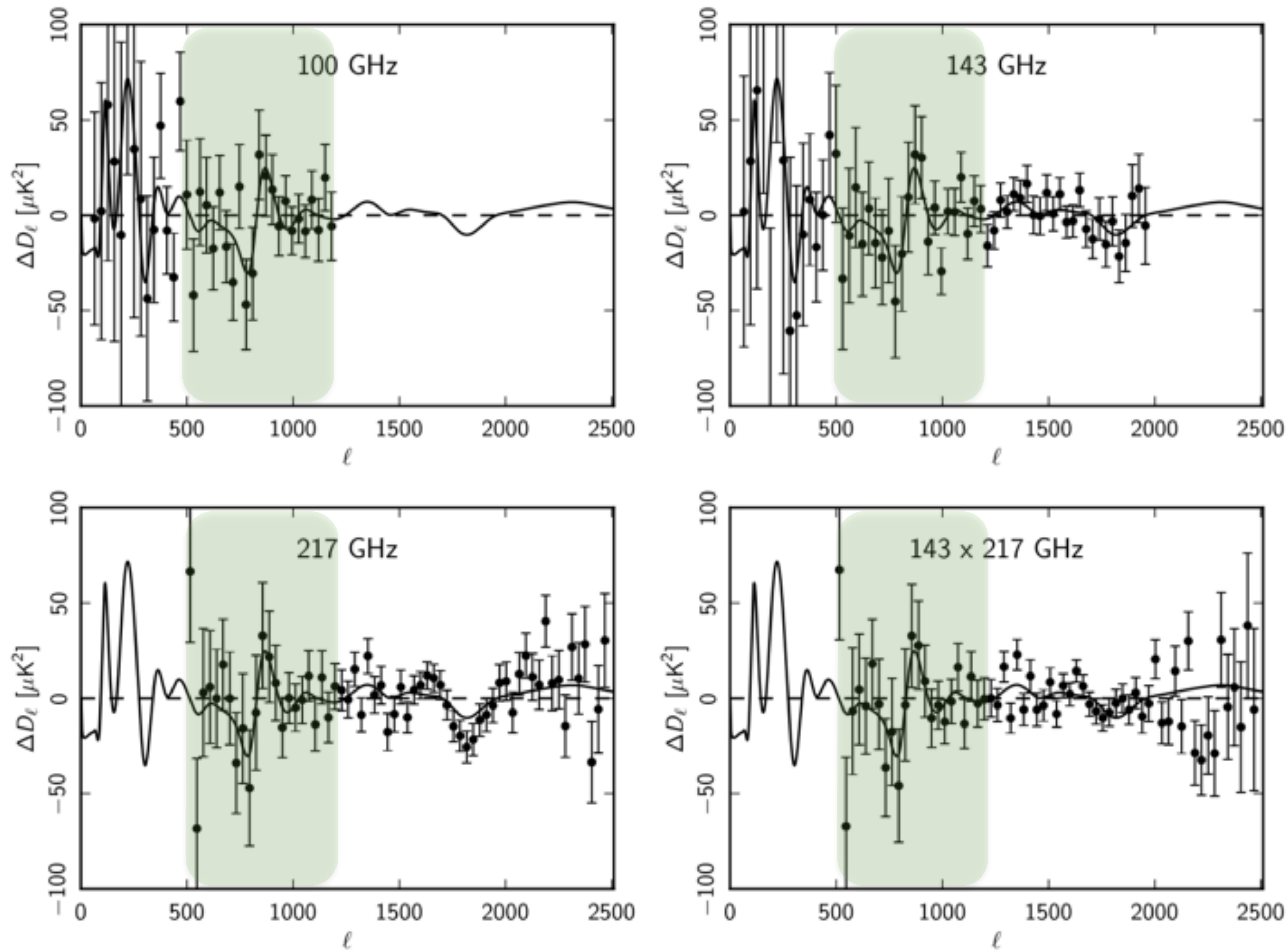
TT spectrum residual from best-fit LCDM model



[Planck-2013: XXII]

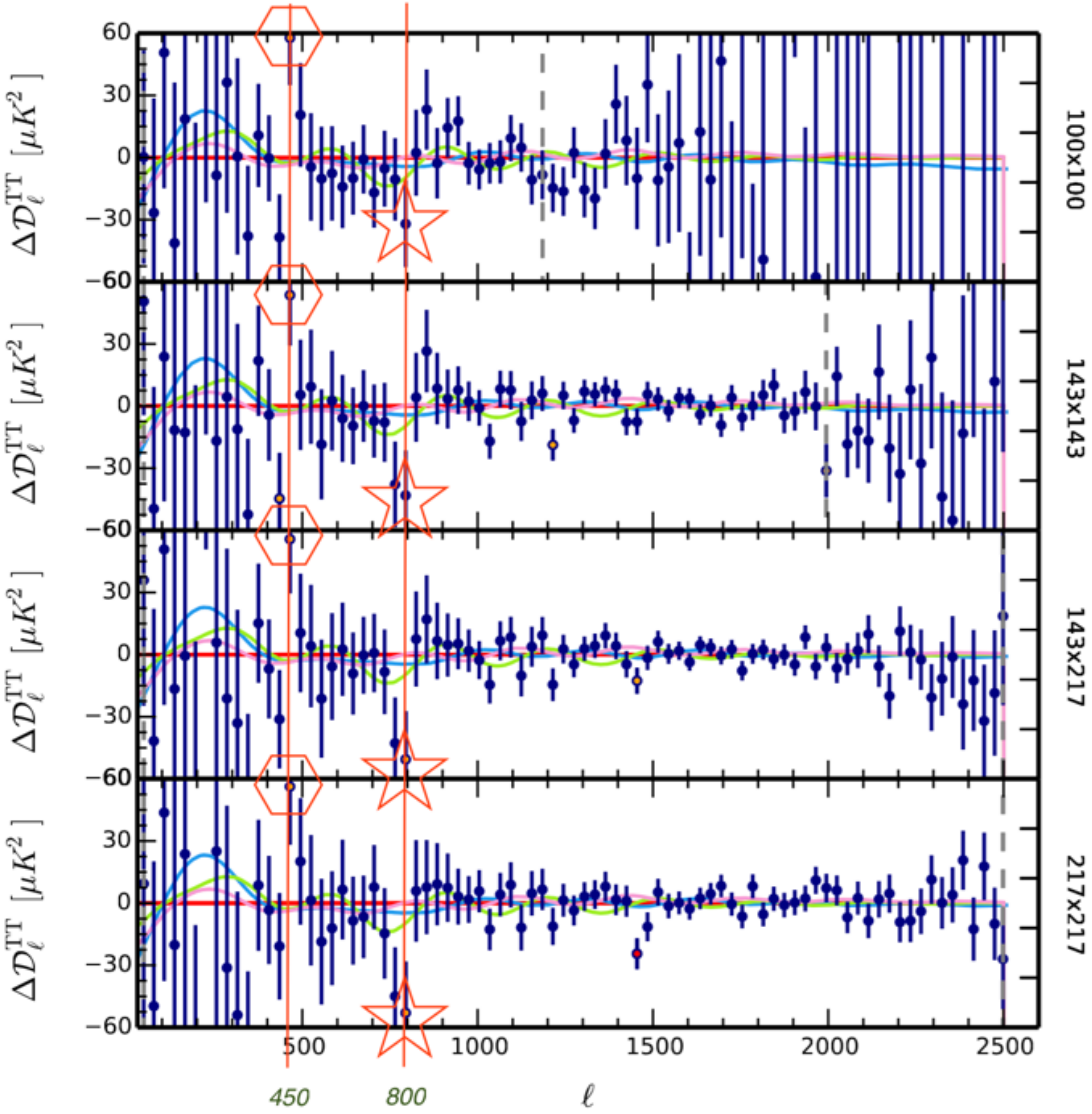
Spectrum residual from best-fit LCDM model

$$l \in (500, 1200)$$



Appears in all channels

2015



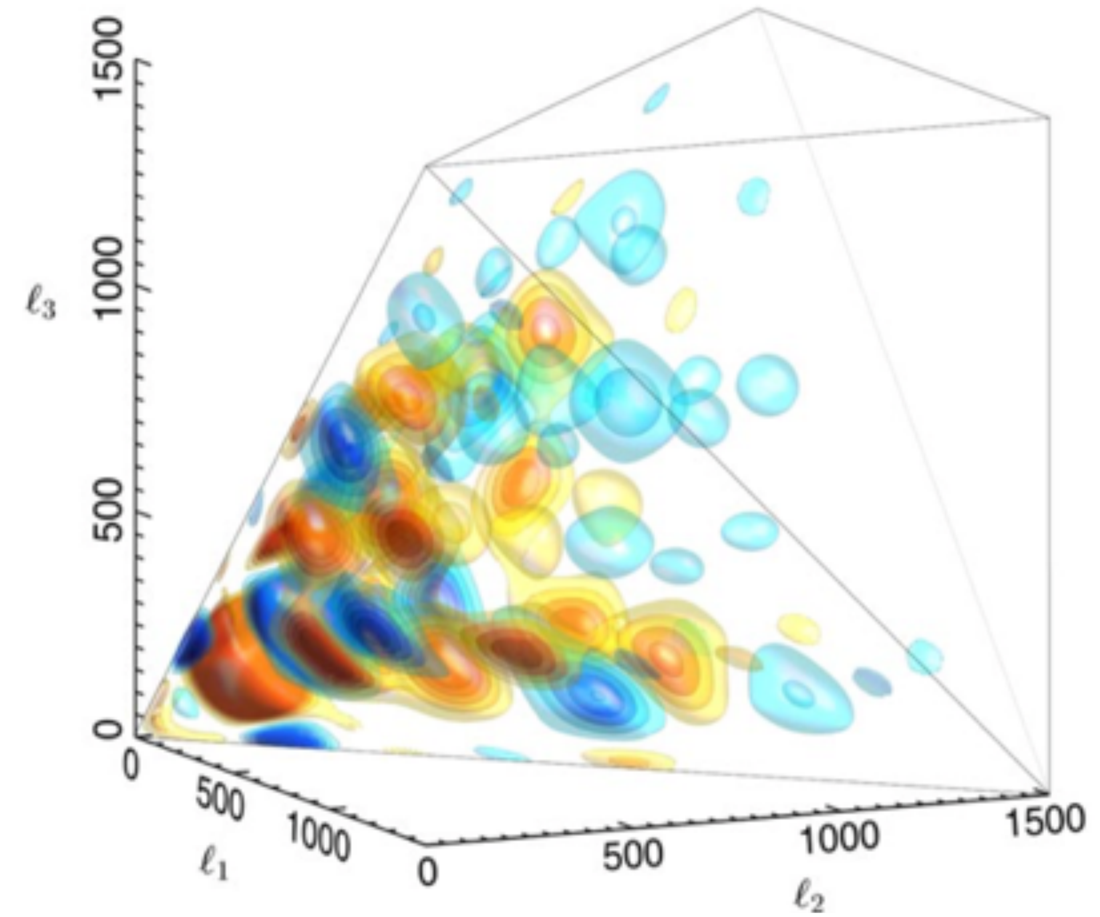
60
30
0
−30
−60
500
1000
1500
2000
2500
450
800
ℓ
$\Delta\mathcal{D}_\ell^{TT}\ [\mu K^2]$
100x100
143x143
143x217
217x217

Observational hints of oscillatory features

2. CMB bispectrum

$$B(k_1,k_2,k_3) = \frac{6A^2 f_{\rm NL}^{\rm feat}}{(k_1k_2k_3)^2} \sin\left(2\pi \frac{\sum_{i=1}^3 k_i}{3k_c} + \phi\right)$$

The best-fit template to the reconstructed CMB bisp
$\sim 3\sigma$ detection



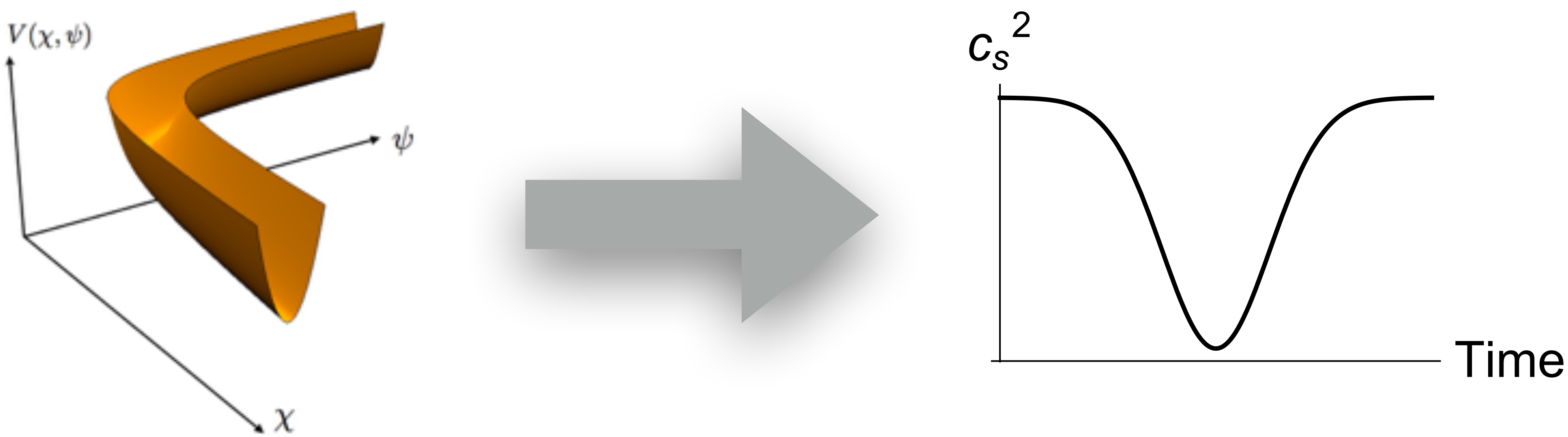
Wavenumber k_c; phase	$f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ) $\Delta k = 0.015$	$\Delta k = 0.03$	$\Delta k = 0.045$	Full
0.01125; $\phi = 0$	765 ± 275 (2.8)	703 ± 241 (2.9)	648 ± 218 (3.0)	434 ± 170 (2.6)
0.01750; $\phi = 0$	−661 ± 234 (−2.8)	−494 ± 192 (−2.6)	−425 ± 171 (−2.5)	−335 ± 137 (−2.4)
0.01750; $\phi = 3\pi/4$ . .	399 ± 207 (1.9)	438 ± 183 (2.4)	442 ± 165 (2.7)	366 ± 126 (2.9)
0.01875; $\phi = 0$	−562 ± 211 (−2.7)	−559 ± 180 (−3.1)	−515 ± 159 (−3.2)	−348 ± 118 (−3.0)
0.01875; $\phi = \pi/4$ . . .	−646 ± 240 (−2.7)	−525 ± 189 (−2.8)	−468 ± 164 (−2.9)	−323 ± 120 (−2.7)
0.02000; $\phi = \pi/4$ . . .	−665 ± 229 (−2.9)	−593 ± 185 (−3.2)	−500 ± 160 (−3.1)	−298 ± 119 (−2.5)

[Planck-2013: XXIV]

2. Models with a transient reduction of the speed of sound

Two field model: $$S = \int d^4x \sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}g^{\mu\nu}\gamma_{ab}\partial_\mu\phi^a\partial_\nu\phi^b - V(\phi)\right]$$

Assumption: 1 light & 1 heavy fields



derivative coupling, e.g. $\dot{\phi}_1\phi_2$ => a turn

EFT for inflation: $$\phi^a(t,\boldsymbol{x}) = \phi_0^a(t+\pi) + N^a(t+\pi)\mathcal{F}$$

light adiabatic heavy isocurvature

[C. Cheung et. al. JHEP 0803 (2008) 014]
[S. Weinberg Phys.Rev. D77 (2008) 123541]
[A. Achucarro et. al. JHEP 1205 (2012) 066]

After Integrating out heavy field

effective action for light field:

$$S_{\rm eff} = -\int d^4x \, a^3 M_{\rm pl}^2 \dot{H} \left\{ \dot{\pi}^2 - \frac{(\nabla\pi)^2}{a^2} + (c_s^{-2}-1)\dot{\pi}^2 + (c_s^{-2}-1)\,\dot{\pi}\left[\dot{\pi}^2 - \frac{(\nabla\pi)^2}{a^2}\right] + (c_s^{-2}-1)^2\frac{\dot{\pi}^3}{2} - 2\frac{\dot{c}_s}{c_s^3}\pi\dot{\pi}^2 + \cdots \right\}$$

slow roll sound speed

Primordial sprectrum: $\mathcal{P}_{\mathcal{R}} \propto \mathcal{O}(\epsilon) + \mathcal{O}\left(\epsilon(1-c_s^{-2})\right)$ sub-leading

Primordial bispectrum: $\mathcal{B} \propto \mathcal{O}\left(\frac{\dot{c}_s}{Hc_s}\right) + \mathcal{O}(\epsilon)$ leading

$$\epsilon \sim \mathcal{O}(0.01) \qquad 1 - c_s^{-2} \sim \mathcal{O}(0.1) \qquad \frac{\dot{c}_s}{Hc_s} \sim \mathcal{O}(0.1)$$

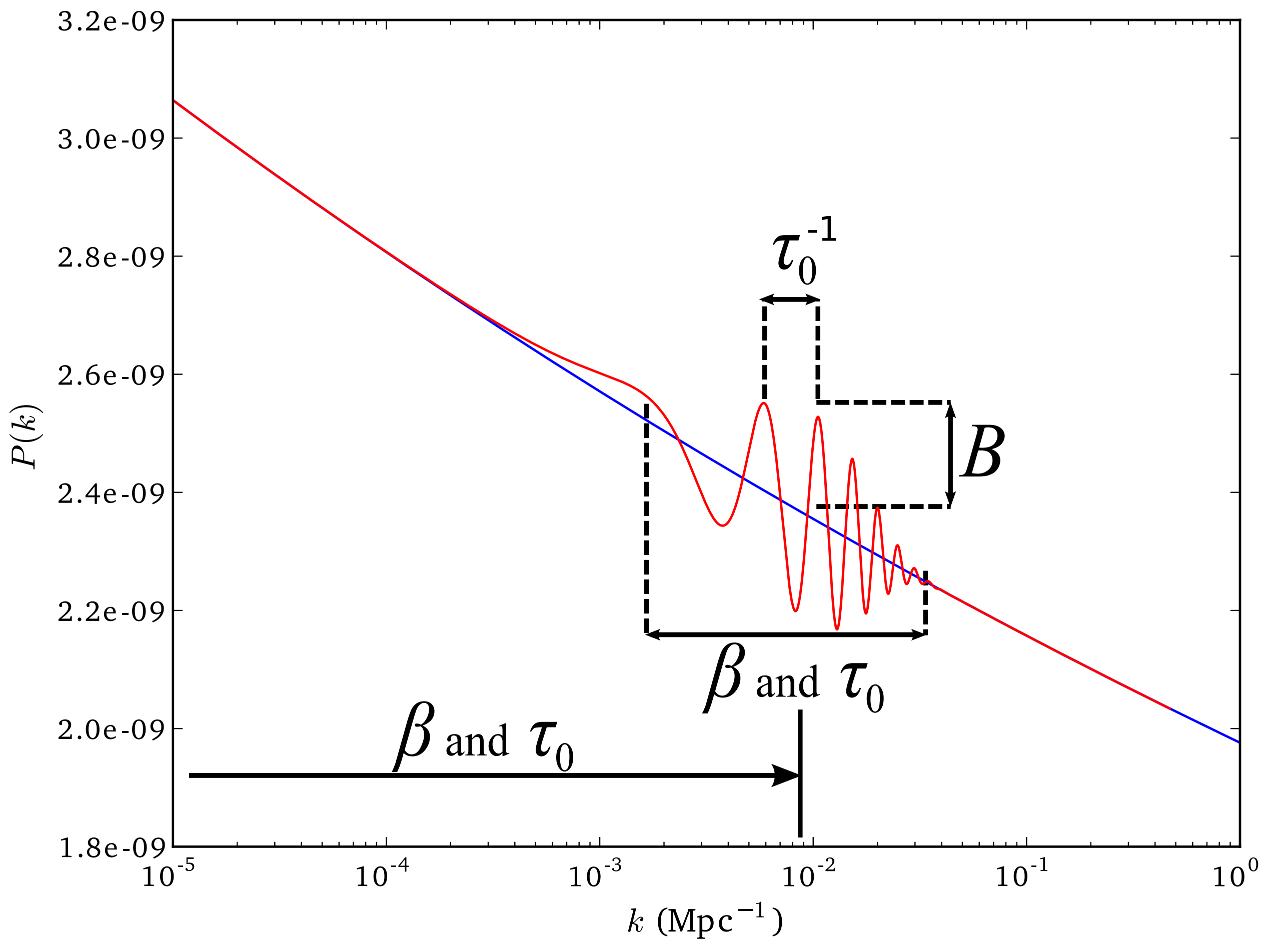
Do NOT interrupt slow roll condition!

