See also J.Torrado Poster

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]
[arXiv:1410.4804]

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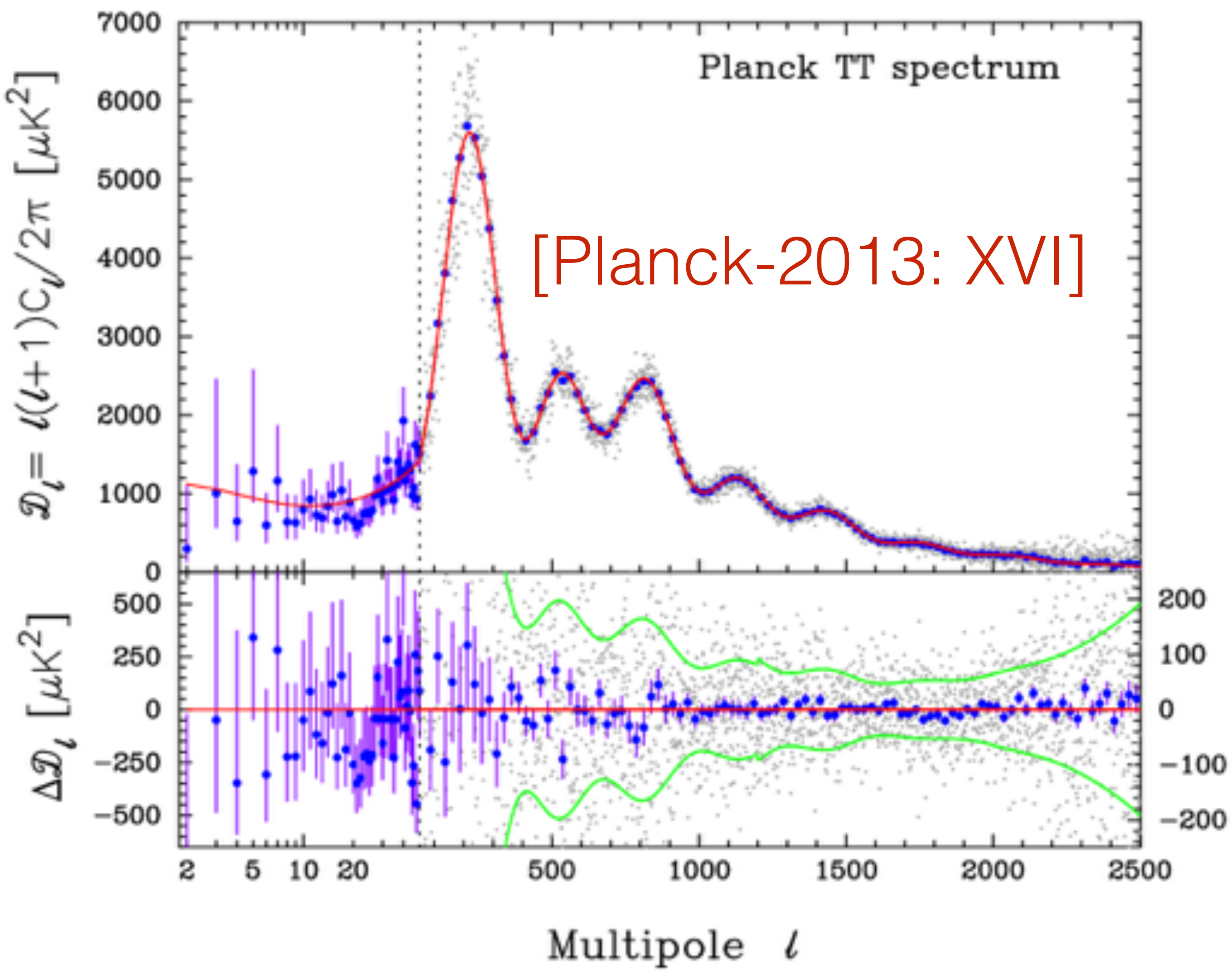
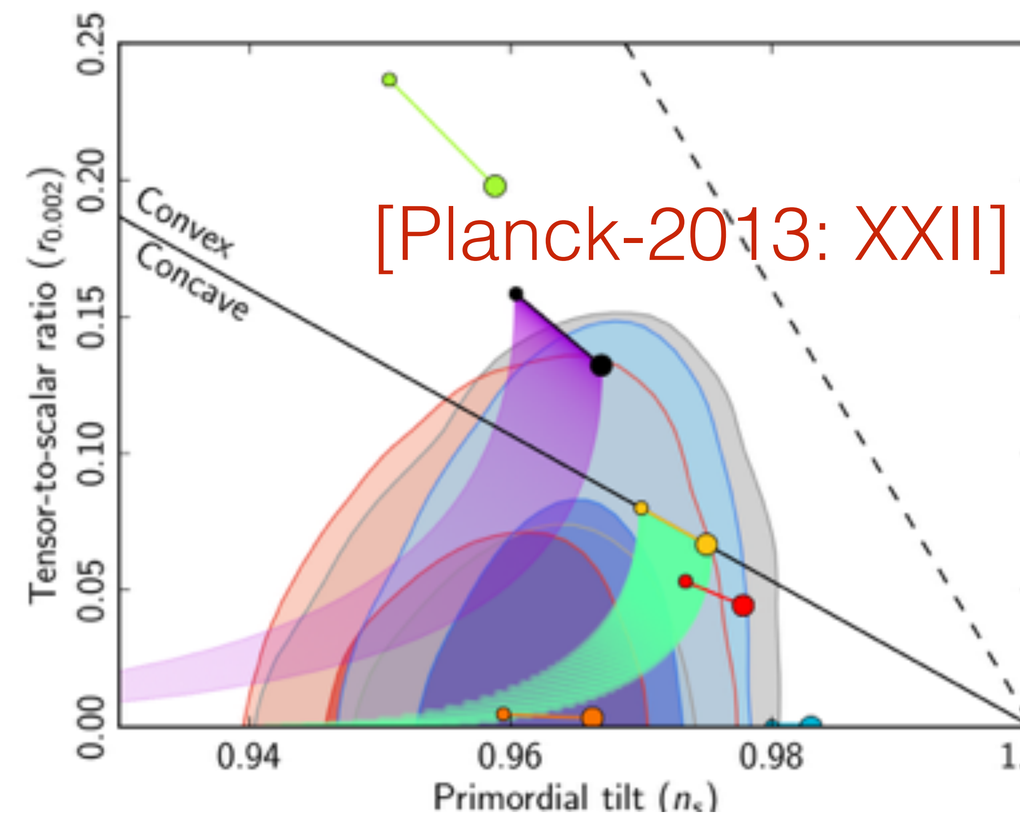
The primordial Universe after Planck, IAP, Paris, Dec. 2014