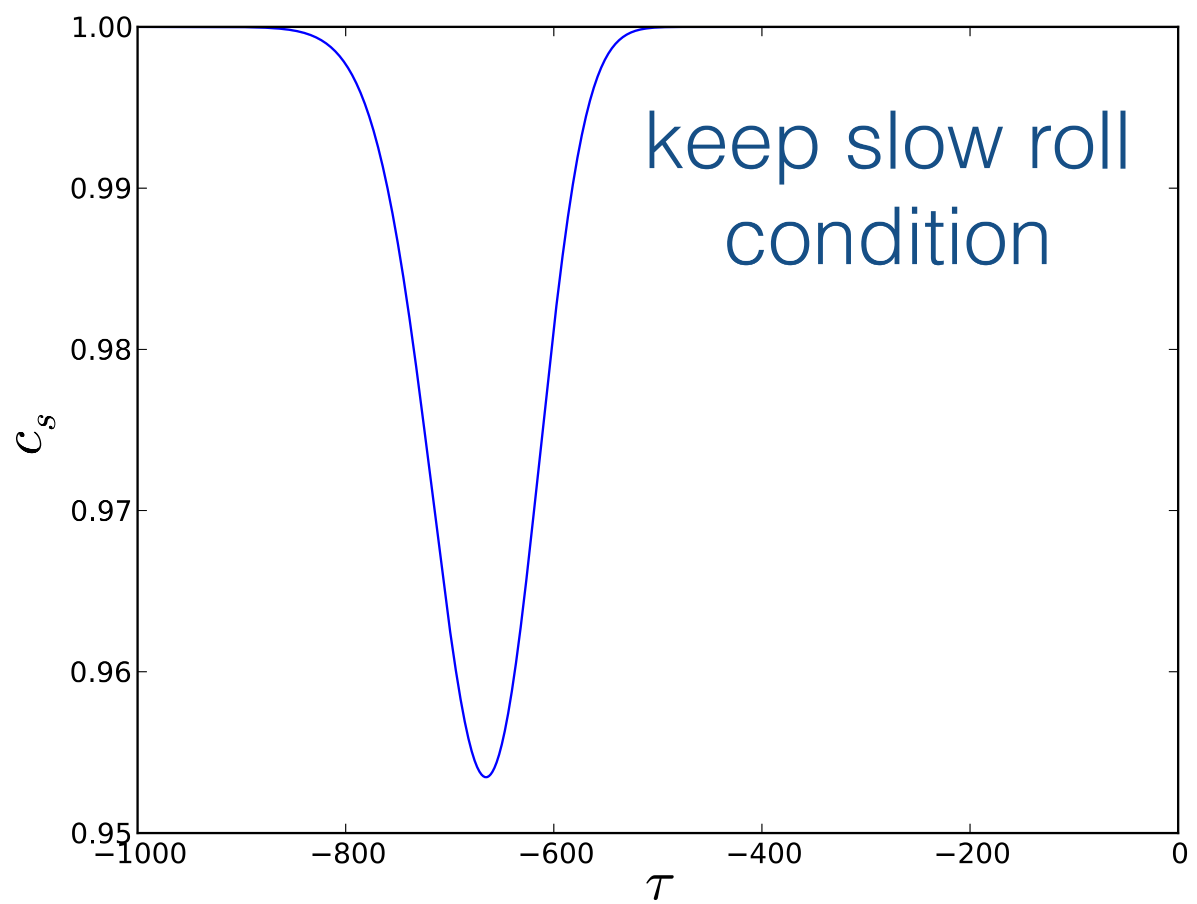
Oscillatory features in the transient sound speed reduction models— Power spectrum

$$\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}}}(k) = k\int_{-\infty}^{0} d\tau\,\left(1-c_s^{-2}\right)\sin(2k\tau)$$

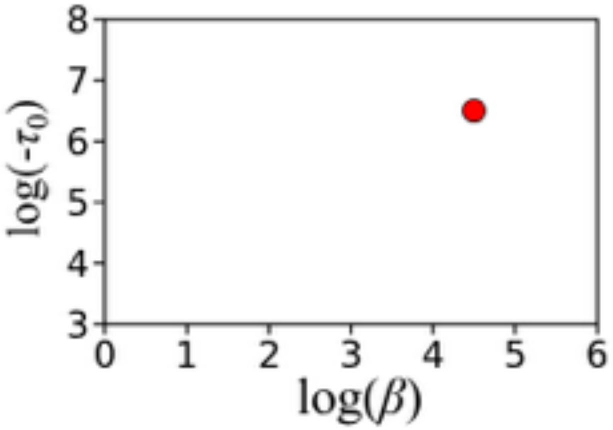
Gaussian reduction in e-folds [A.Achucarro et. al. PRD 89 (2014) 103006]

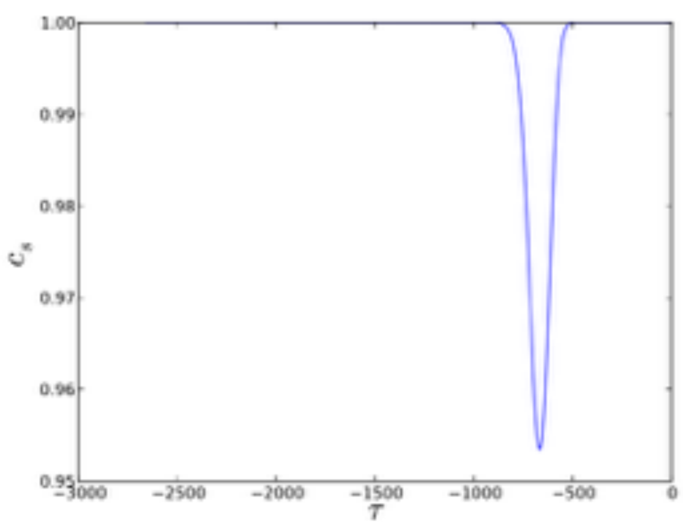
$$1-c_s^{-2} = Be^{-\beta\left(\log\frac{\tau}{\tau_0}\right)^2}$$

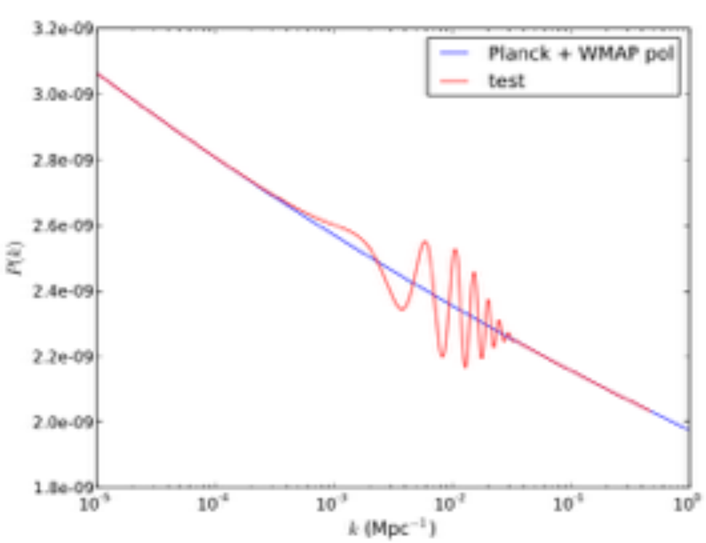


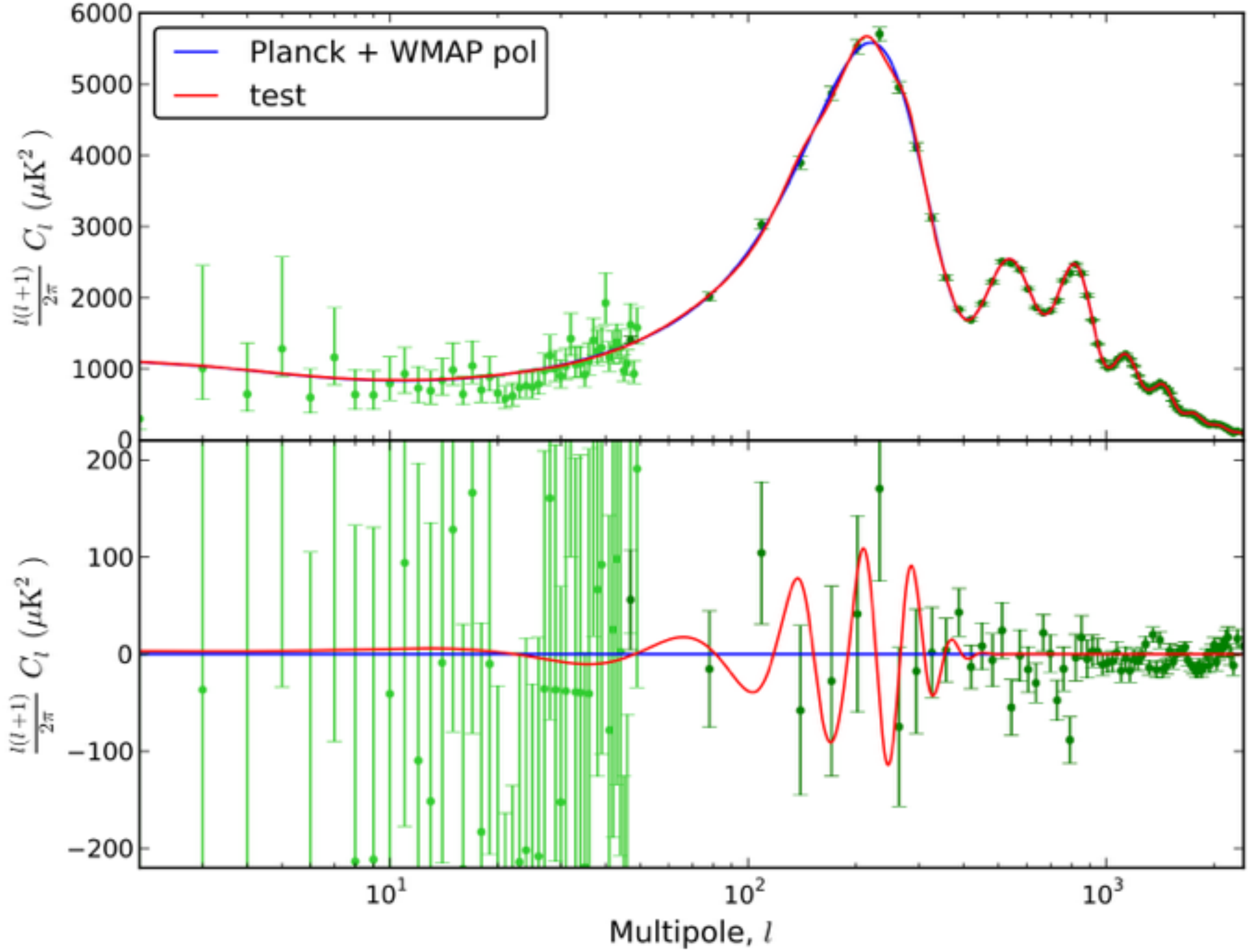


Some examples ($B = -0.1$)









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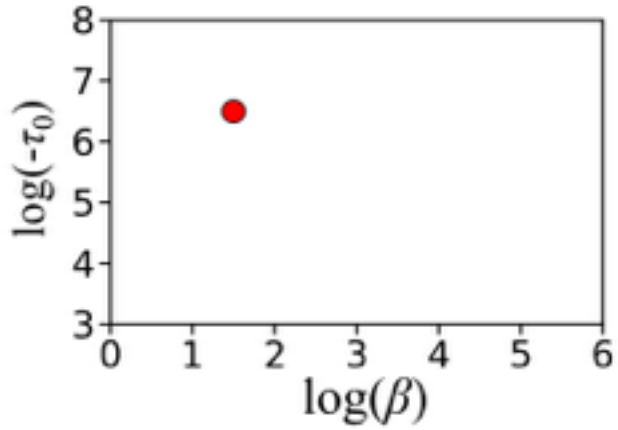

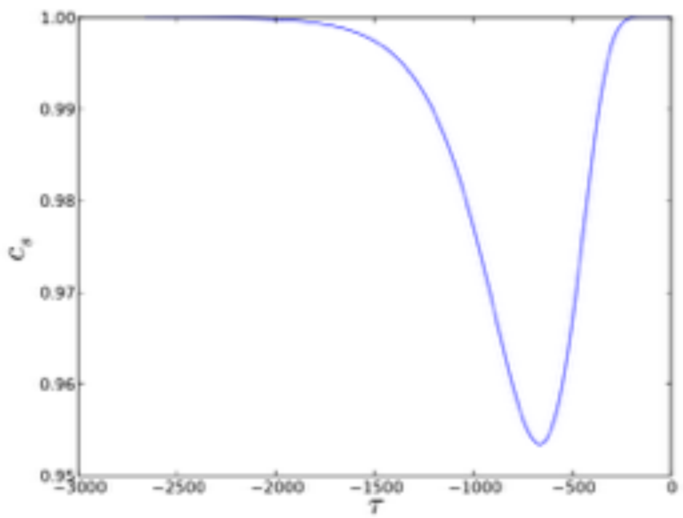

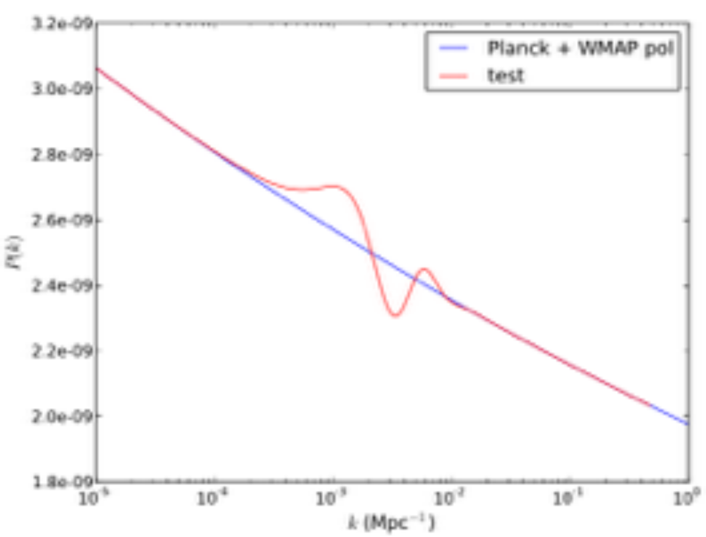

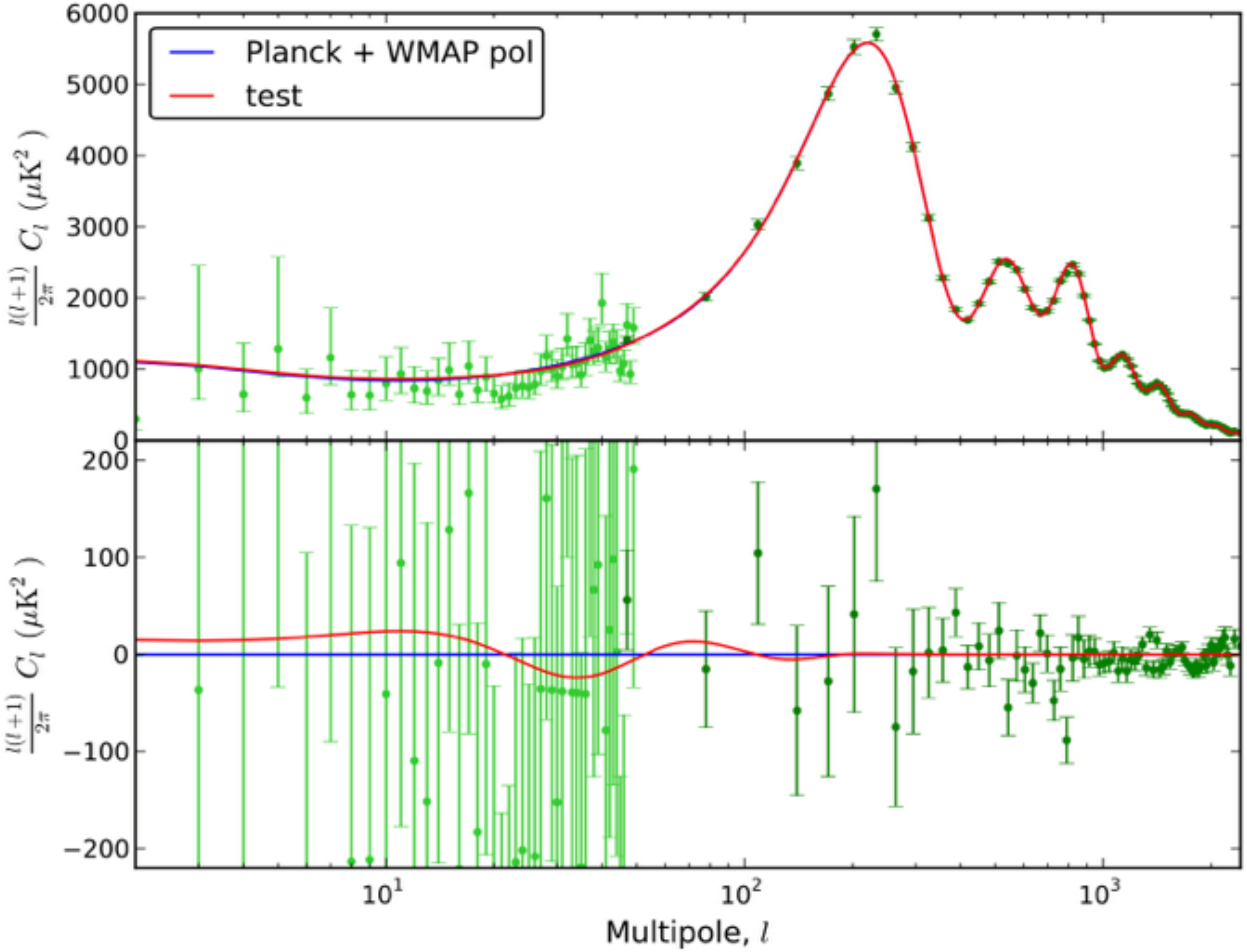

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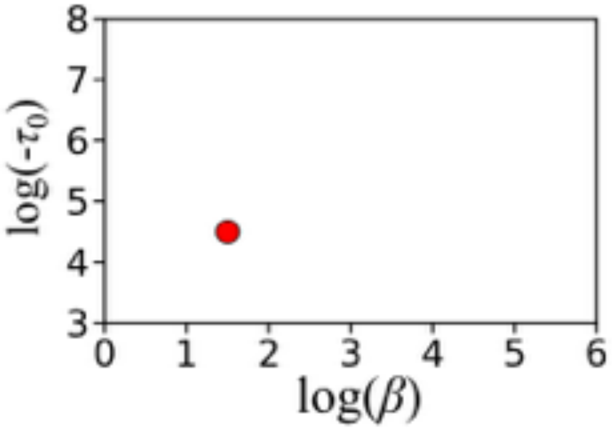