Outline

1. Observational hints of oscillatory features
2. Models with a transient reduction of the speed of sound
3. Search with CMB map
4. Search with LSS survey
5. Conclusion

Planck-2013: Great success of base-LCDM & single-field slow-roll inflationary model



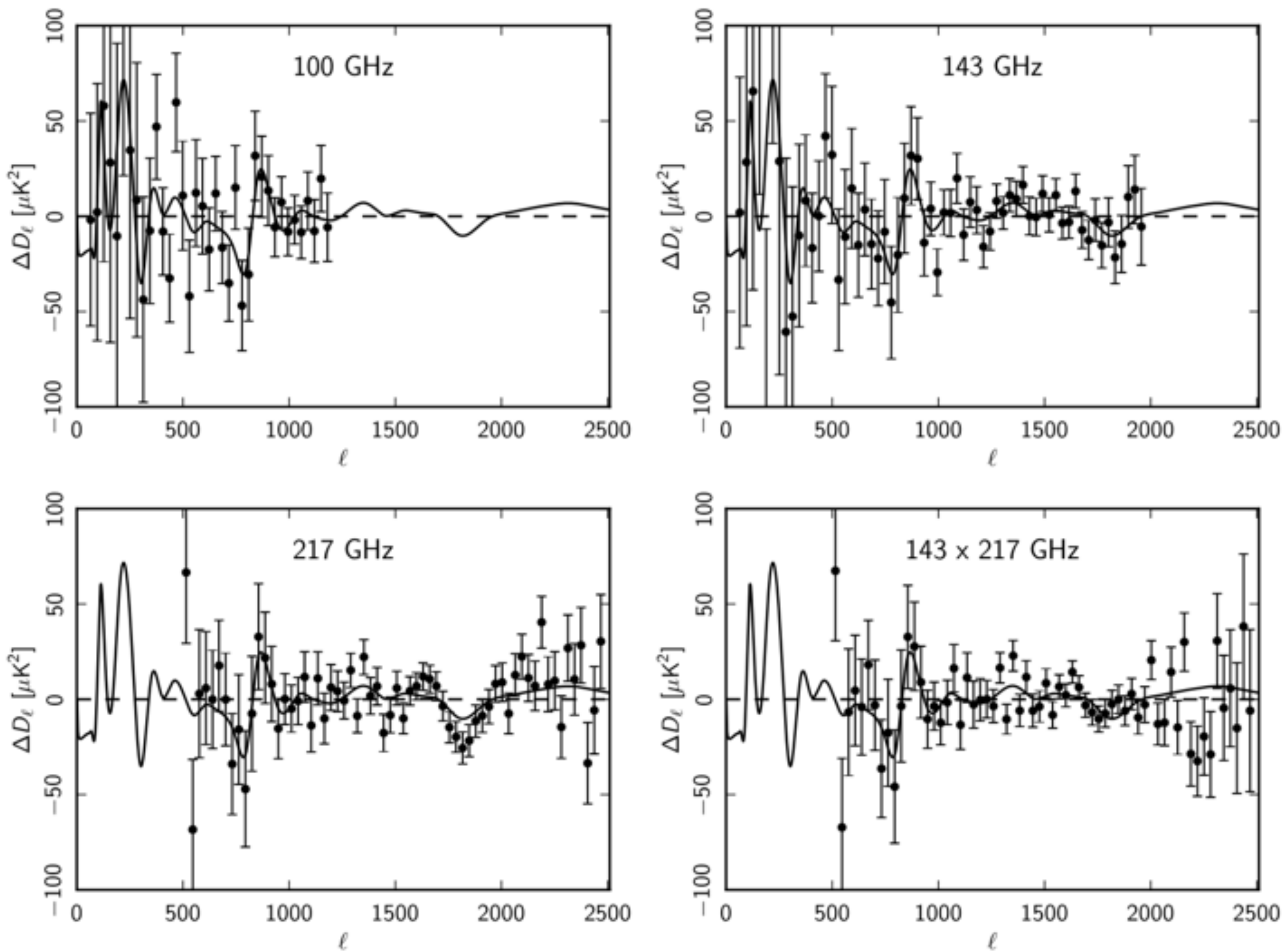


[Planck-2013: XXIV]