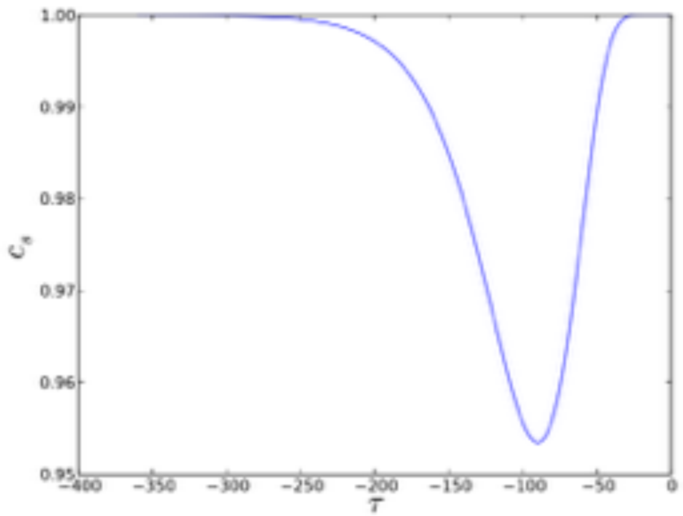

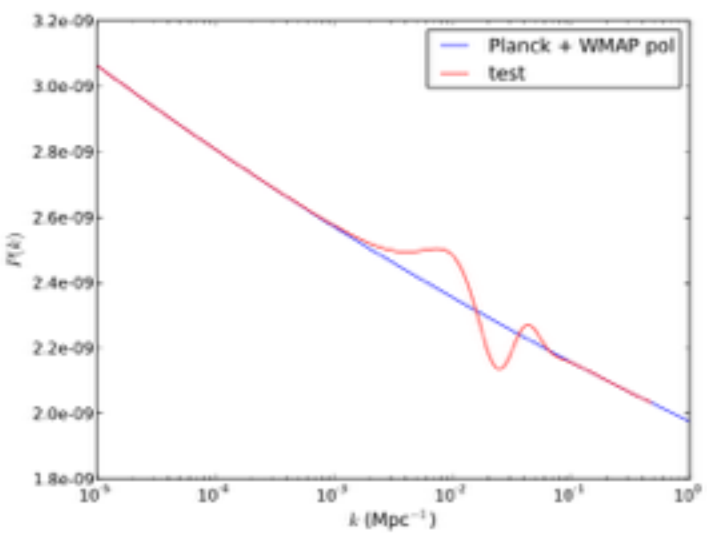

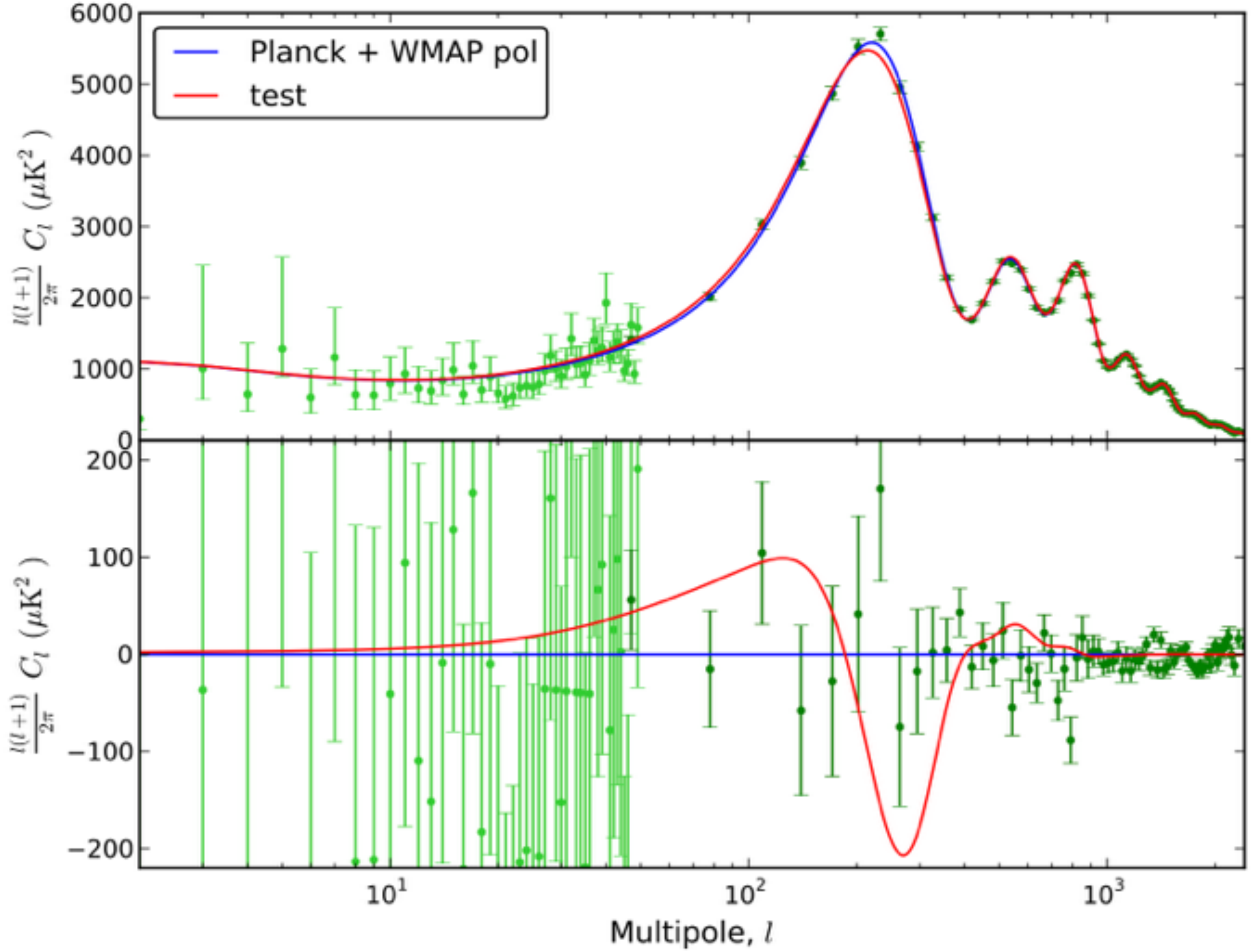

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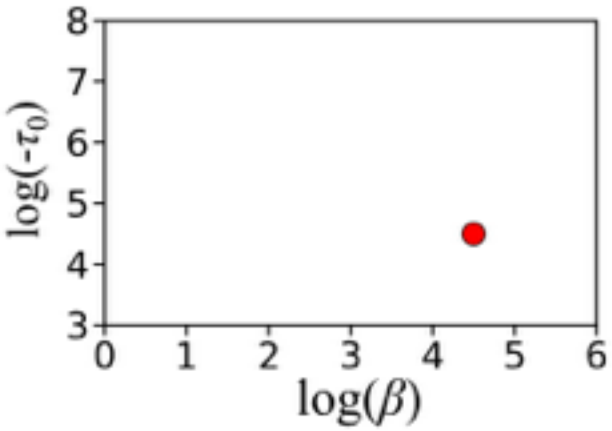
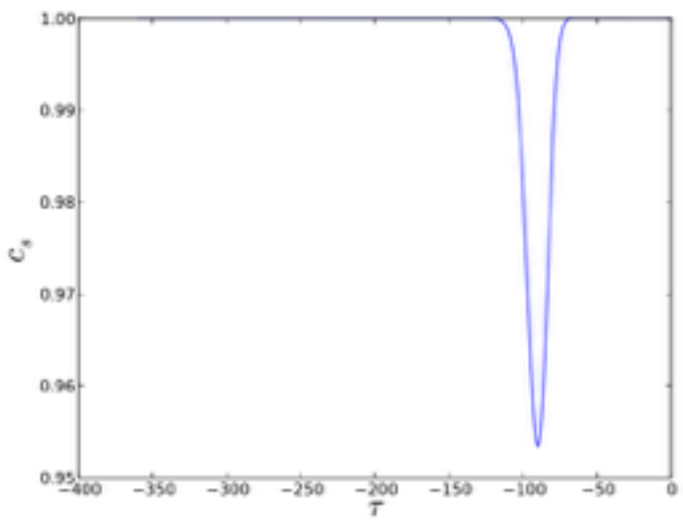
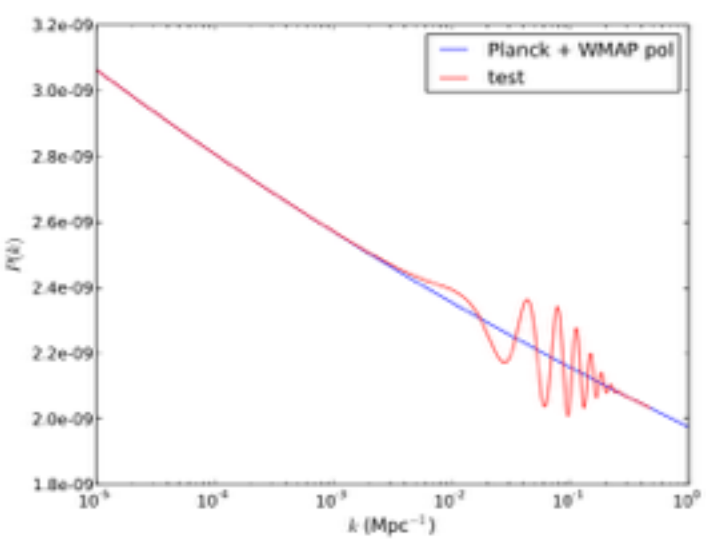
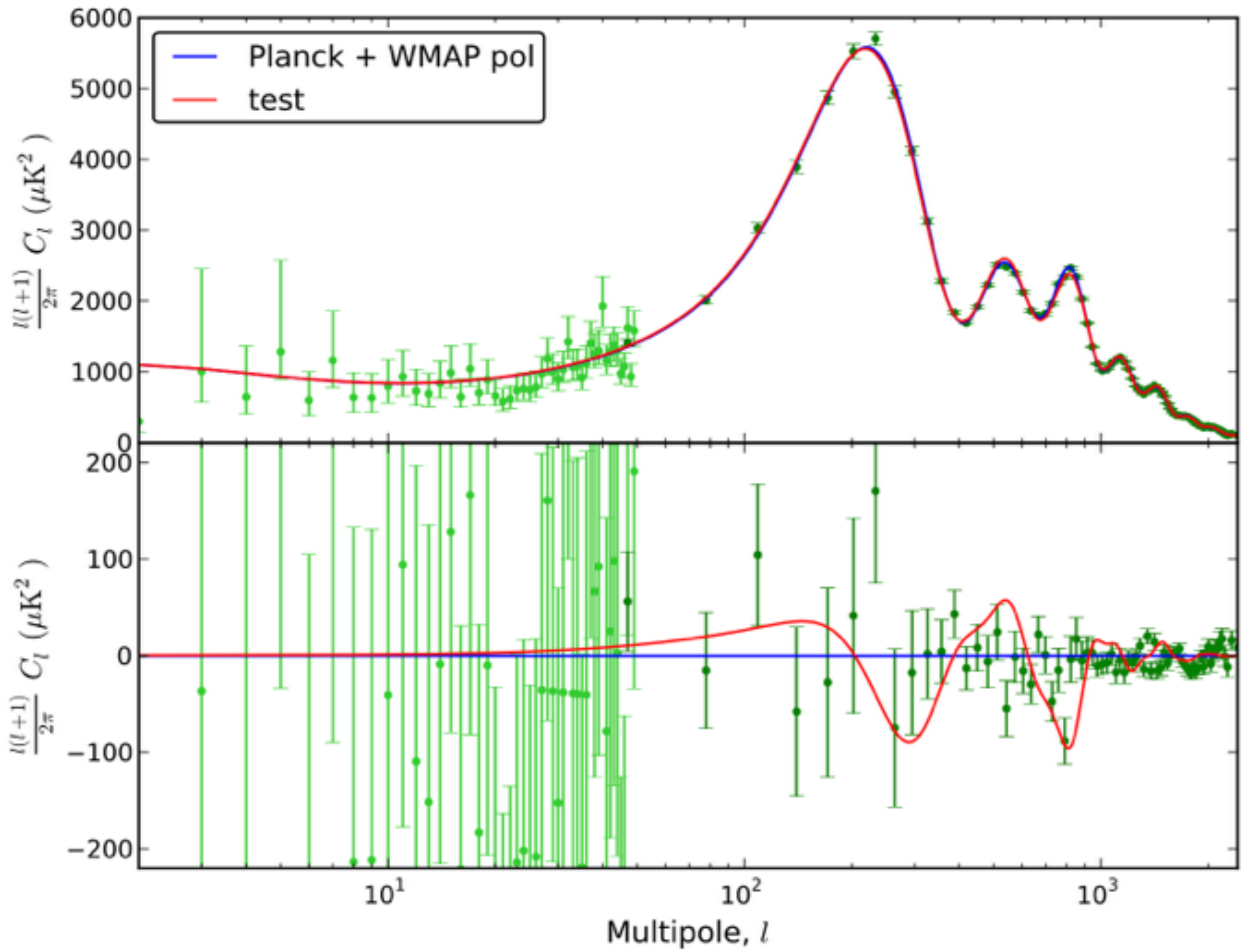
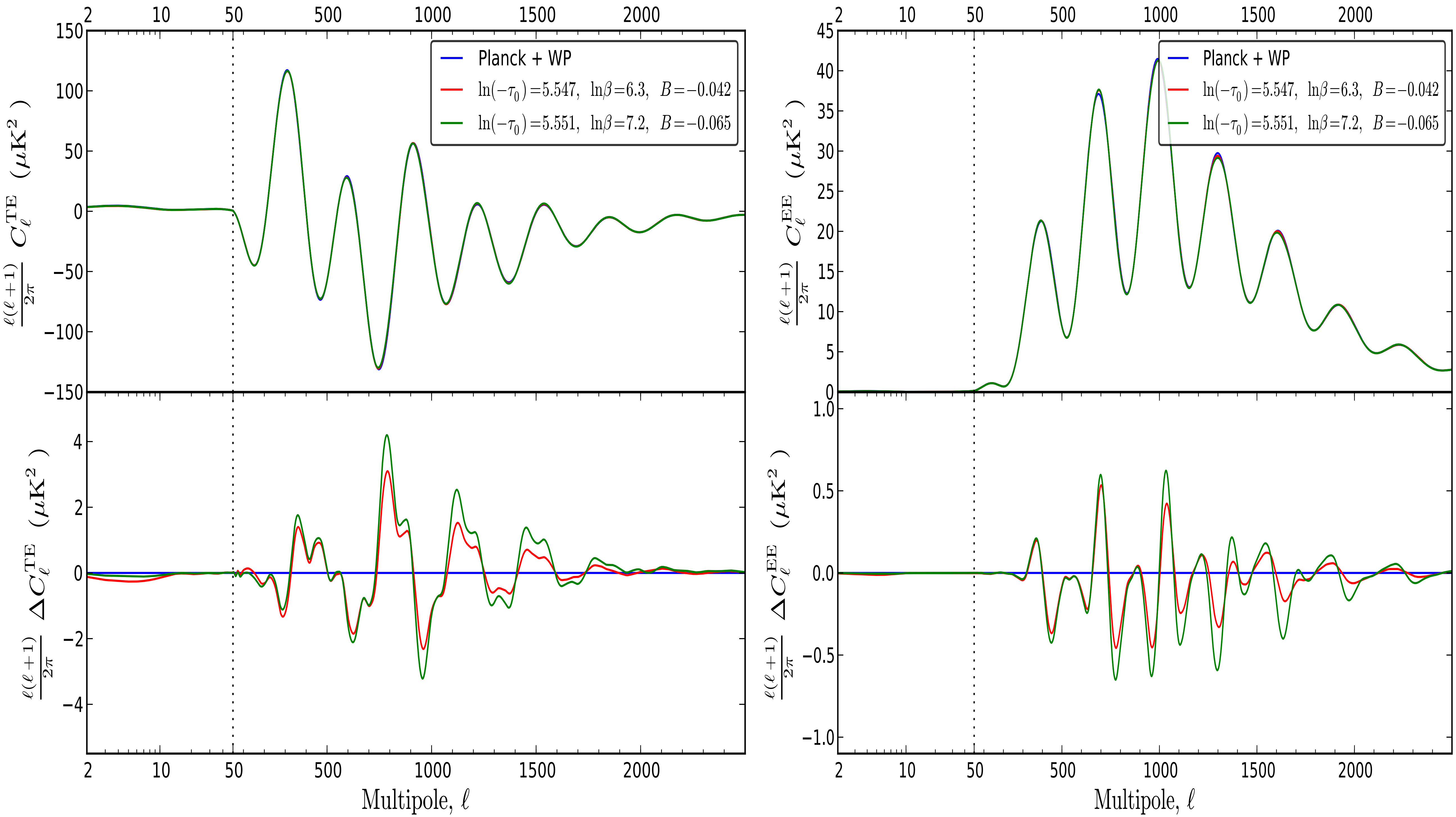










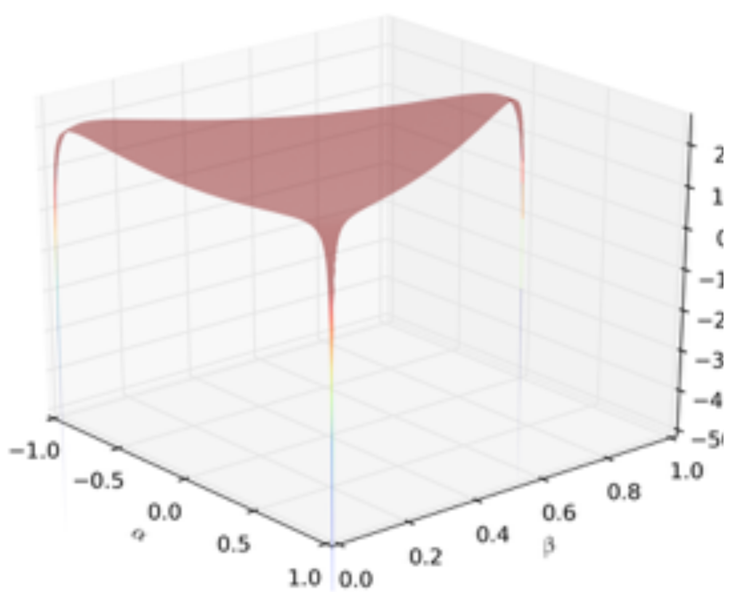
Planck + WP
$\ln(-\tau_0)=5.547,\ \ln\beta=6.3,\ B=-0.042$
$\ln(-\tau_0)=5.551,\ \ln\beta=7.2,\ B=-0.065$
$\frac{\ell(\ell+1)}{2\pi}\ C_\ell^{\rm TE}\ (\mu{\rm K}^2)$
$\frac{\ell(\ell+1)}{2\pi}\ \Delta C_\ell^{\rm TE}\ (\mu{\rm K}^2)$
$\frac{\ell(\ell+1)}{2\pi}\ C_\ell^{\rm EE}\ (\mu{\rm K}^2)$
$\frac{\ell(\ell+1)}{2\pi}\ \Delta C_\ell^{\rm EE}\ (\mu{\rm K}^2)$
Multipole, ℓ
Multipole, ℓ

~ 10% effect

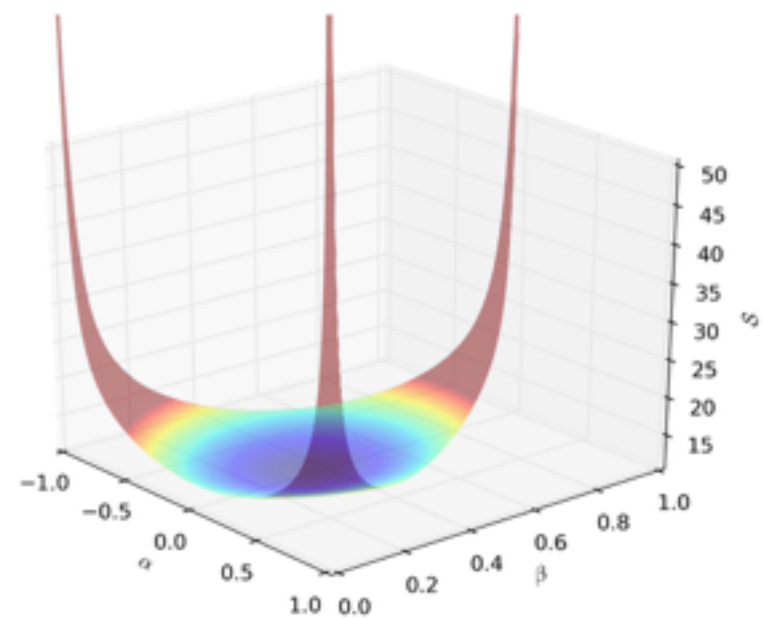
2. Primordial Bispectrum (leading order)

$$\mathcal{D}_s(K) = -\sqrt{\frac{\pi}{\beta}}2K\tau_0 \exp\left(-\frac{K^2\tau_0^2}{4\beta}\right)\ ,\ K = k_1+k_2+k_3$$