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**

1. Observational hints of oscillatory features

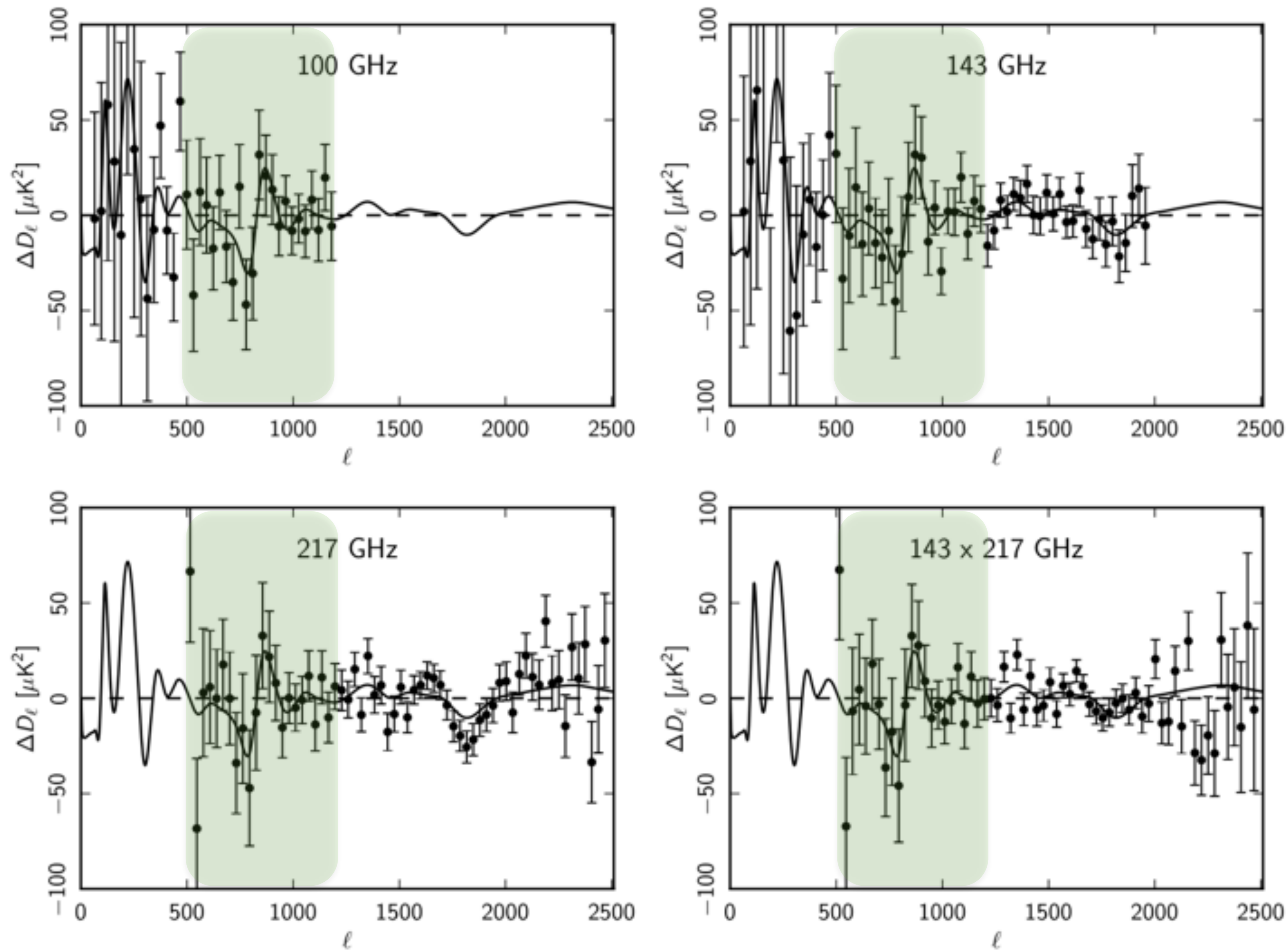
TT spectrum residual from best-fit LCDM model



[Planck-2013: XXII]

Spectrum residual from best-fit LCDM model

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



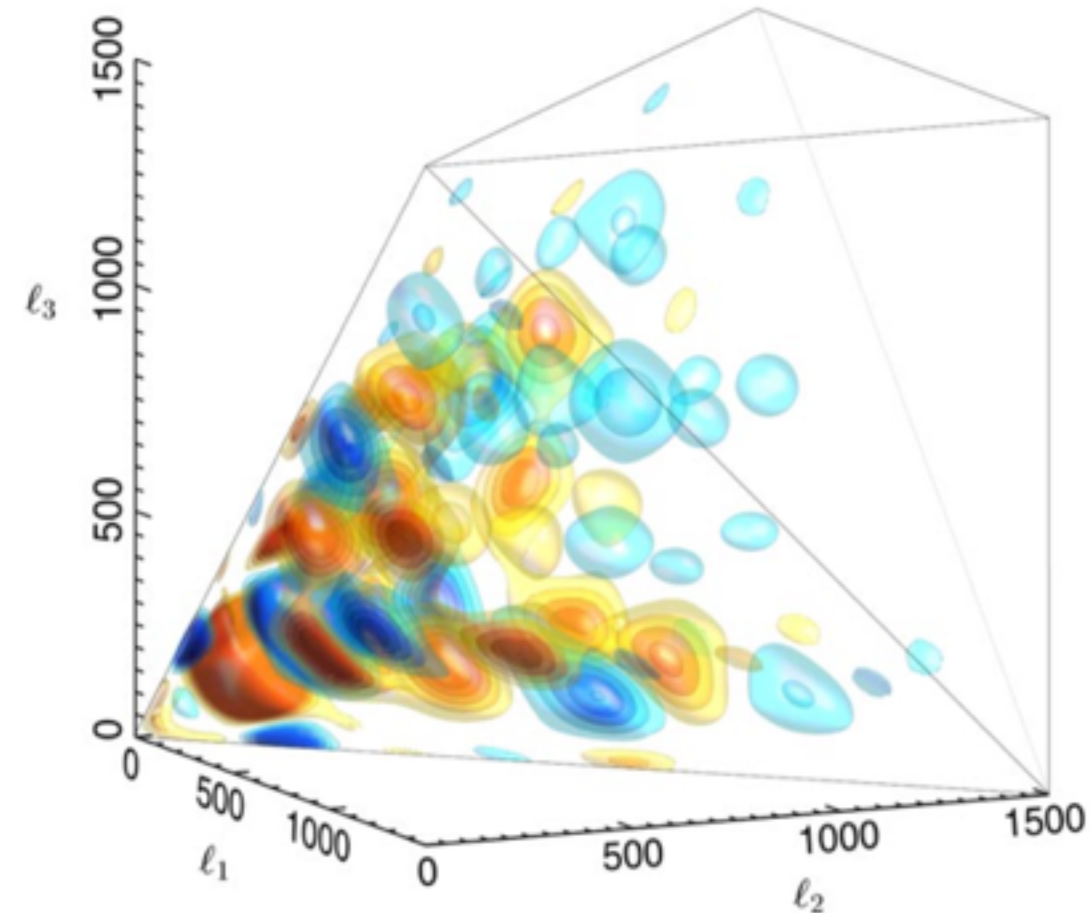
Appears in all channels

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]

Main results

1. A transient reduction of sound speed 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.

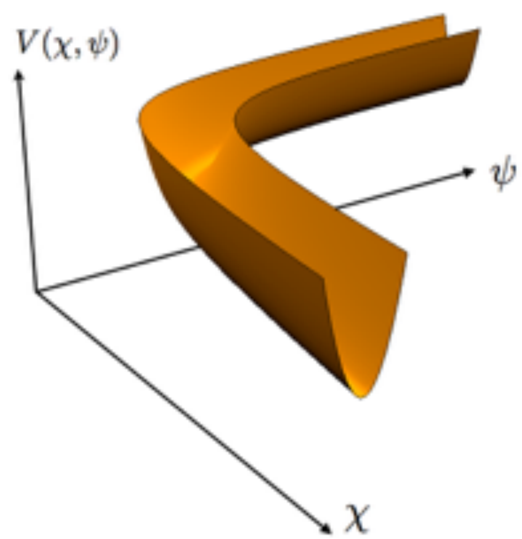
4. The statistical significance is not big enough to claim a detection.