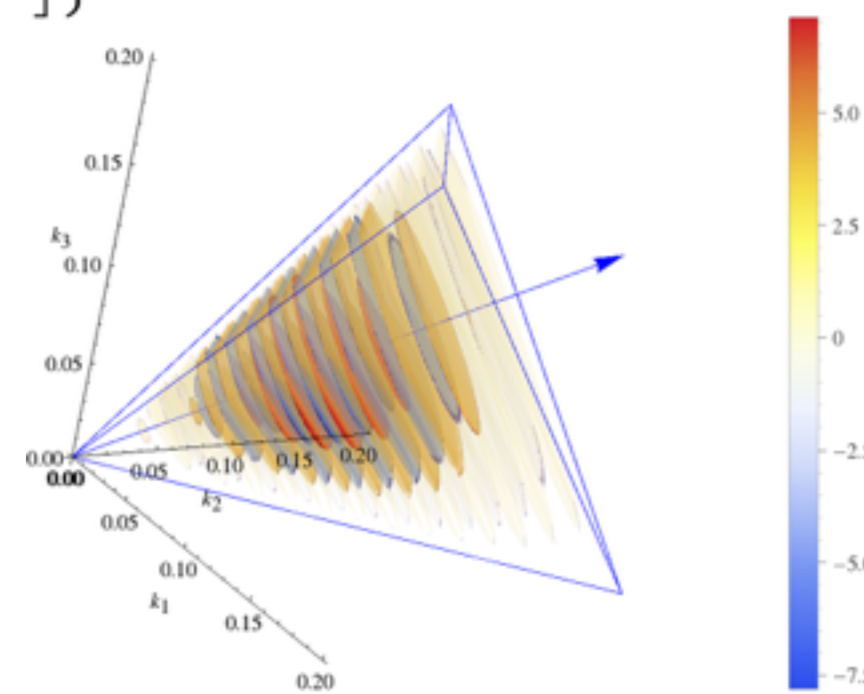
$$B(k_1,k_2,k_3) = \frac{6\Delta_\phi^2}{k_1^2k_2^2k_3^2}\frac{(2\pi)^4}{96}\frac{|B|\mathcal{D}_s(K)k_1^2}{k_1k_2k_3}$$
$$\left\{\tau_0\cos(\tau_0 K)\left[k_2(k_1-k_3)+\frac{\tau_0^2}{2\beta}Kk_2k_3\left(\frac{3}{2}k_1-k_2\right)-\frac{1}{2\beta}\left(\frac{1}{2}k_1^2-k_2^2\right)\right]\right.$$
$$\left.+\sin(\tau_0K)\left[\frac{1}{2}\tau_0^2k_1k_2k_3-\frac{1}{K}\left(\frac{1}{2}k_1^2-2k_2^2\right)-\frac{\tau_0^2}{2\beta}k_2\left(2k_1^2-k_2k_3\right)\right]\right\}+5\ \text{perm.}$$



$K=0.19$



$K=0.21$

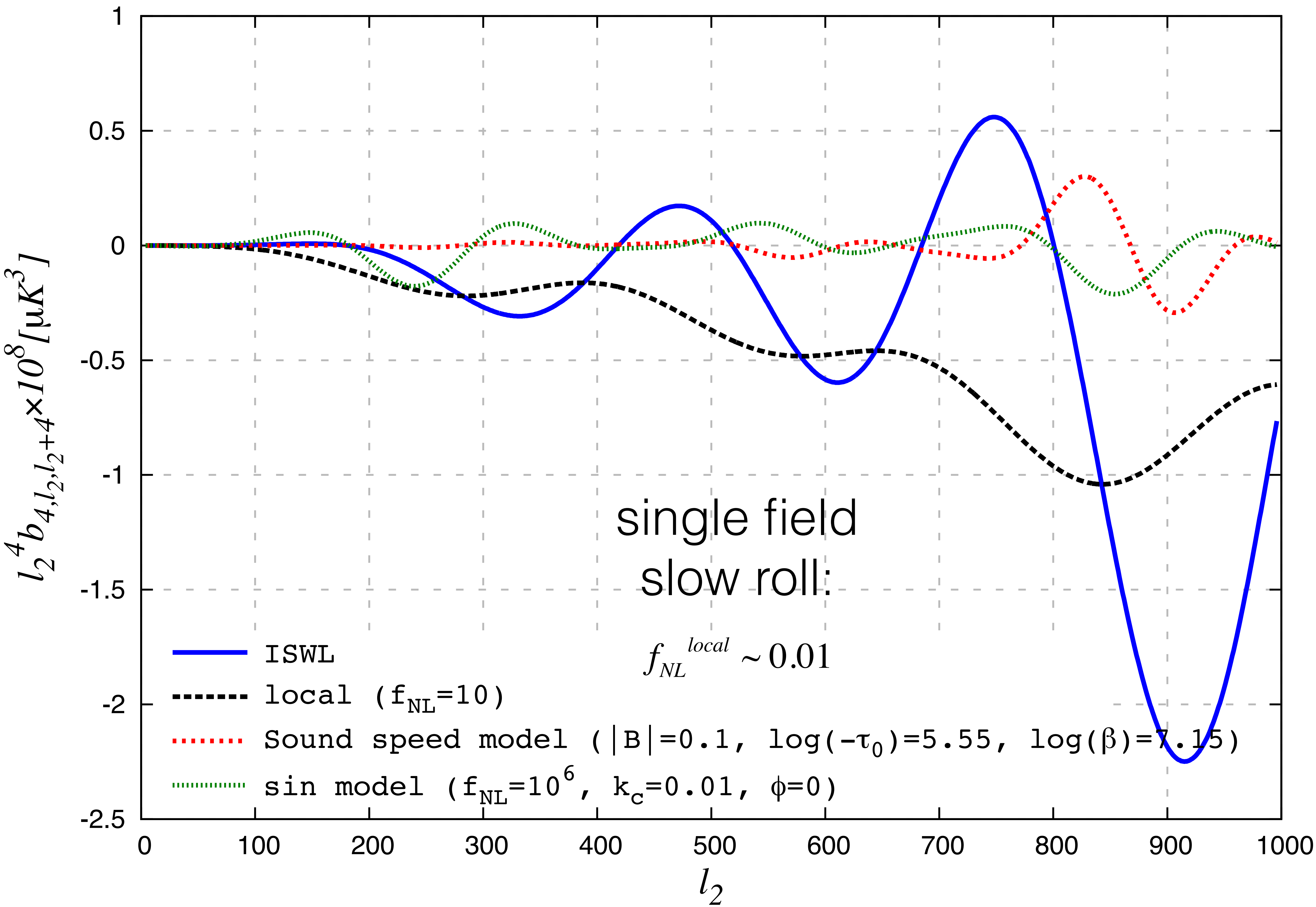


removing $\frac{1}{k_1^3k_2^3}+\frac{1}{k_1^3k_3^3}+\frac{1}{k_2^3k_3^3}$

Step in sound speed:

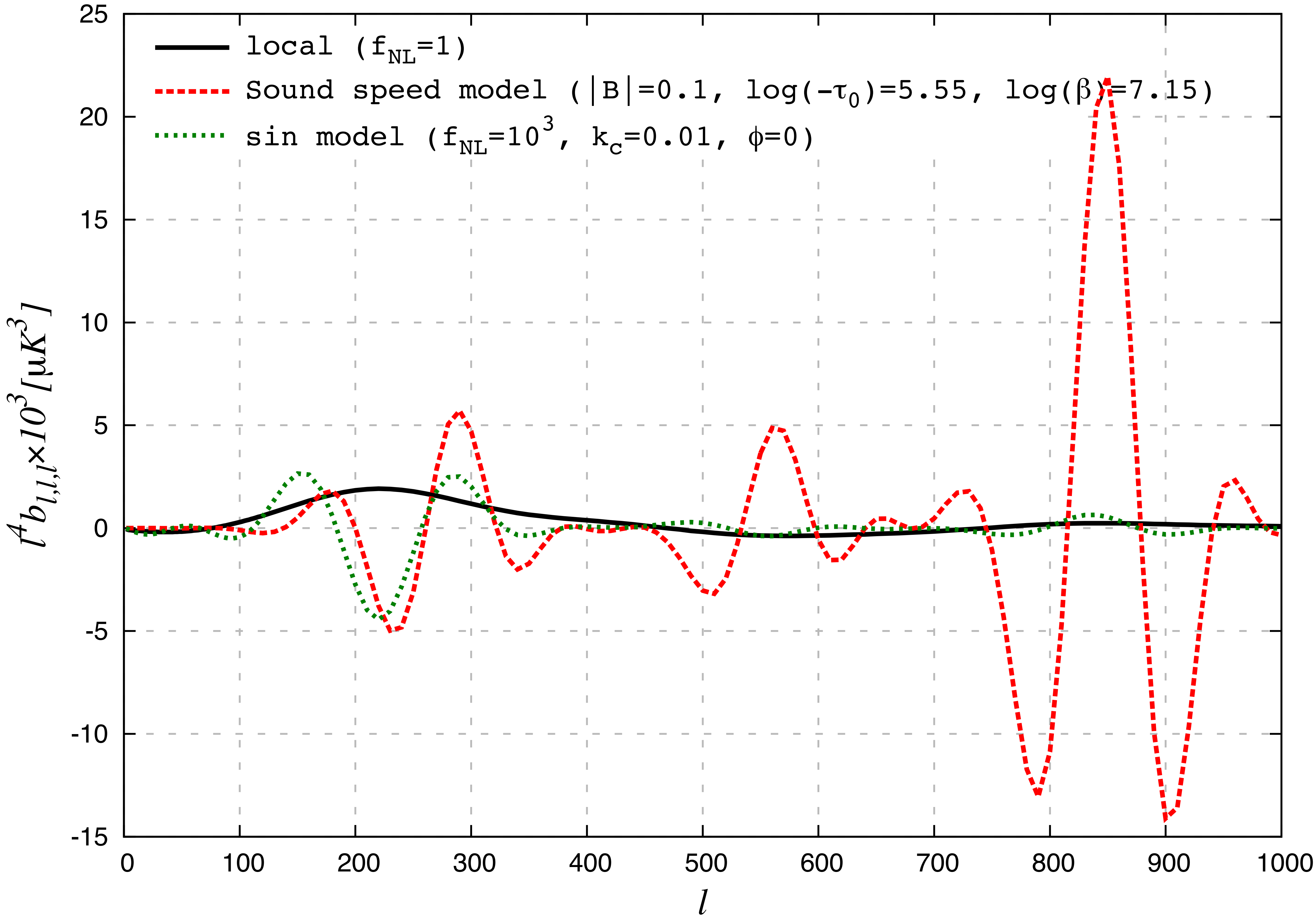
[Adshead et al. PhysRevD.84.043519], [Bartolo et al. JCAP 1310 (2013) 038]
[Miranda et al. Phys.Rev. D86 (2012)], [Park et al. Phys.Rev. D85 (2012)]
[Adshead et al. PhysRevD.84.043519], [Nakashima et al. Prog.Theor.Phys. 125 (2011)]
[Bean et al. JCAP 0803 (2008) 026], [Cannone et al. Phys.Rev. D89 (2014)]

$l_1 = 4, l_3 = l_2 + 4$ squeezed



$l_1 = l_2 = l_3$ equilateral

Also see Munchmeyer's & Van Tent's talks



Other studies and searches for features in the CMB Power spectrum and bispectrum

Linear oscillation (e.g. step-like features in V)

Adshead, Hu, Miranda (2013), Benetti (2013), Miranda, Hu (2013) Fergusson et al. 1410.5114

Log-spaced oscillation (e.g. monodromy inflation)

Meerburg, Spergel, Wandelt (2013a, 2013b, 2014) (incl. also linear) Peiris, Easther, Flauger (2013), Münchmeyer, Meerburg, Wandelt (2014)

Others sources of features
(e.g. multi-field dynamics, non-Bunch-Davis vacuum)

Danielsson (2002), Greene, Schalm, Shiu, v.d. Schaar (2004) Meerburg, v.d. Schaar, Corasaniti (2009), Jackson, Schaalm (2010), Gao, Langlois, Mizuno (2012, 2013), Saito, Takamizu (2013), Noumi, Yamaguchi (2013), Miranda, Hu, Dvorkin (2014), Cai, Chen, Ferreira, Quintin (2014) ...

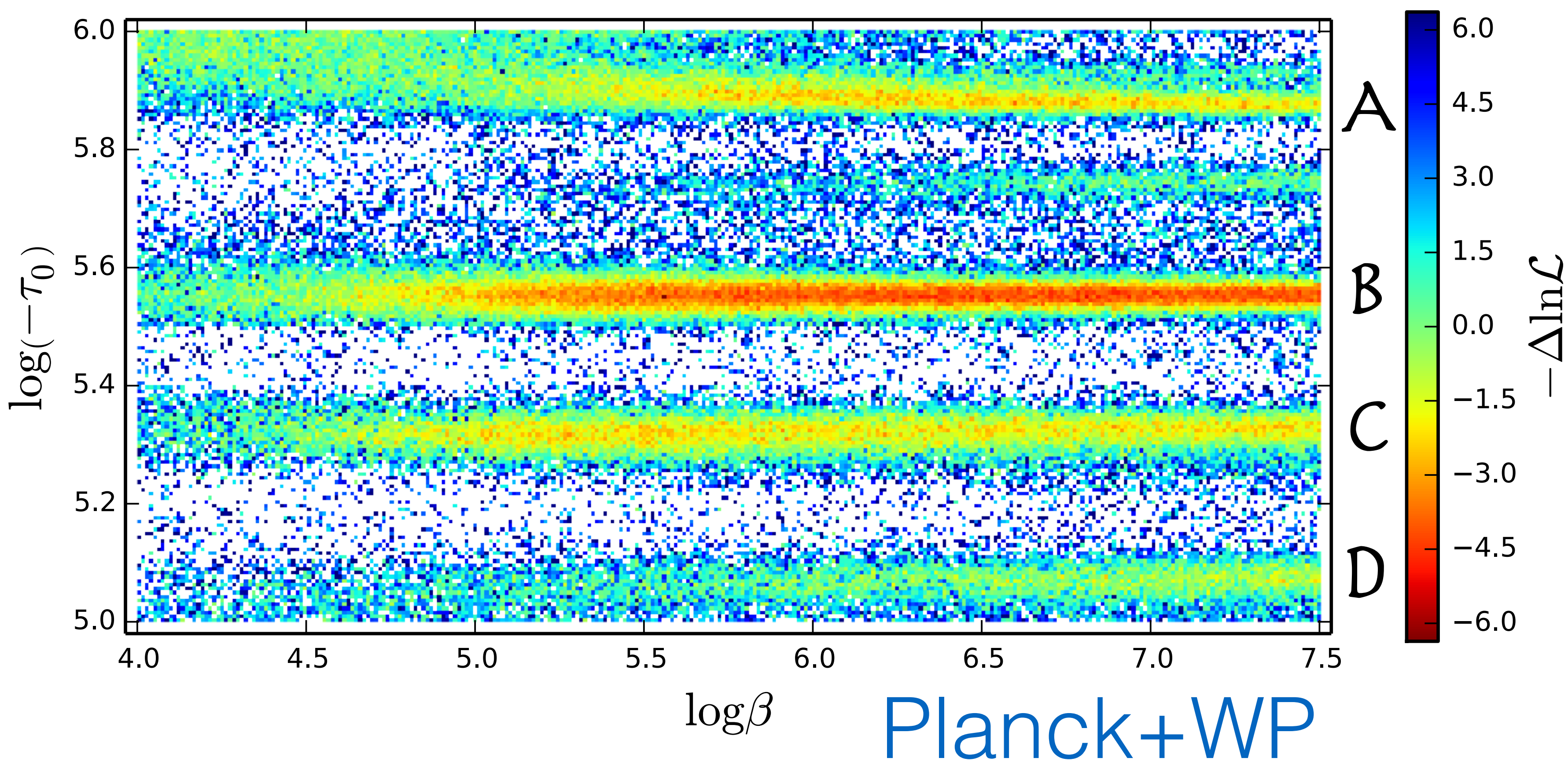
And, of course, Planck's team search for features:

Ade et al. (2013) "Constraints on Inflation"

3. Search with CMB map—TT spectrum

2013

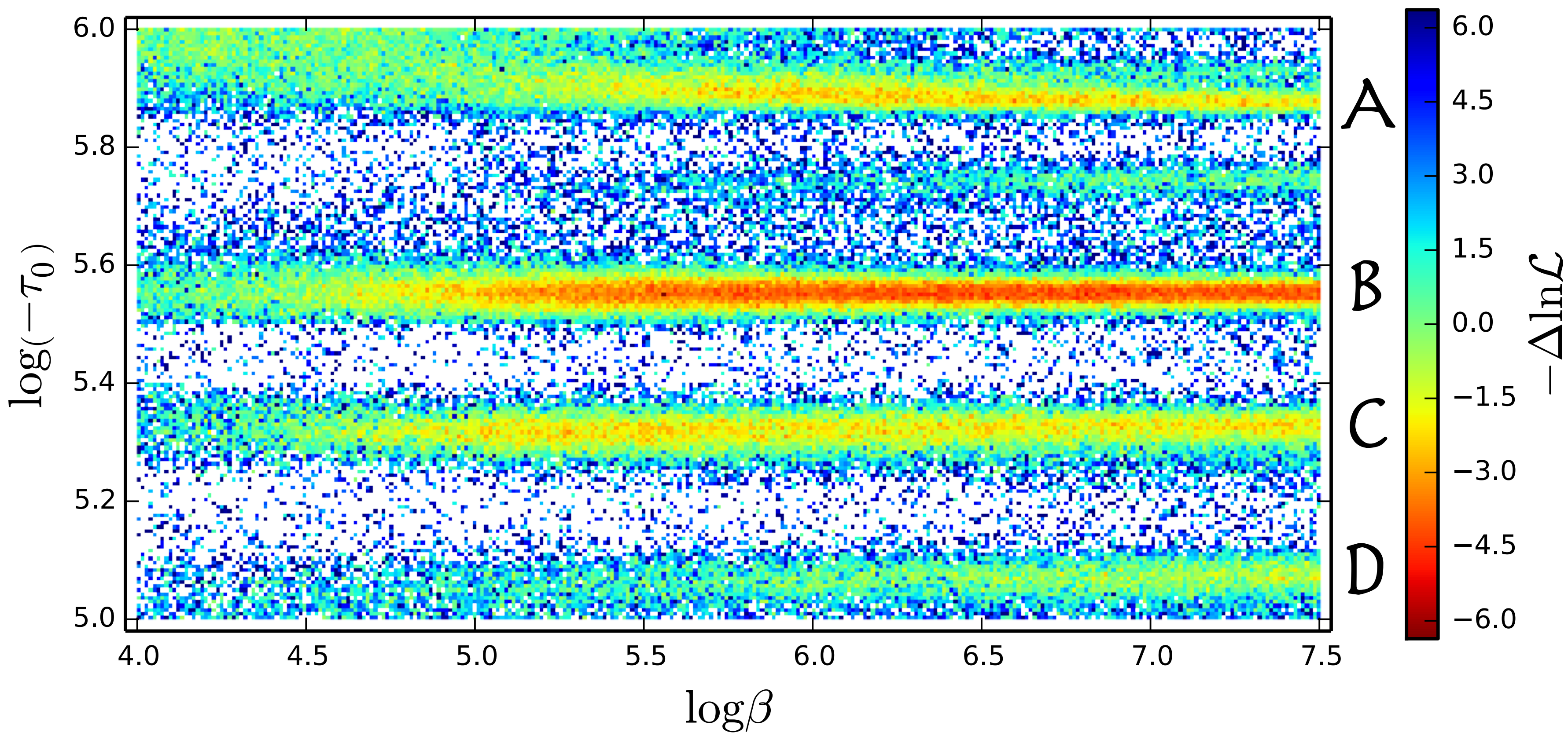
profile likelihood



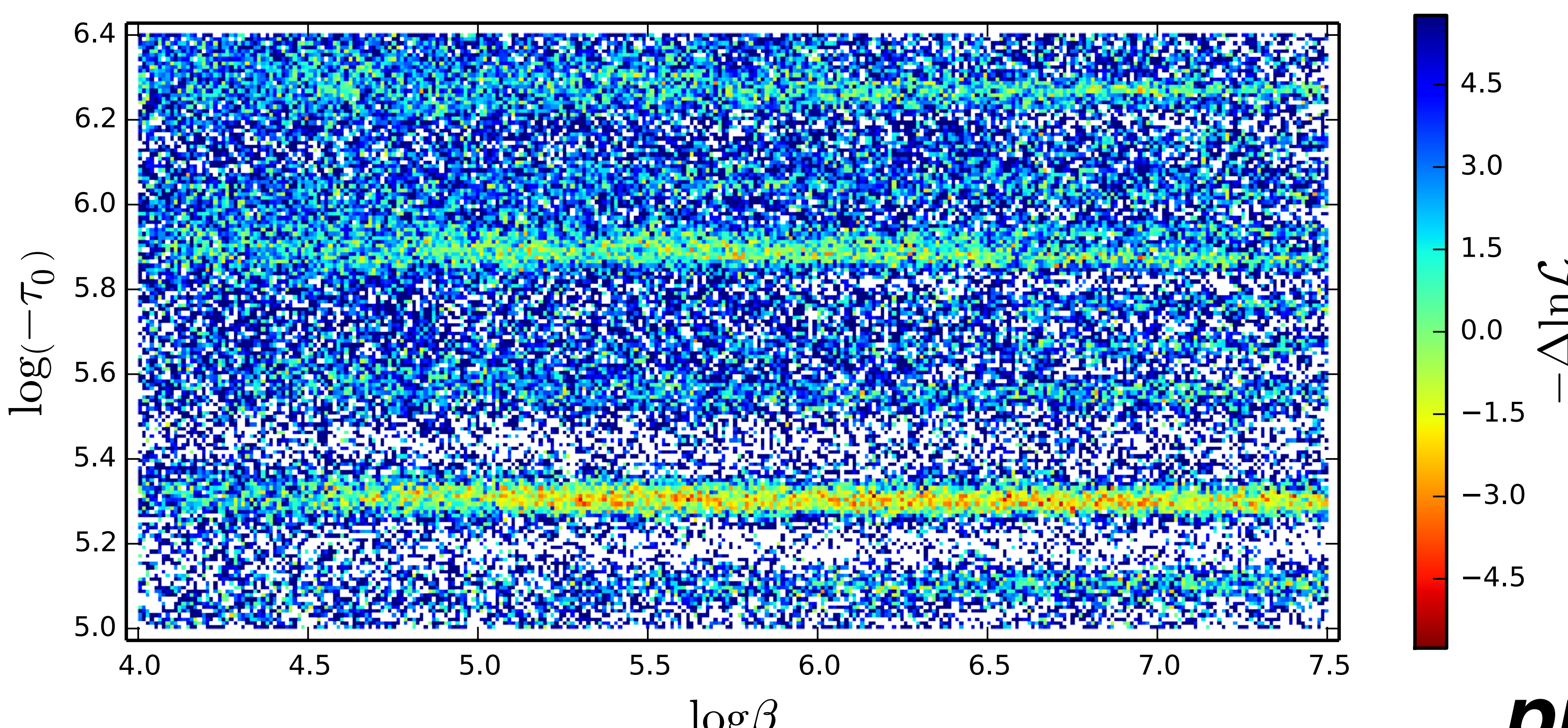
#	$-B\times 10^2$	$\ln\beta$	$\ln(-\tau_0)$	$\Delta\chi^2$
$\mathcal{A}$	$(4.5)\,3.7^{+1.6}_{-3.0}$	$(5.7)\,5.7^{+0.9}_{-1.0}$	$(5.895)\,5.910^{+0.027}_{-0.035}$	-4.3
$\mathcal{B}$	$(4.2)\,4.3\pm 2.0$	$(6.3)\,6.3^{+1.2}_{-0.4}$	$(5.547)\,5.550^{+0.016}_{-0.015}$	-8.3
$\mathcal{C}$	$(3.6)\,3.1^{+1.6}_{-1.9}$	$(6.5)\,5.6^{+1.9}_{-0.7}$	$(5.331)\,5.327^{+0.026}_{-0.034}$	-6.2
$\mathcal{D}$	(4.4)	(6.5)	(5.06)	-3.3

degeneracy of featured and vanilla parameters is negligible

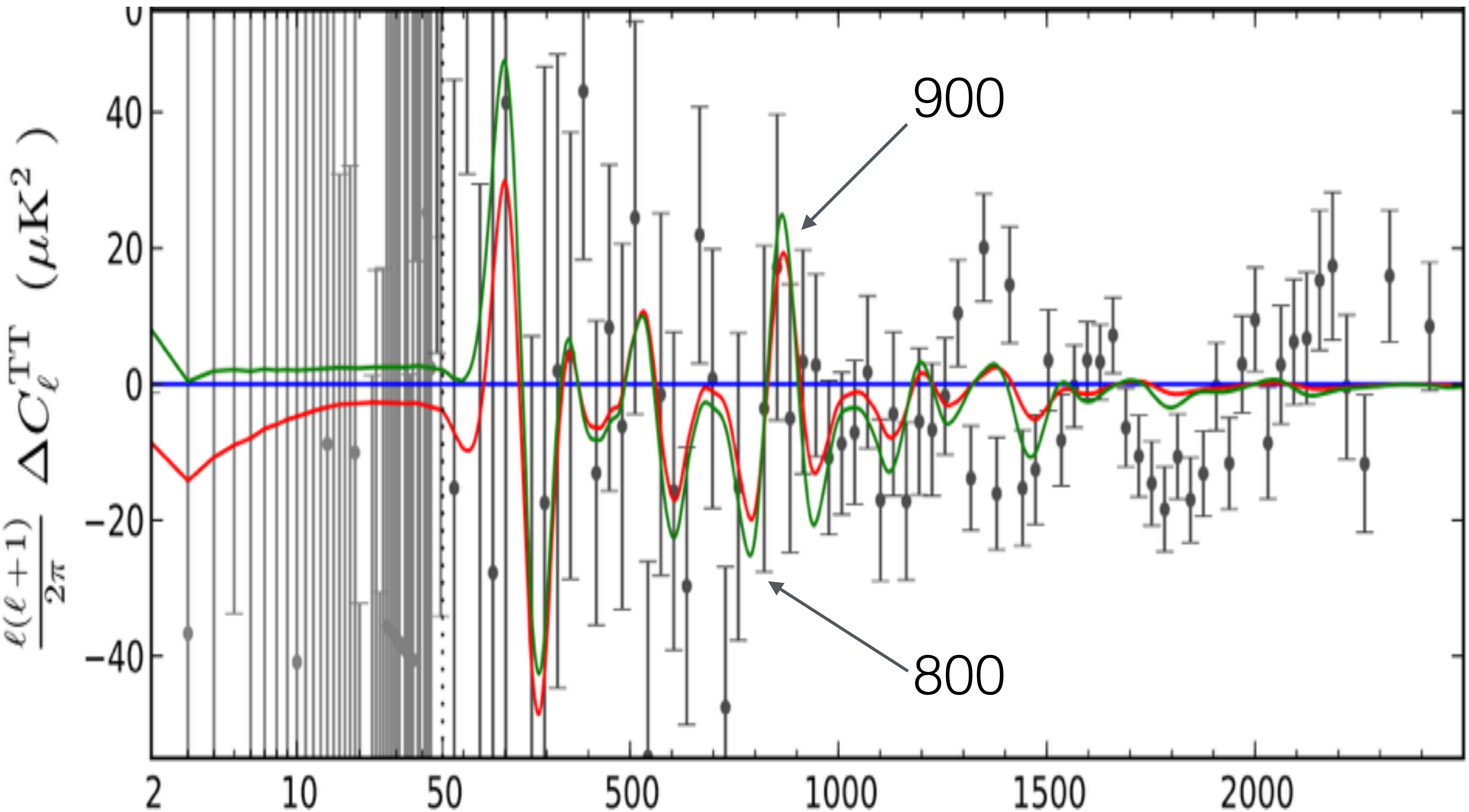
2013



2015

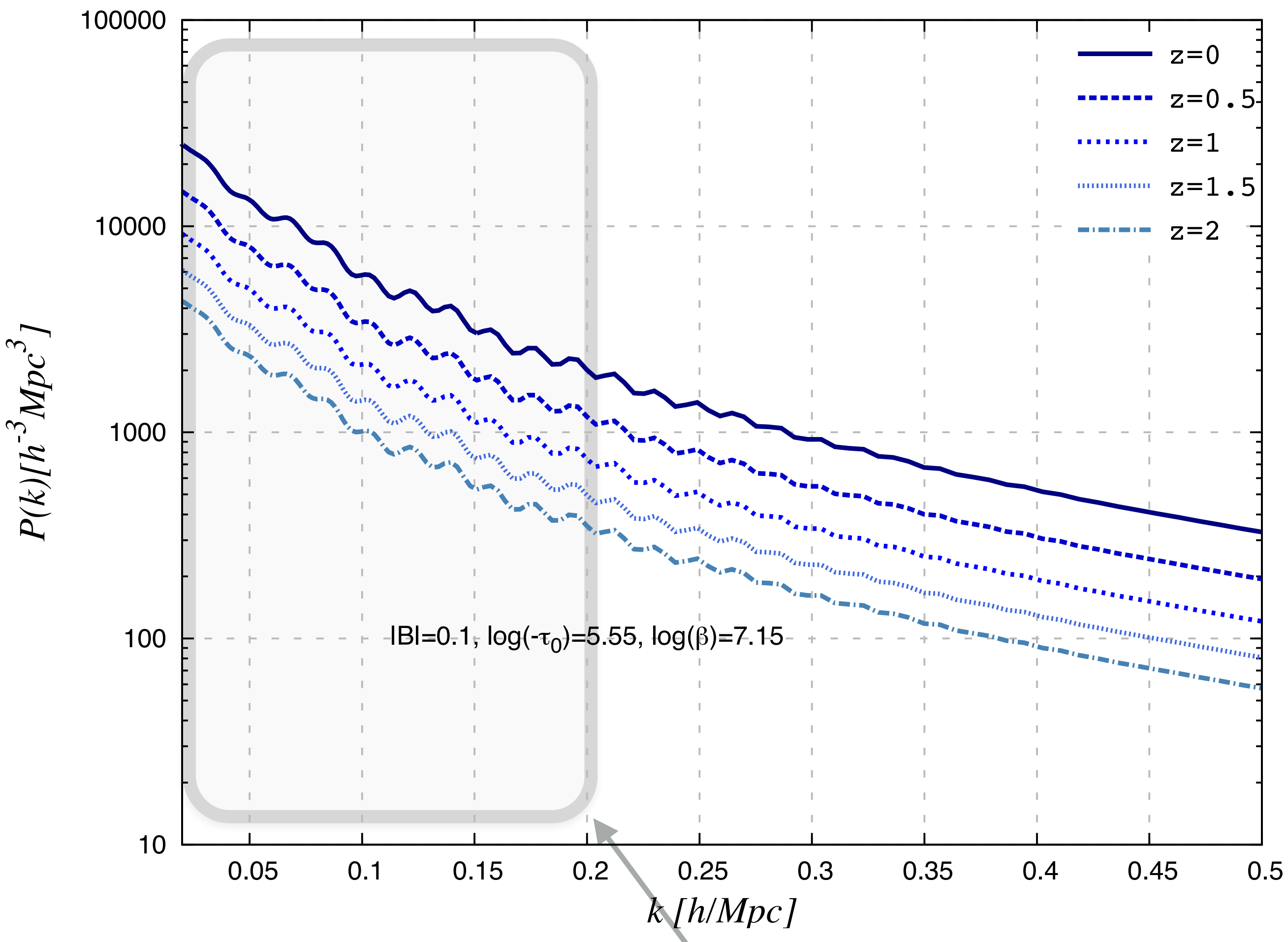


preliminary

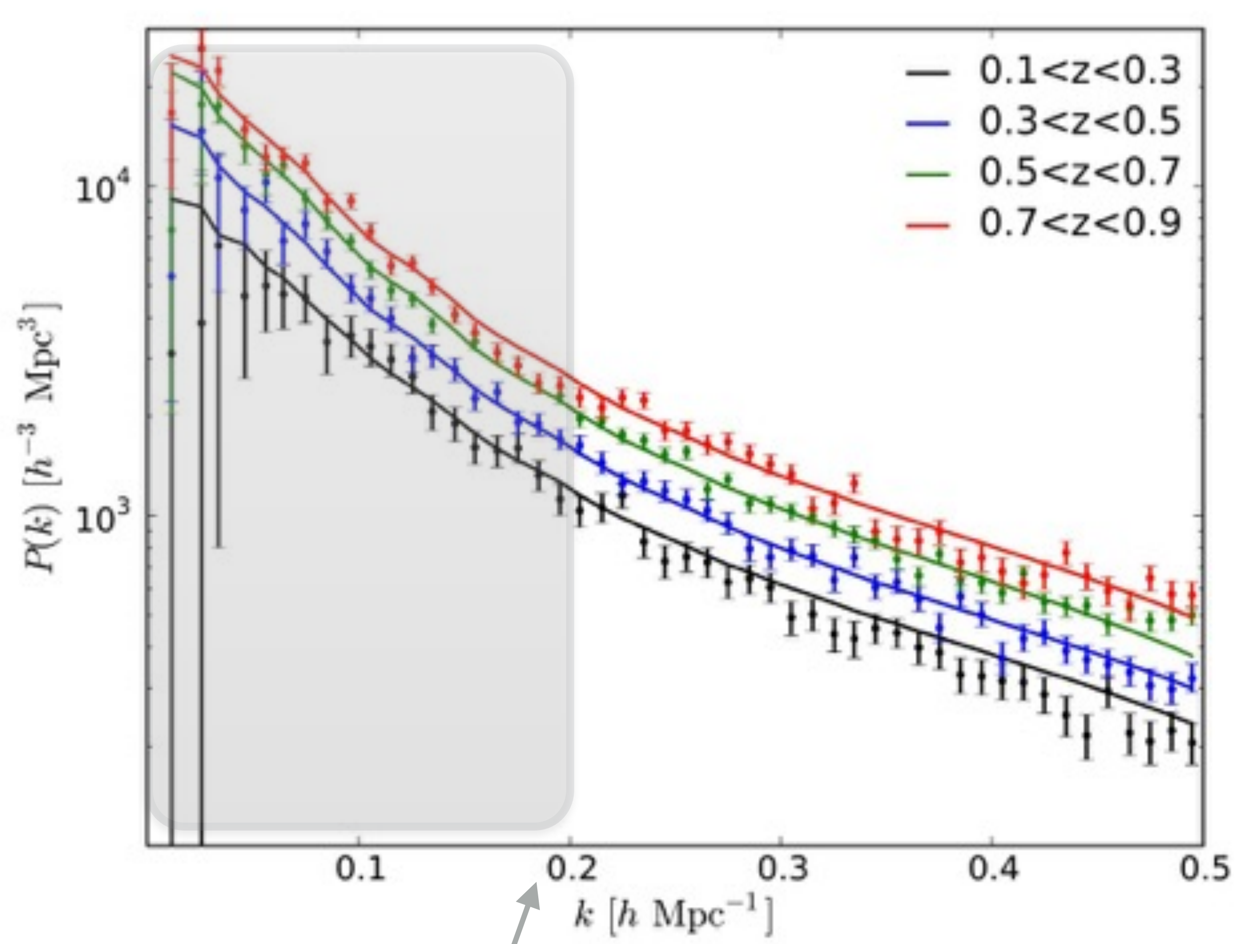


900
800
40
20
0
−20
−40
2
10
50
500
1000
1500
2000
$\frac{\ell(\ell+1)}{2\pi} \Delta C_\ell^{TT} \ (\mu K^2)$

4. Search with LSS survey—WiggleZ

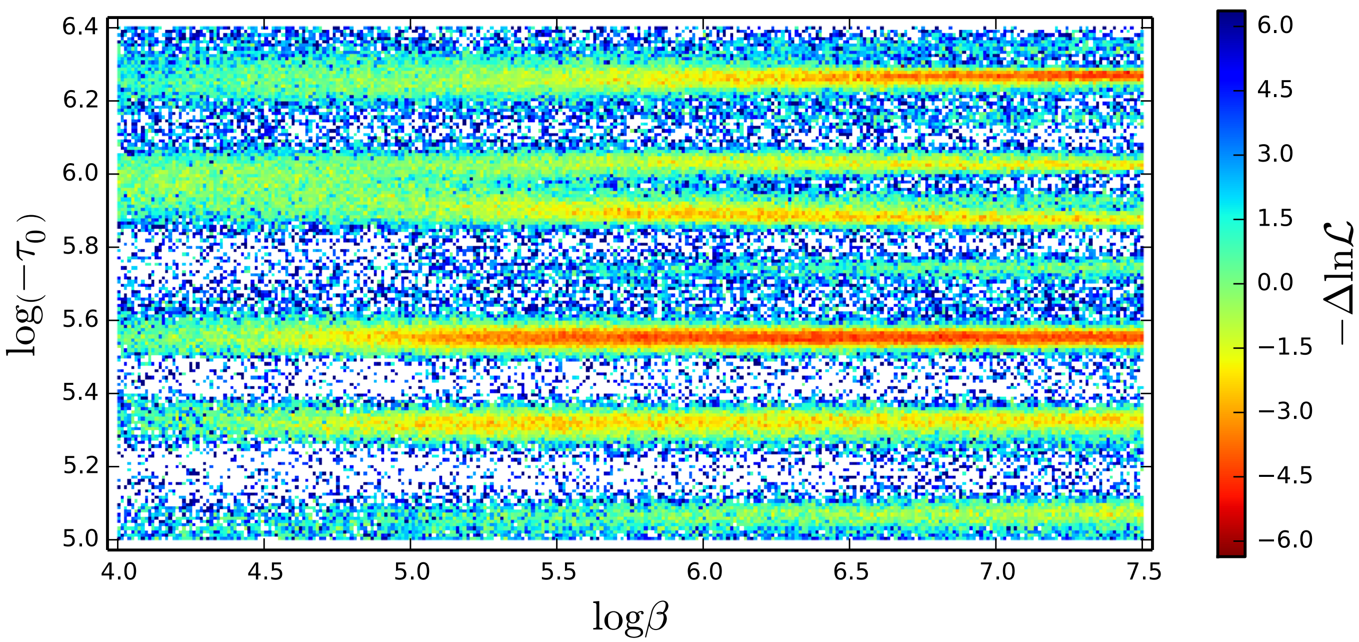


features shows around k~(0.1,0.2)