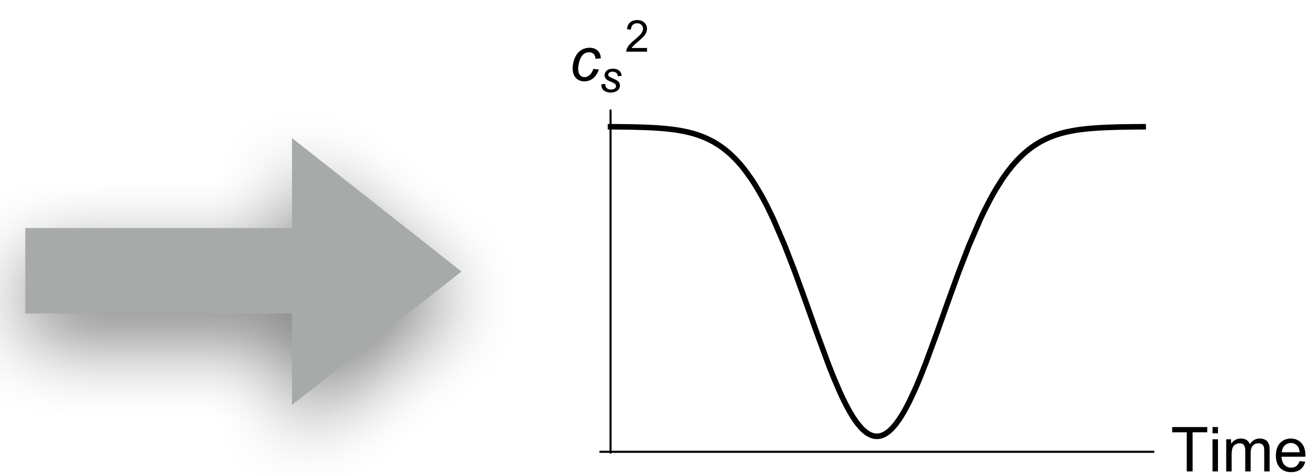
5. Based on our best-fit mode from power spectra, we have a specific **prediction** on the bispectrum, and we are waiting for Planck-2014(5) test.

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:

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

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

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

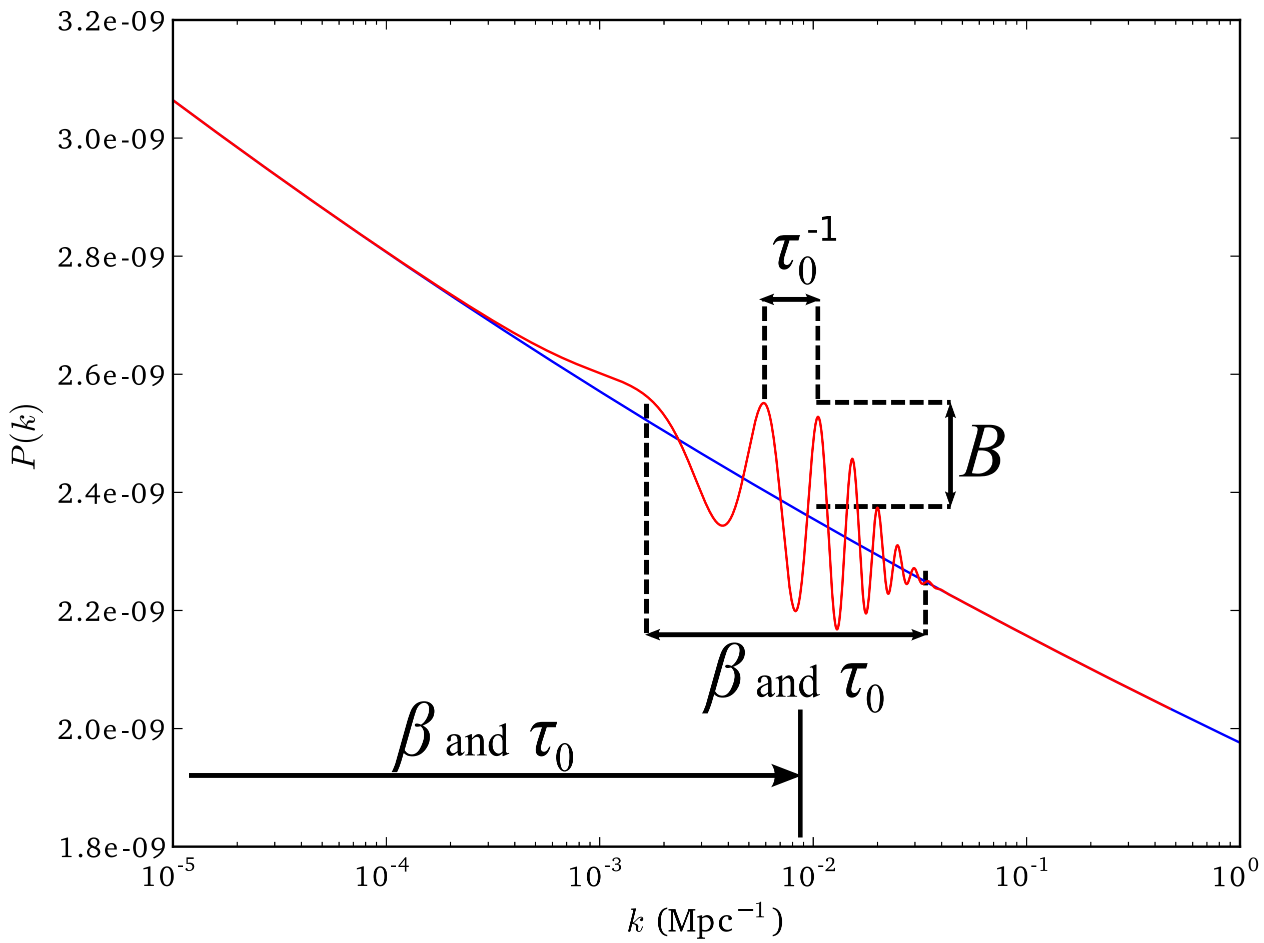
Do NOT interrupt slow roll condition!