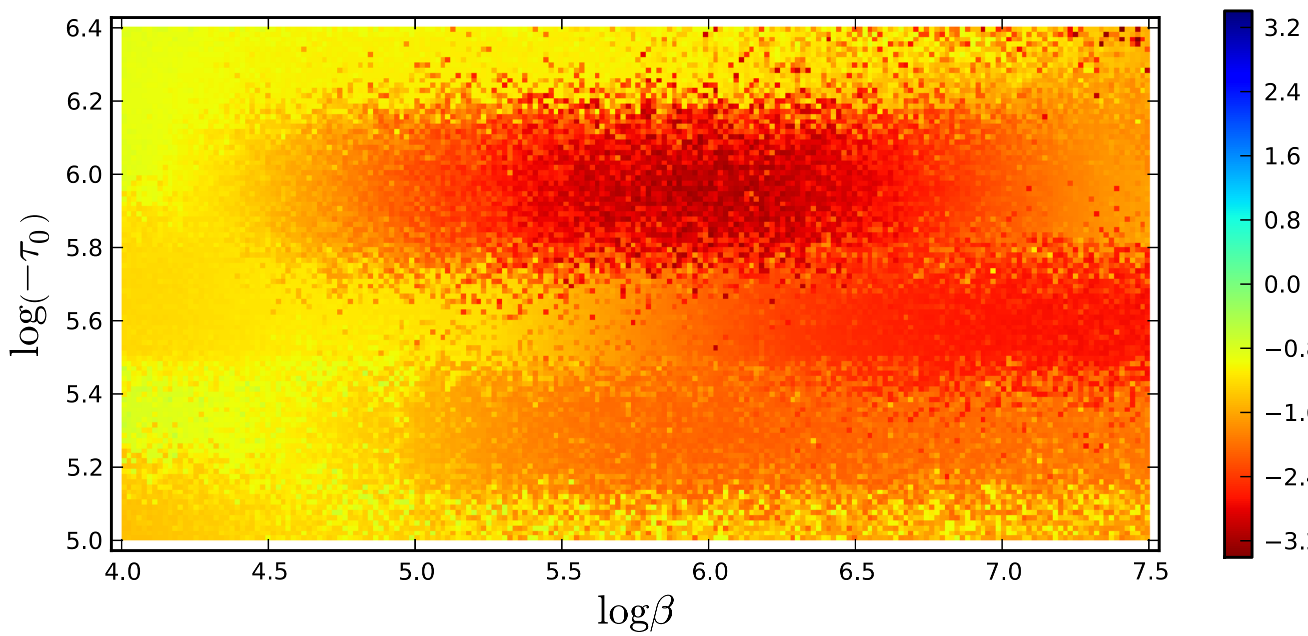


Search up to k=0.2

Independent search with different data

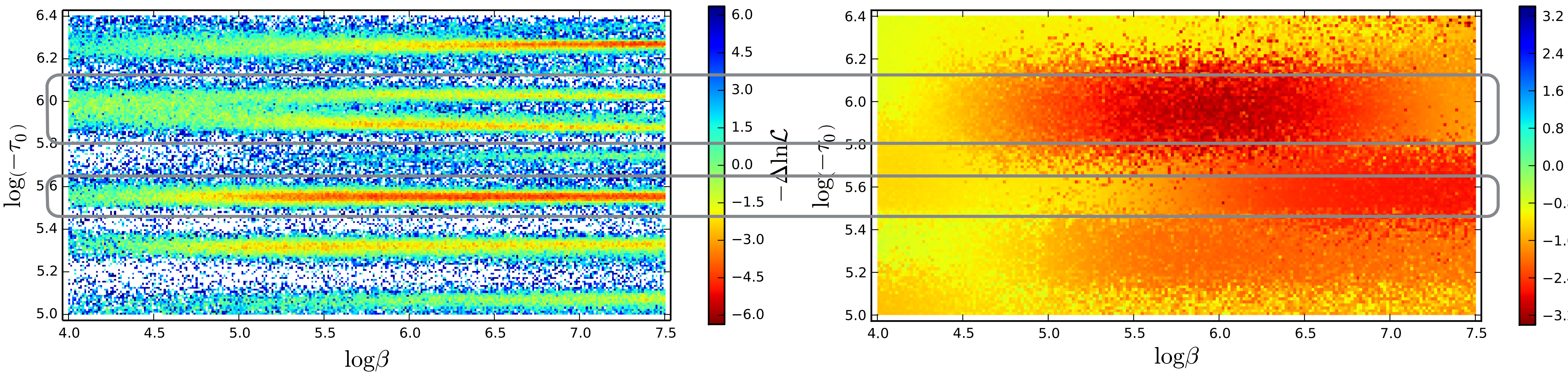


Planck+WP



WiggleZ

Independent search with different data

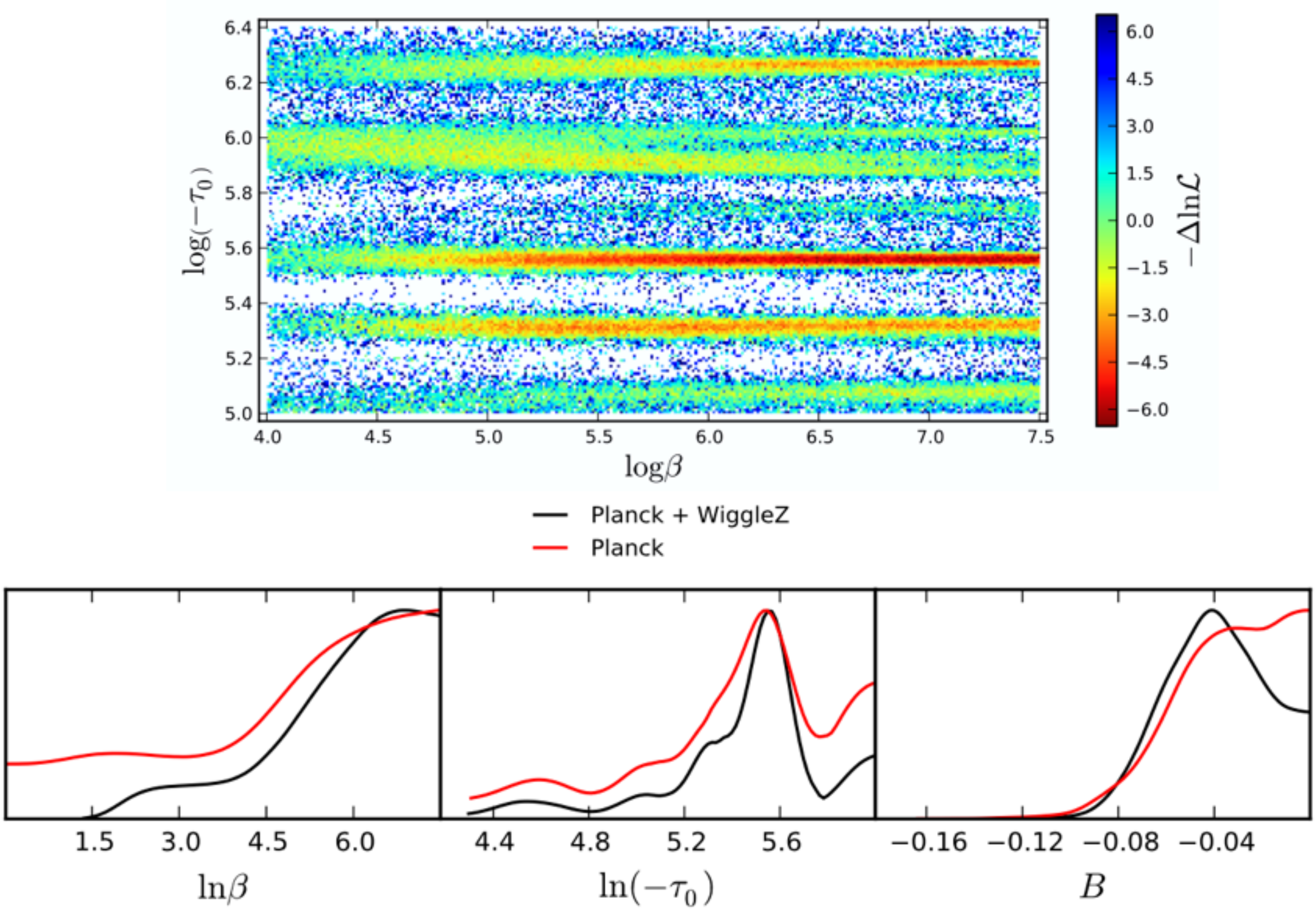


Planck+WP

WiggleZ

Two coincident modes
including the best-fit mode

Combine Planck and WiggleZ



get better constrained in Planck+WiggleZ

Bayesian Evidence

Evidence: $\mathcal{Z} = \int \mathcal{L}(\mathbf{D}|M(\boldsymbol{\theta}))\, \pi(\boldsymbol{\theta})\, \mathrm{d}^D \boldsymbol{\theta}$

M_0 : Base-LCDM model

M_1 : Sound speed model

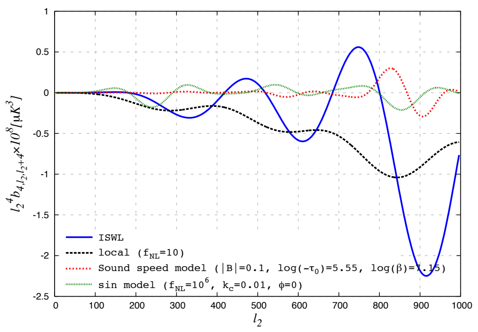
R<1: data faver M0

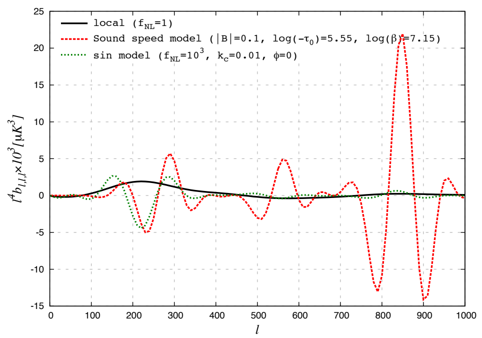
R>1: data faver M1

posterior — evidence — Beyesian ratio

Model	Data set	$-2\ln\mathcal{L}$	$\ln\mathcal{Z}$	R
M_1	Planck	9801.918 (9796.27)	-4955.61 ± 0.31	$\exp(0.46) \simeq 1.6$
M_0	Planck	9807.154 (9805.90)	-4956.07 ± 0.31	
M_1	Planck+WiggleZ	10253.570 (10249.20)	-5183.05 ± 0.32	$\exp(0.62) \simeq 1.9$
M_0	Planck+WiggleZ	10262.042 (10258.80)	-5183.67 ± 0.31	

Jeffreys's criterion (1<R<3): *Barely worth mentioning!*





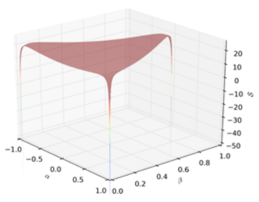
Conclusion

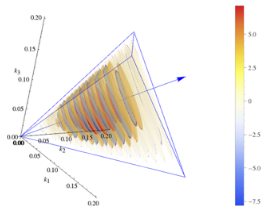
1. A transient reduction of the speed of sound generically gives primordial oscillatory features.

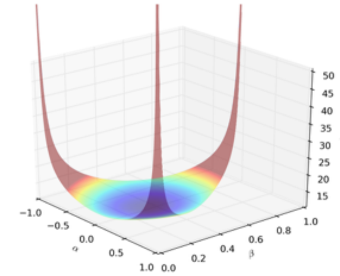
2. It could produce sizeable and distinguishable features in CMB spectrum, bispectrum and matter spectrum.

3. Planck-2013 and WiggleZ data shows a coincidence in the best-fit mode.

4. The statistical significance is not big enough to claim a detection.

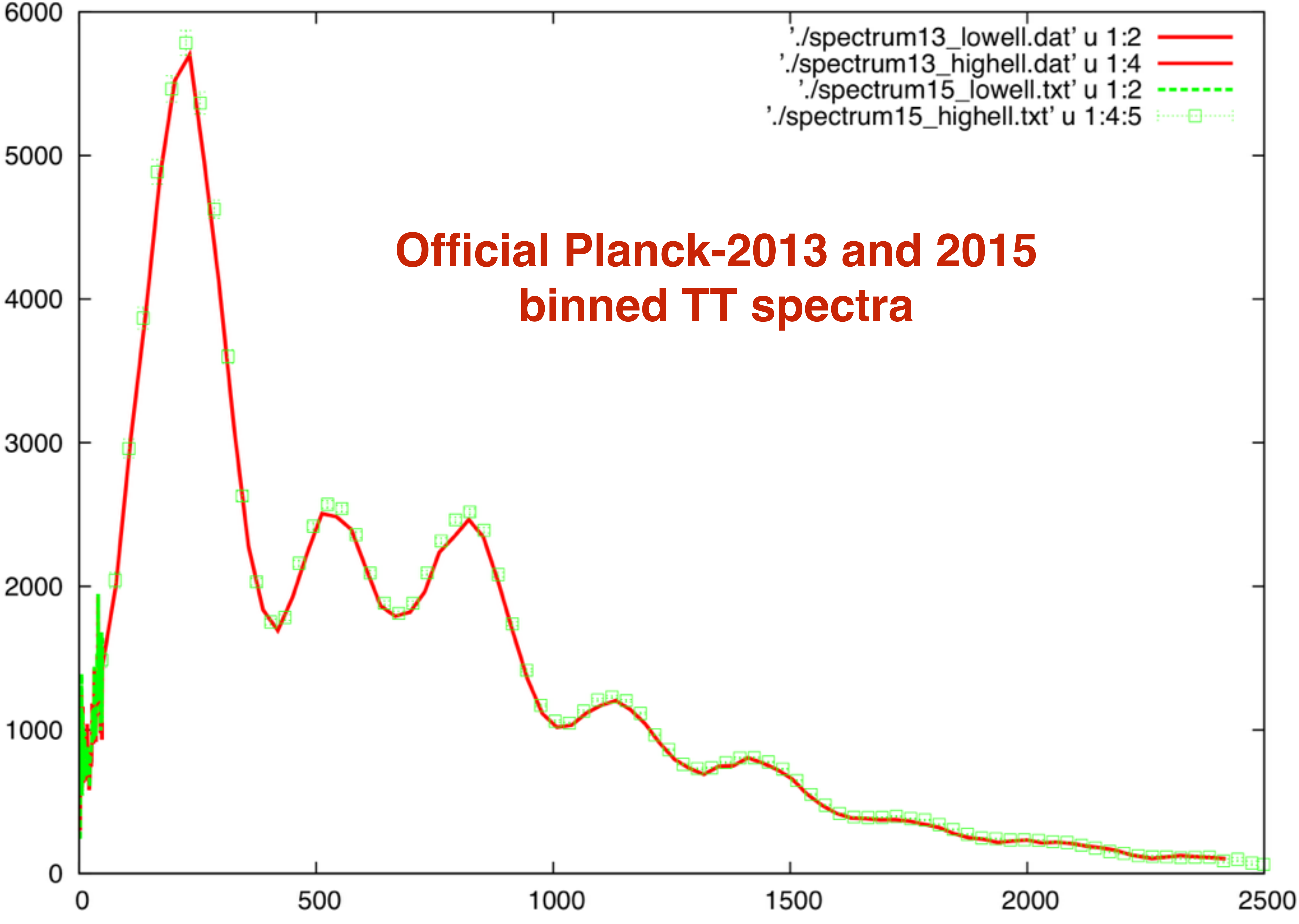






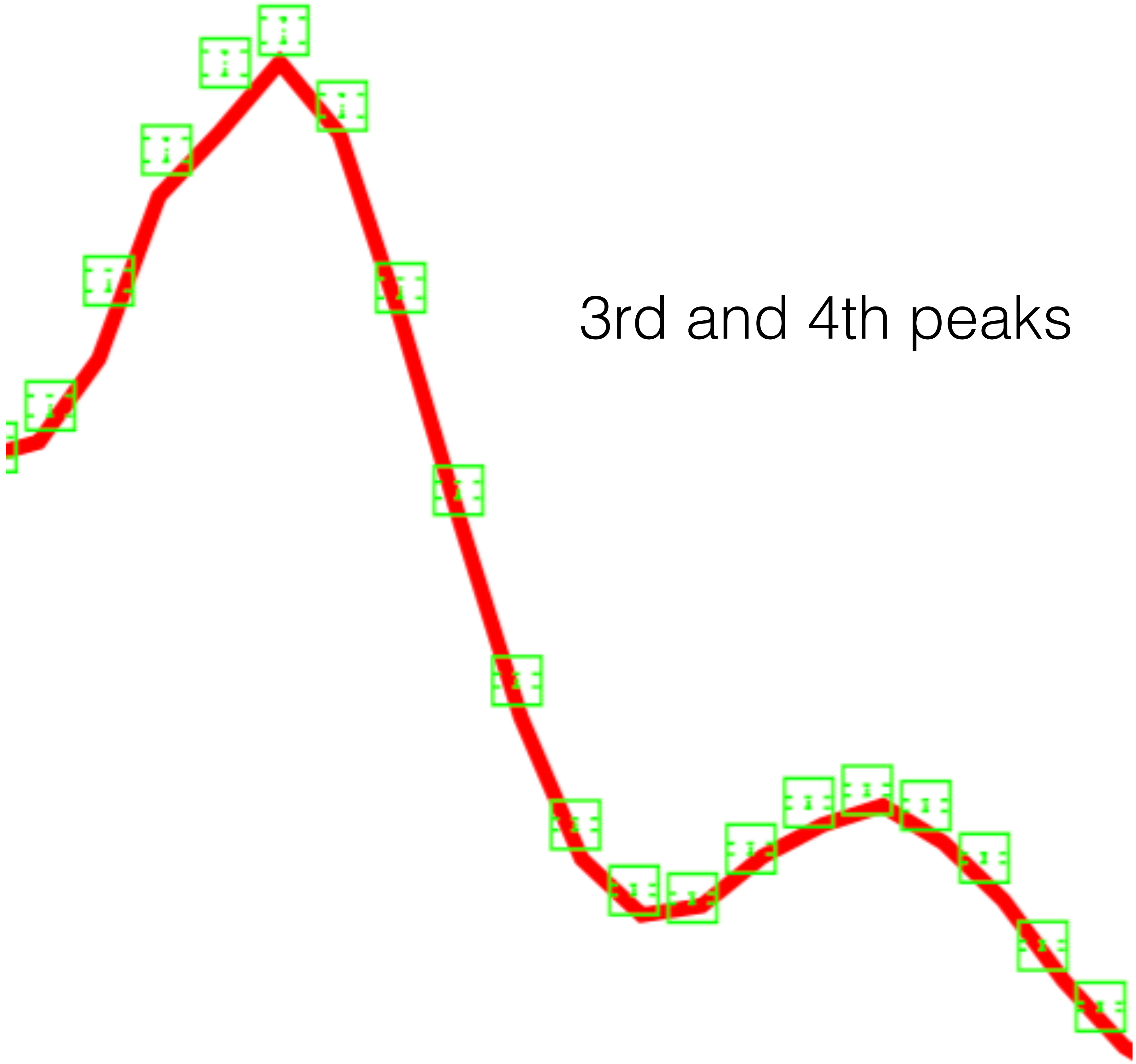
Thank you!

bonus slide



'./spectrum13_lowell.dat' u 1:2
'./spectrum13_highell.dat' u 1:4
'./spectrum15_lowell.txt' u 1:2
'./spectrum15_highell.txt' u 1:4:5
Official Planck-2013 and 2015
binned TT spectra
0
1000
2000
3000
4000
5000
6000
0
500
1000
1500
2000
2500

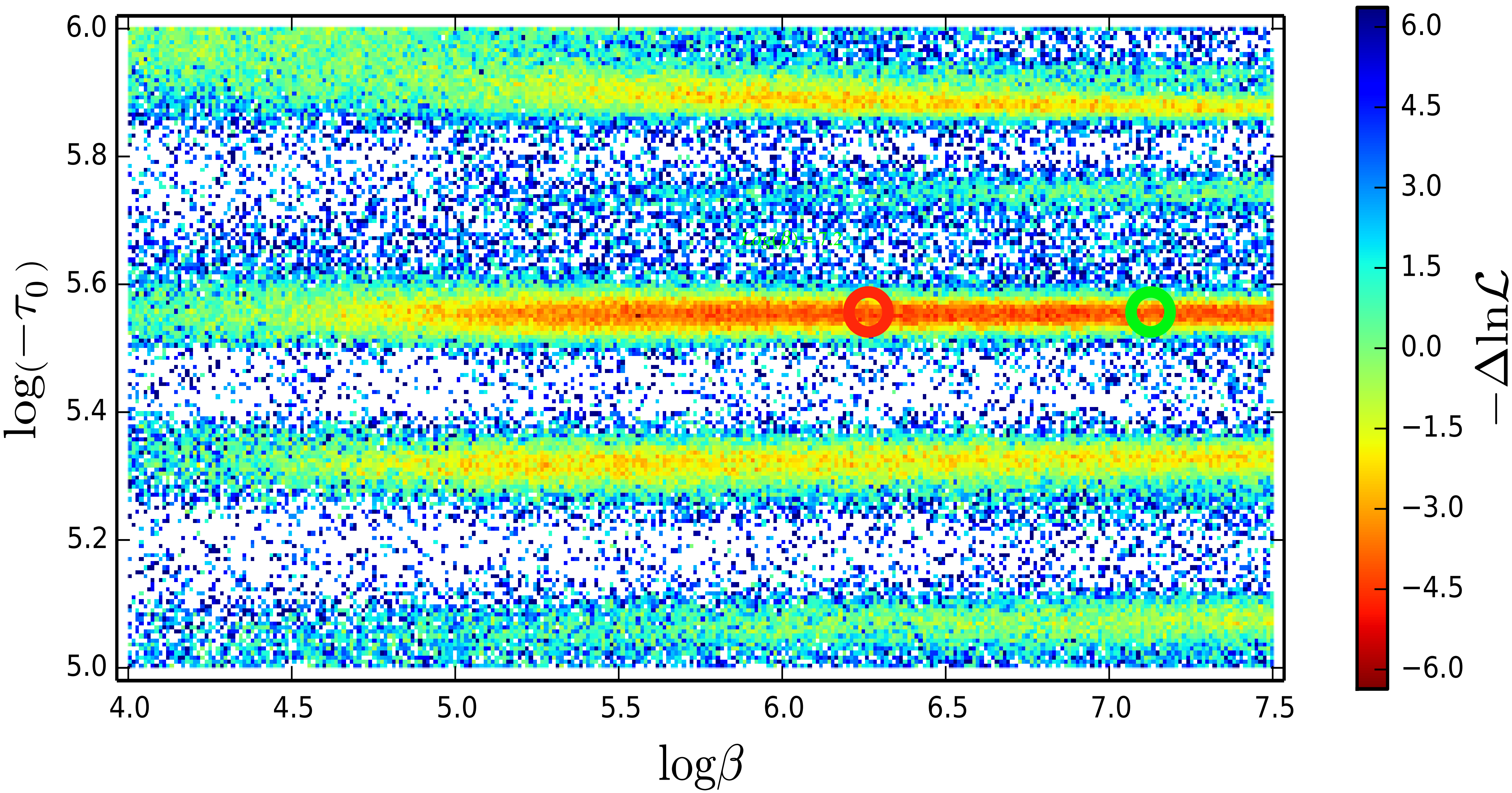

1st and 2nd peak



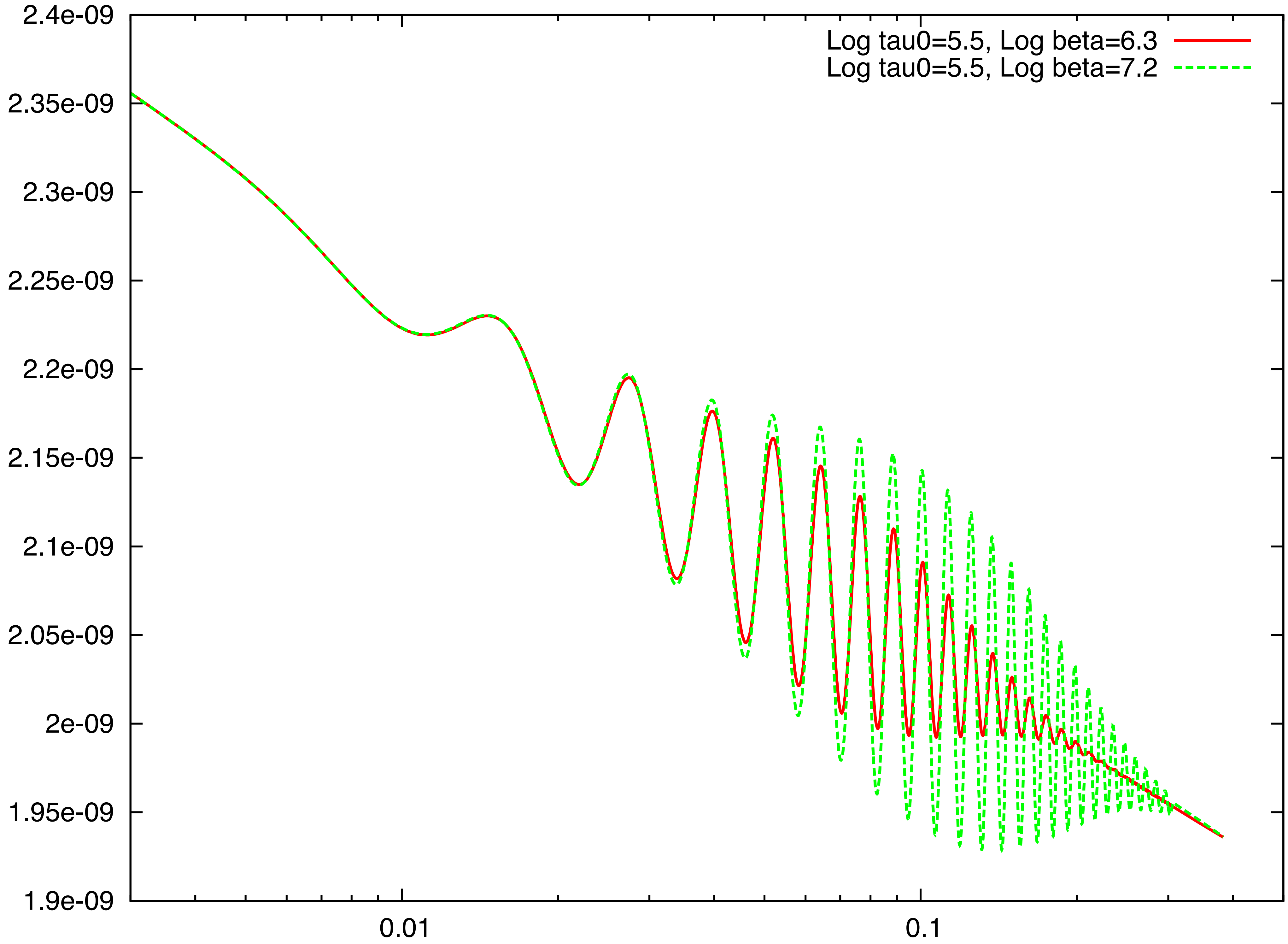
3rd and 4th peaks

Two mode with the same frequency $Log(-\tau_0) = 5.5$

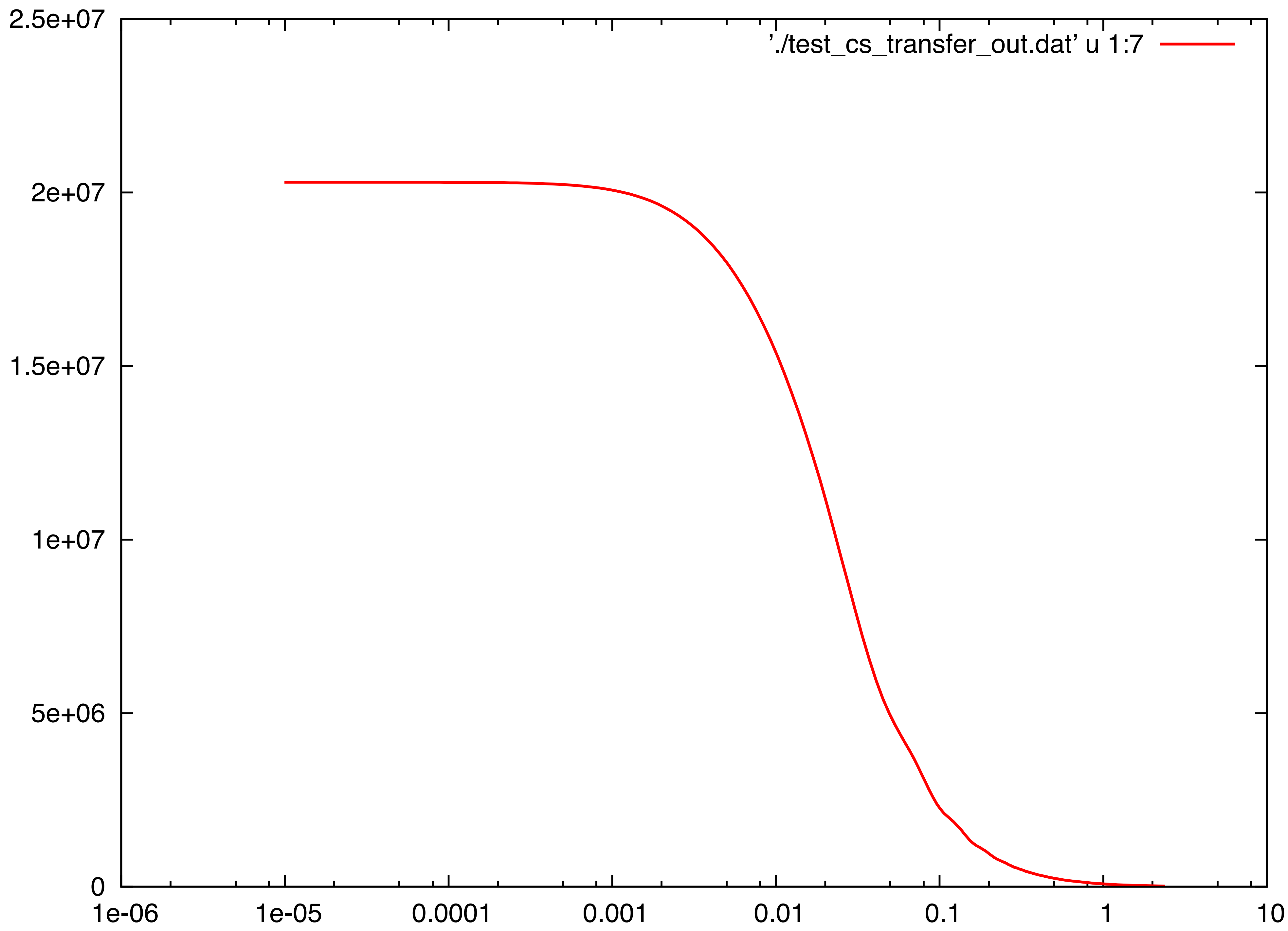
but with different location $Log(\beta) = 6.3$ (red) $Log(\beta) = 7.2$ (green)



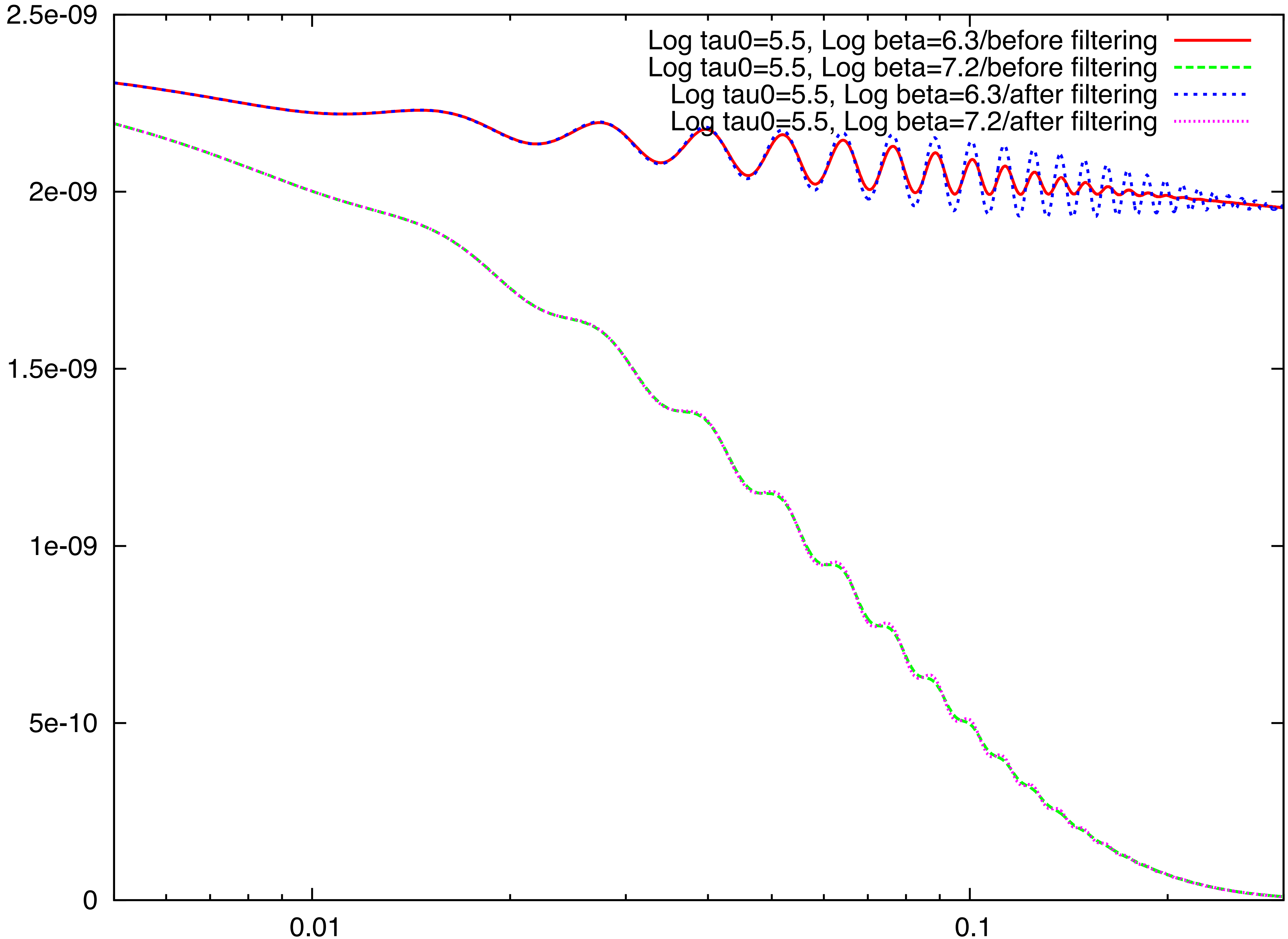
Primordial power spectrum



Transfer function

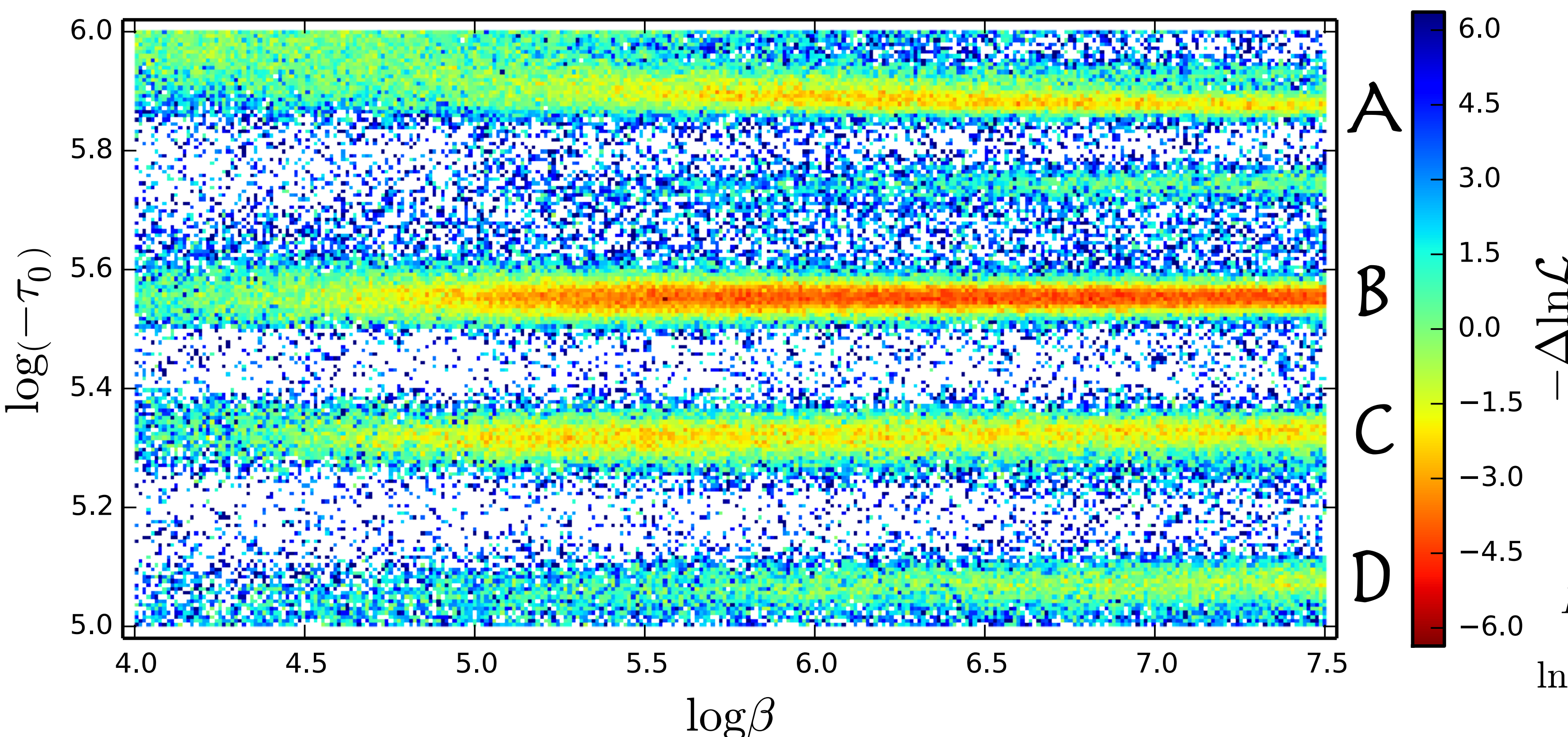


After convolving with transfer function they looks similar, due to the damping effect on small scale



3. Search with CMB map—TT spectrum

profile likelihood



#	$-B\times10^2$	$\ln\beta$	$\ln(-\tau_0)$	$\Delta\chi^2$
$\mathcal{A}$	$(4.5)\,3.7^{+1.6}_{-3.0}$	$(5.7)\,5.7^{+0.9}_{-1.0}$	$(5.895)\,5.910^{+0.027}_{-0.035}$	-4.3
$\mathcal{B}$	$(4.2)\,4.3\pm2.0$	$(6.3)\,6.3^{+1.2}_{-0.4}$	$(5.547)\,5.550^{+0.016}_{-0.015}$	-8.3
$\mathcal{C}$	$(3.6)\,3.1^{+1.6}_{-1.9}$	$(6.5)\,5.6^{+1.9}_{-0.7}$	$(5.331)\,5.327^{+0.026}_{-0.034}$	-6.2
$\mathcal{D}$	(4.4)	(6.5)	(5.06)	-3.3