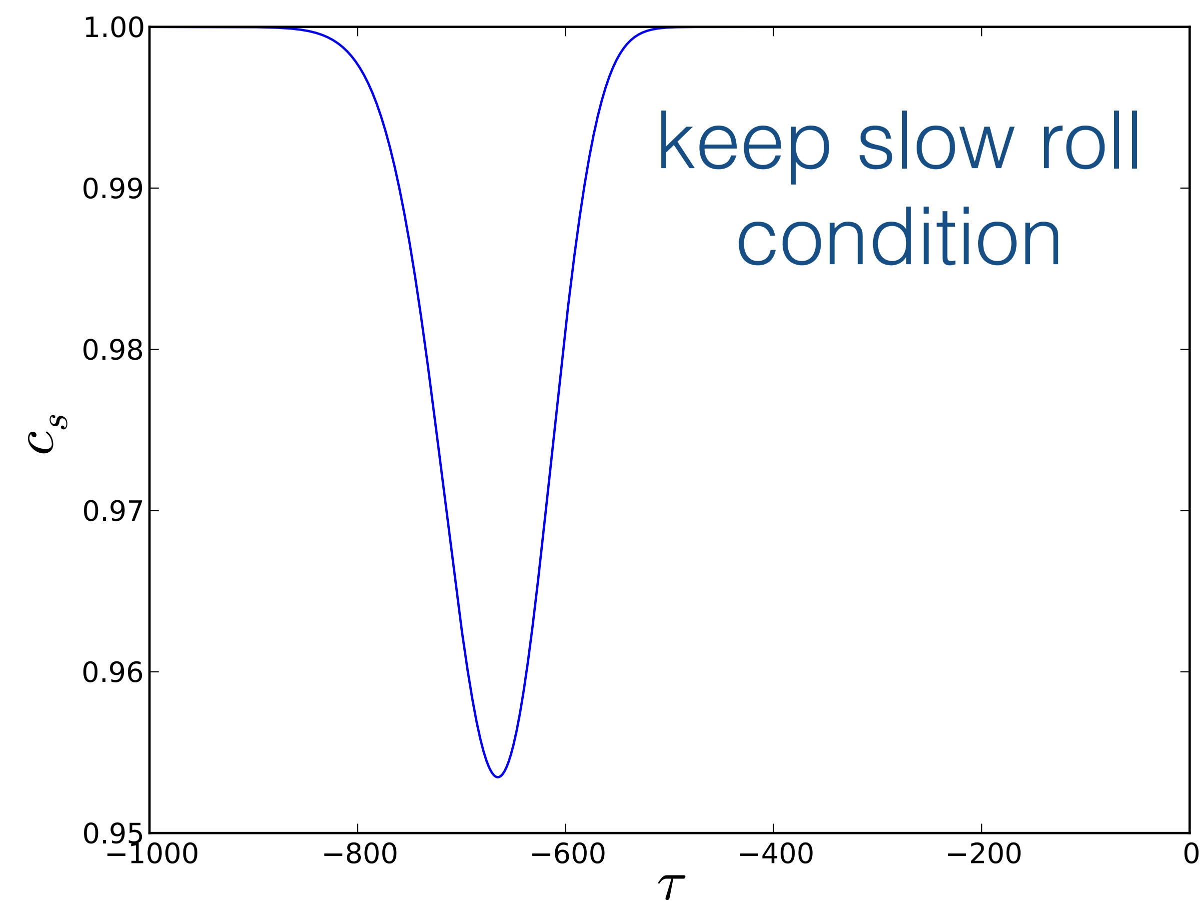
Oscillatory features in the transient sound speed reduction models— Power spectrum

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

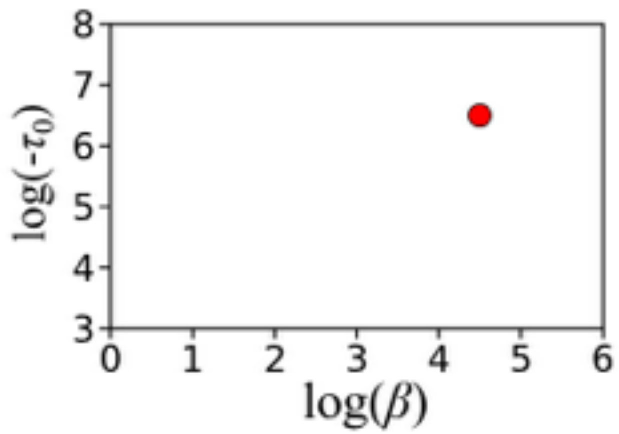
Gaussian reduction in e-folds [A.Achucarro et. al. PRD 89 (2014) 103006]

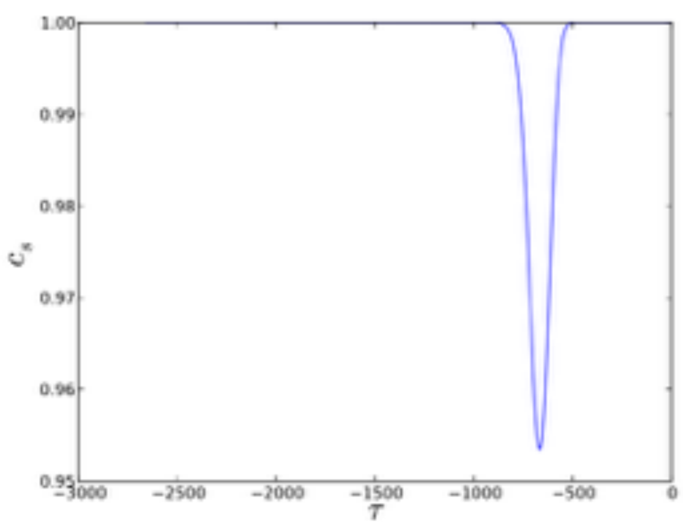
$$1 - c_s^{-2} = Be^{-\beta\left(\log \frac{\tau}{\tau_0}\right)^2}$$