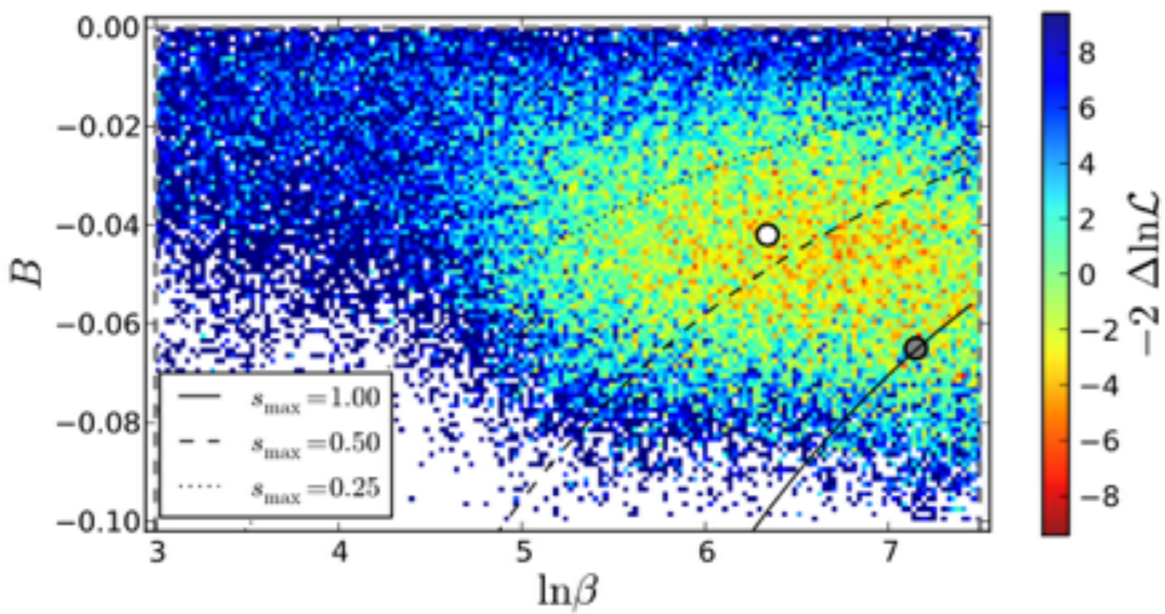
Planck+WP

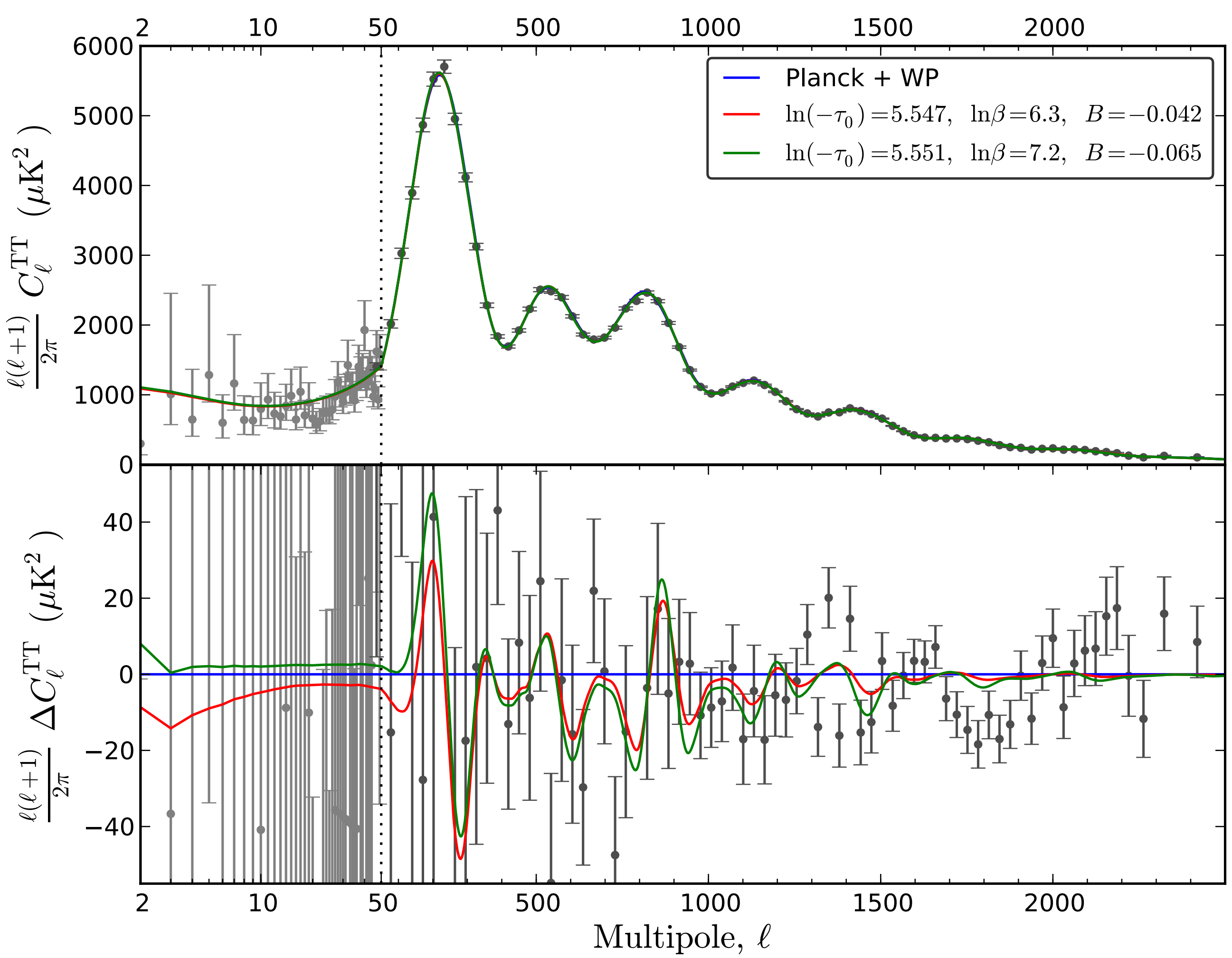
degeneracy with vanilla parameter is negligible

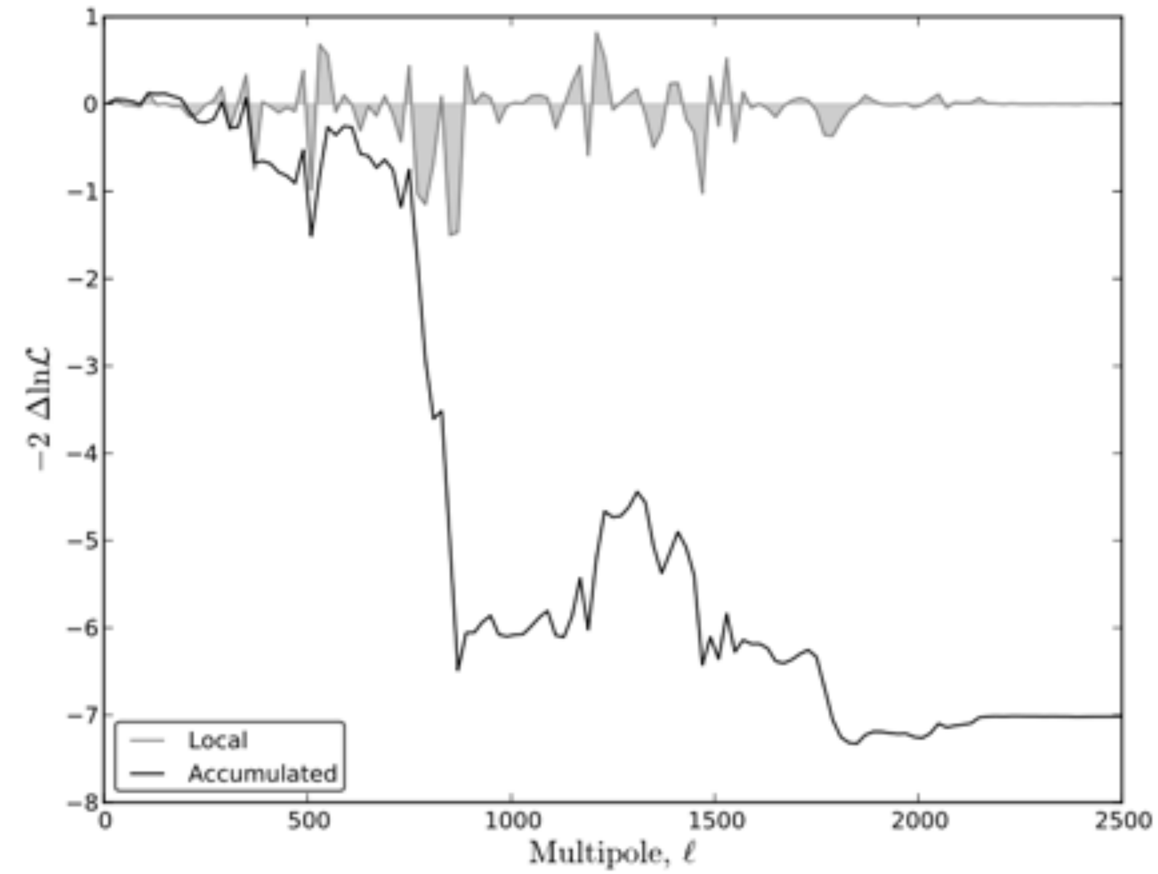
CoV Mat

	B	$\ln\beta$	$\ln(-\tau_0)$	ω_B	ω_C	H_0	A_s	n_s	τ_{reio}
B		-0.34	-0.02	-0.06	-0.05	-0.00	-0.01	-0.01	0.01
$\ln\beta$	-0.34		0.16	0.02	-0.00	0.03	-0.01	0.03	-0.02
$\ln(-\tau_0)$	-0.02	0.16		-0.00	-0.09	0.08	0.00	0.07	0.03
ω_B	-0.06	0.02	-0.00		-0.57	0.72	0.20	0.59	0.30
ω_C	-0.05	-0.00	-0.09	-0.57		-0.97	-0.09	-0.80	-0.33
H_0	-0.00	0.03	0.08	0.72	-0.97		0.13	0.82	0.35
A_s	-0.01	-0.01	0.00	0.20	-0.09	0.13		0.21	0.96
n_s	-0.01	0.03	0.07	0.59	-0.80	0.82	0.21		0.39
τ_{reio}	0.01	-0.02	0.03	0.30	-0.33	0.35	0.96	0.39	

Search with CMB map—Zoom in best-fit







Need to consider

look-elsewhere effect!

Enlarge the parameter space

2. Models with a transient reduction of the speed of sound

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}g^{\mu\nu}\gamma_{ab}\partial_\mu\phi^a\partial_\nu\phi^b - V(\phi)\right]$$

A.Achucarro et. al.
JHEP 1205
(2012) 066

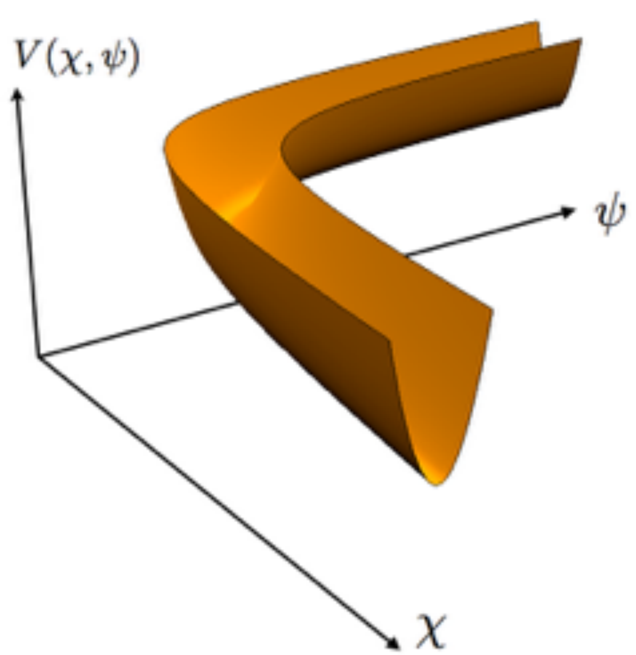
$$\phi^a(t,\boldsymbol{x}) = \phi_0^a(t+\pi) + N^a(t+\pi)\mathcal{F}$$

light adiabatic (→ π) heavy isocurvature (→ $\mathcal{F}$)

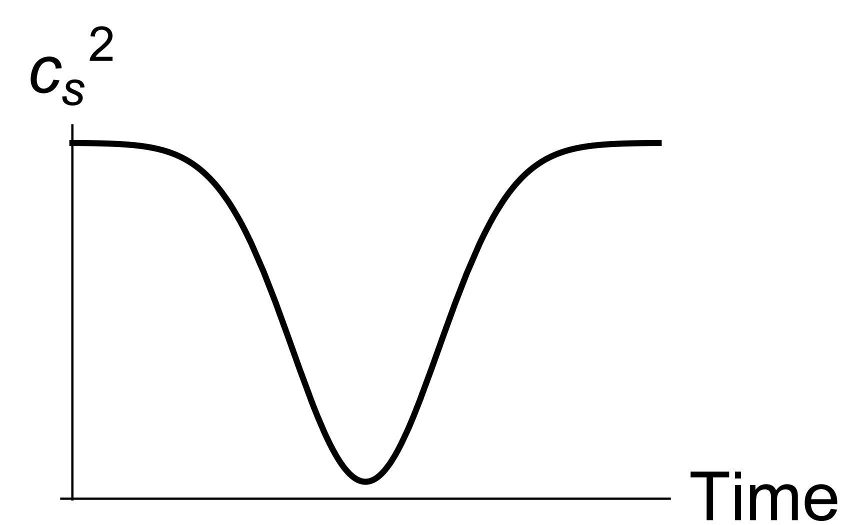
integrating out heavy field

effective action:

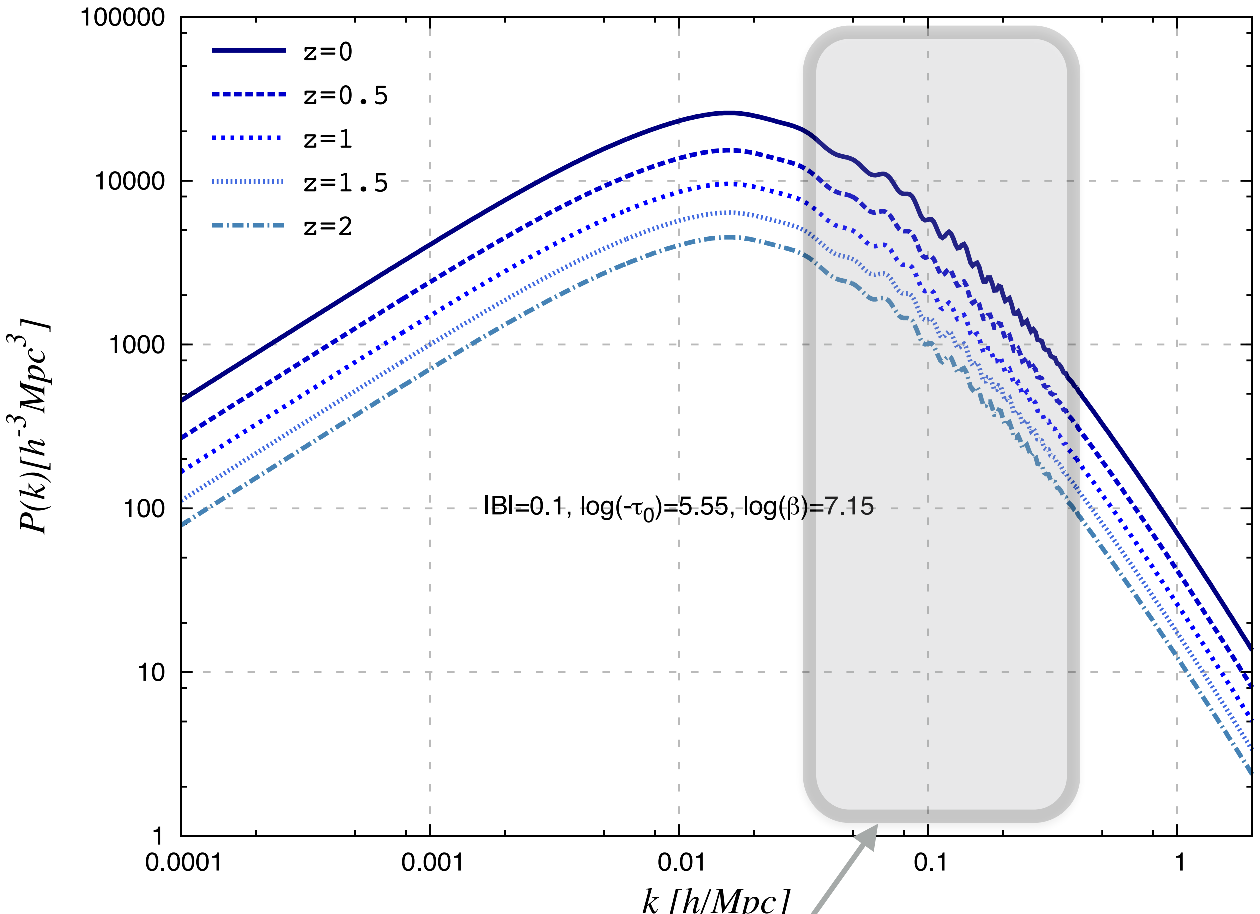
$$S = \frac{1}{2}\int d^4x\dot\phi_0^2\Big\{c_s^{-2}\dot\pi^2 - (\nabla\pi)^2 + \left(\frac{1}{c_s^2}-1\right)\dot\pi\left[\dot\pi^2 - (\nabla\pi)^2\right] + \left(\frac{1}{c_s^2}-1\right)^2\frac{\dot\pi^3}{2} + 2\frac{\ddot\phi_0}{\dot\phi_0}\left[\frac{\dot\pi^2}{c_s^2} - (\nabla\pi)^2\right]\pi - 2\frac{\dot c_s}{c_s^3}\dot\pi^2\pi\Big\},$$

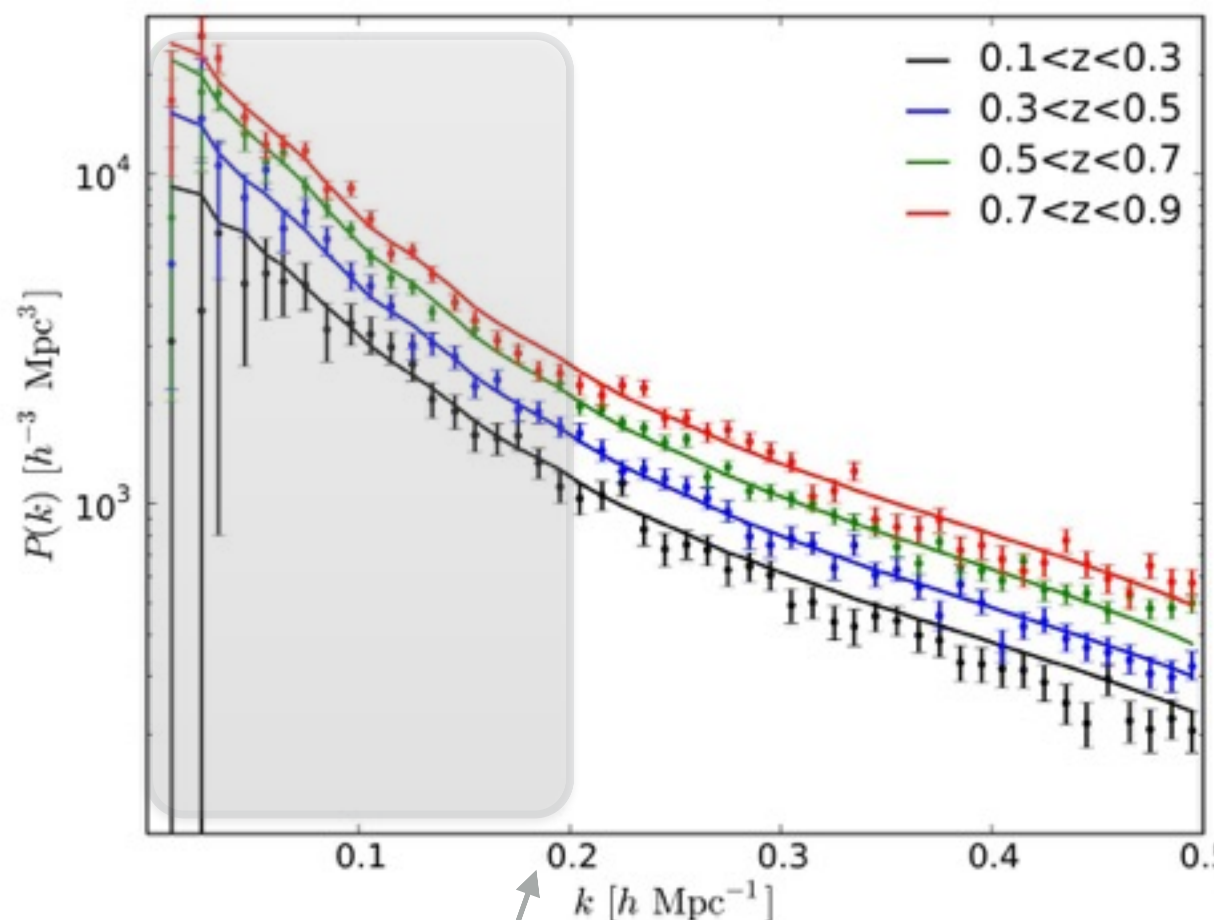


turn → sound speed reduced



4. Search with LSS survey—WiggleZ





features shows around k~(0.1,0.2)

Search up to k=0.2