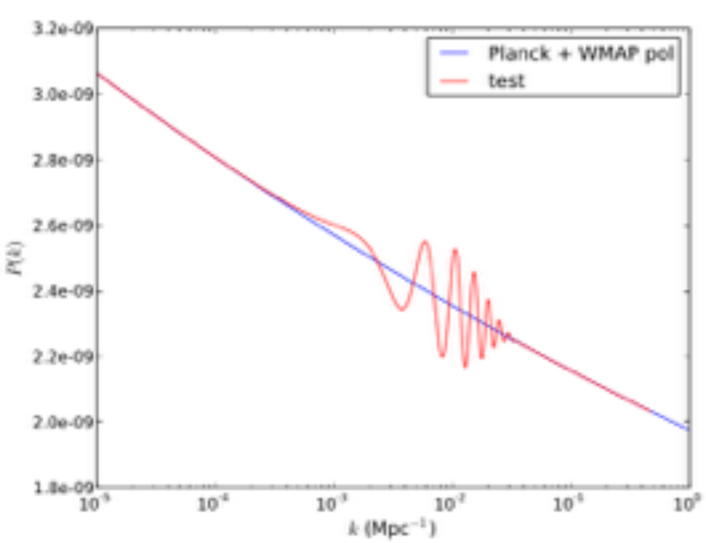


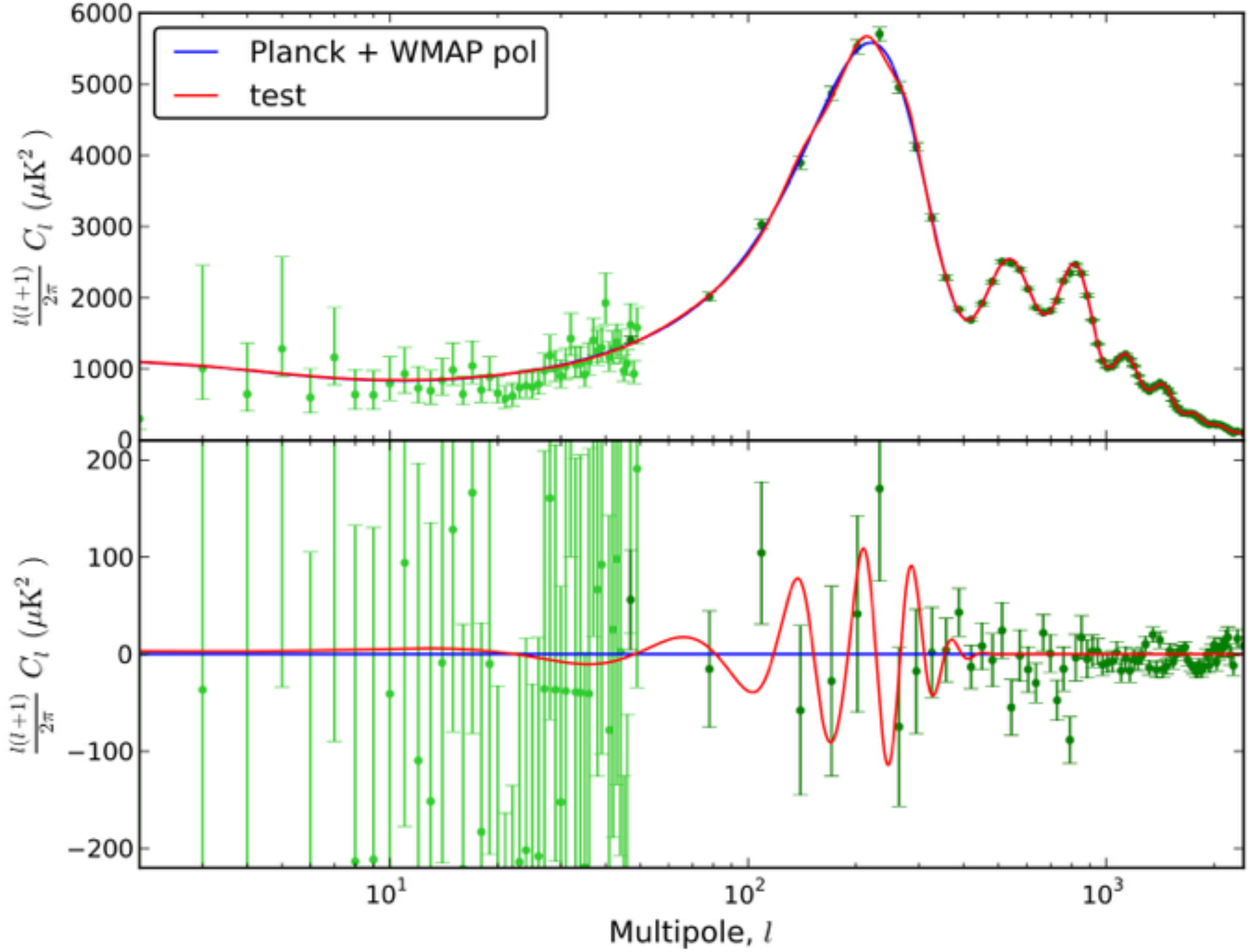


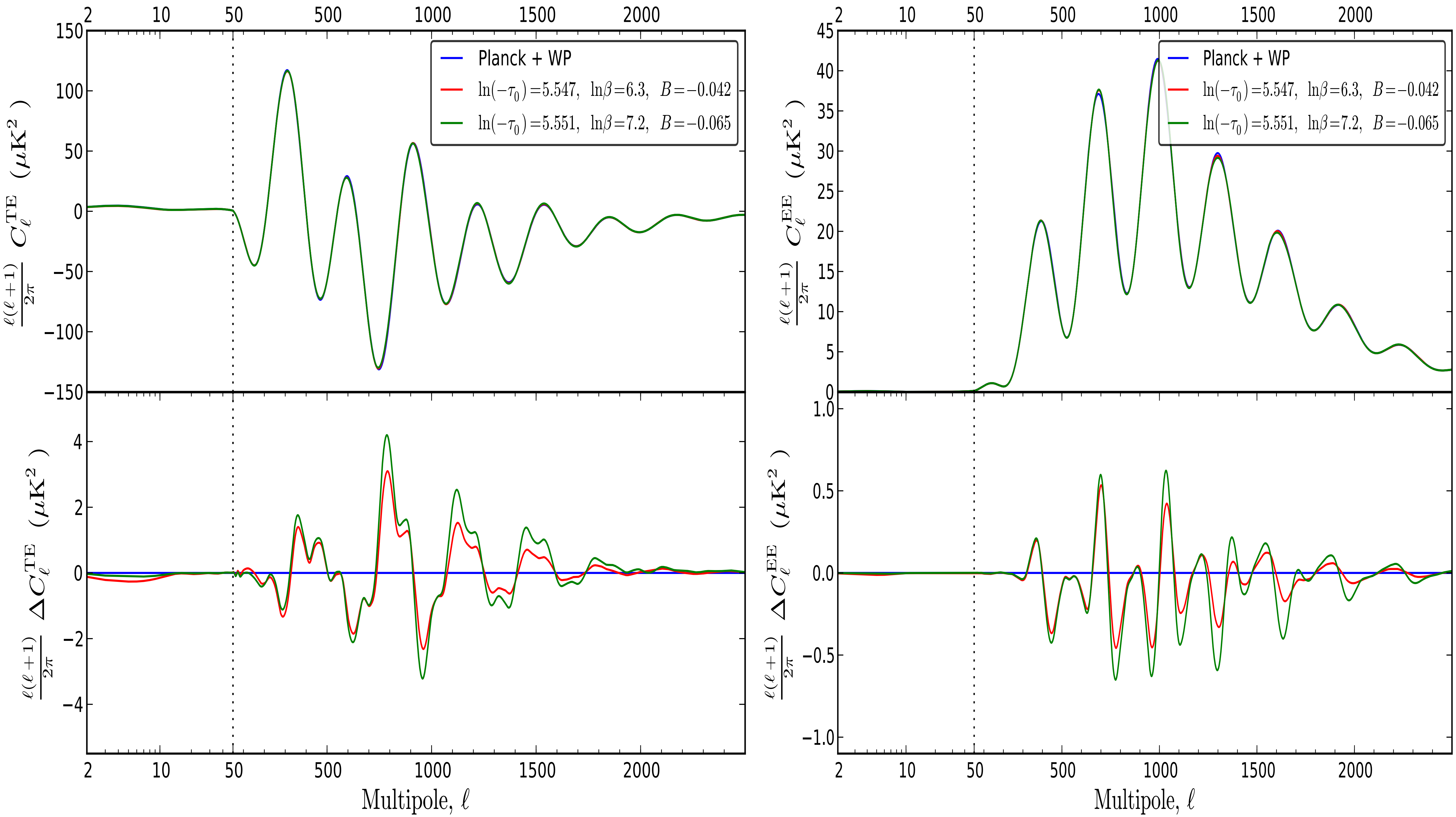
Some examples ($B = -0.1$)











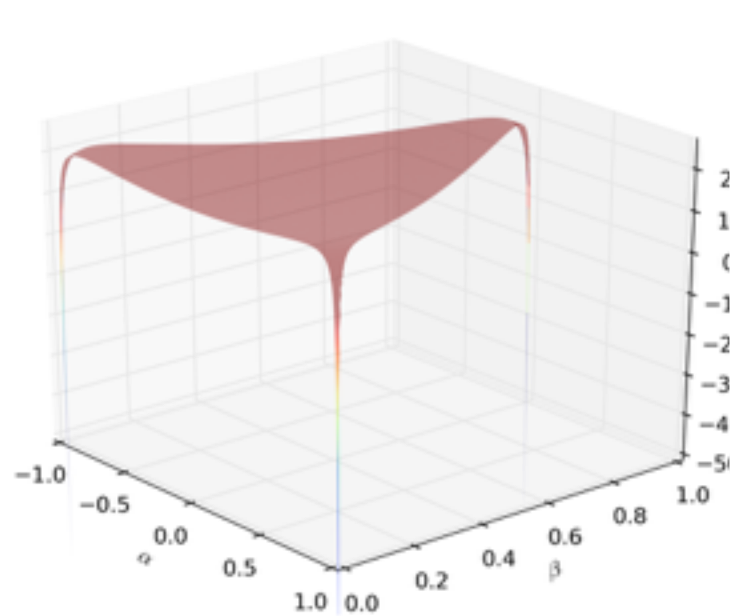
Planck + WP
ln(−τ0)=5.547, lnβ=6.3, B=−0.042
ln(−τ0)=5.551, lnβ=7.2, B=−0.065
Multipole, ℓ

~ 10% effect

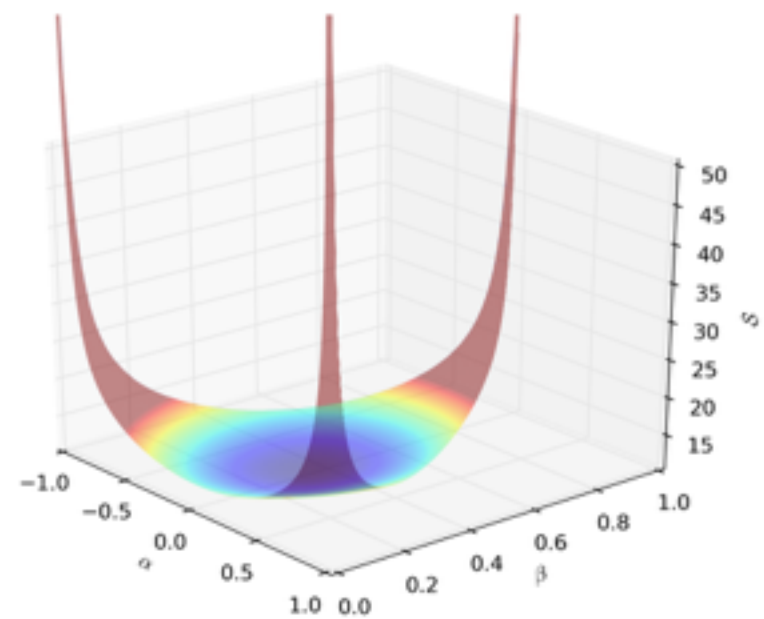
2. Primordial Bispectrum (leading order)

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

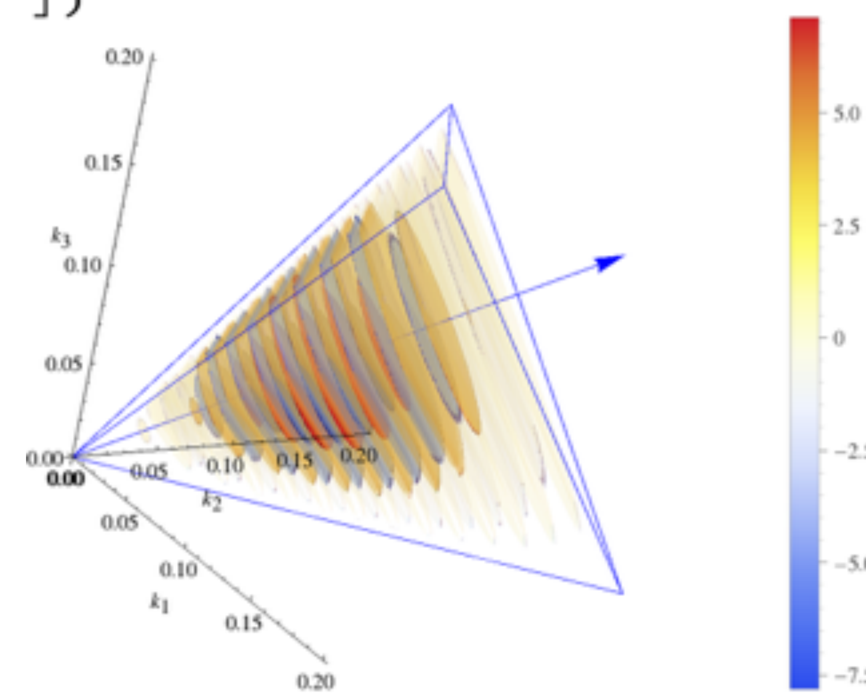
$$B(k_1,k_2,k_3) = \frac{6\Delta_\phi^2}{k_1^2k_2^2k_3^2}\frac{(2\pi)^4}{96}\frac{|B|\mathcal{D}_s(K)k_1^2}{k_1k_2k_3}$$
$$\left\{\tau_0\cos(\tau_0K)\left[k_2(k_1-k_3)+\frac{\tau_0^2}{2\beta}Kk_2k_3\left(\frac{3}{2}k_1-k_2\right)-\frac{1}{2\beta}\left(\frac{1}{2}k_1^2-k_2^2\right)\right]\right.$$
$$\left.+\sin(\tau_0K)\left[\frac{1}{2}\tau_0^2k_1k_2k_3-\frac{1}{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



$K = 0.19$



$K = 0.21$

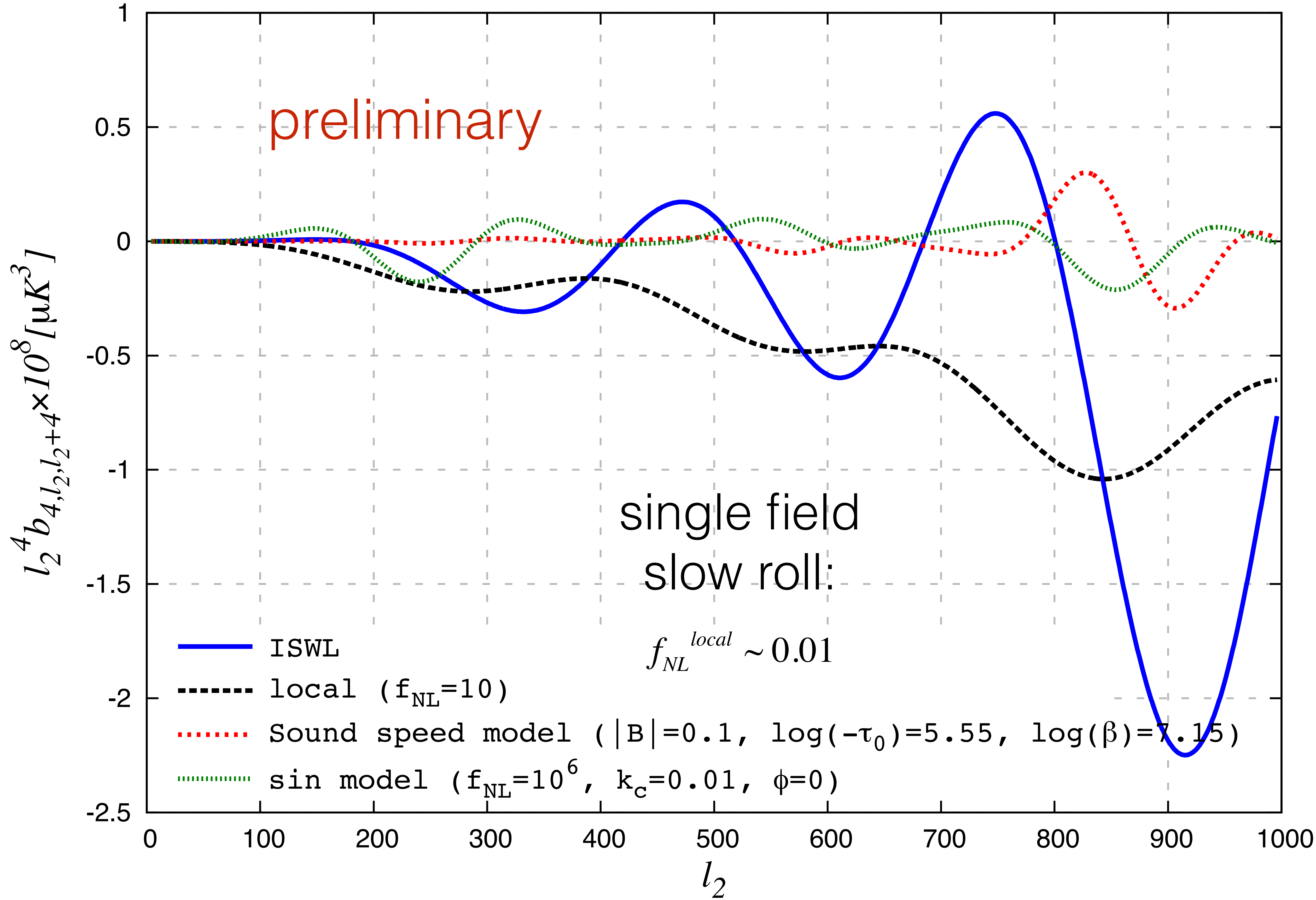


removing $\frac{1}{k_1^3k_2^3}+\frac{1}{k_1^3k_3^3}+\frac{1}{k_2^3k_3^3}$

Step in sound speed:

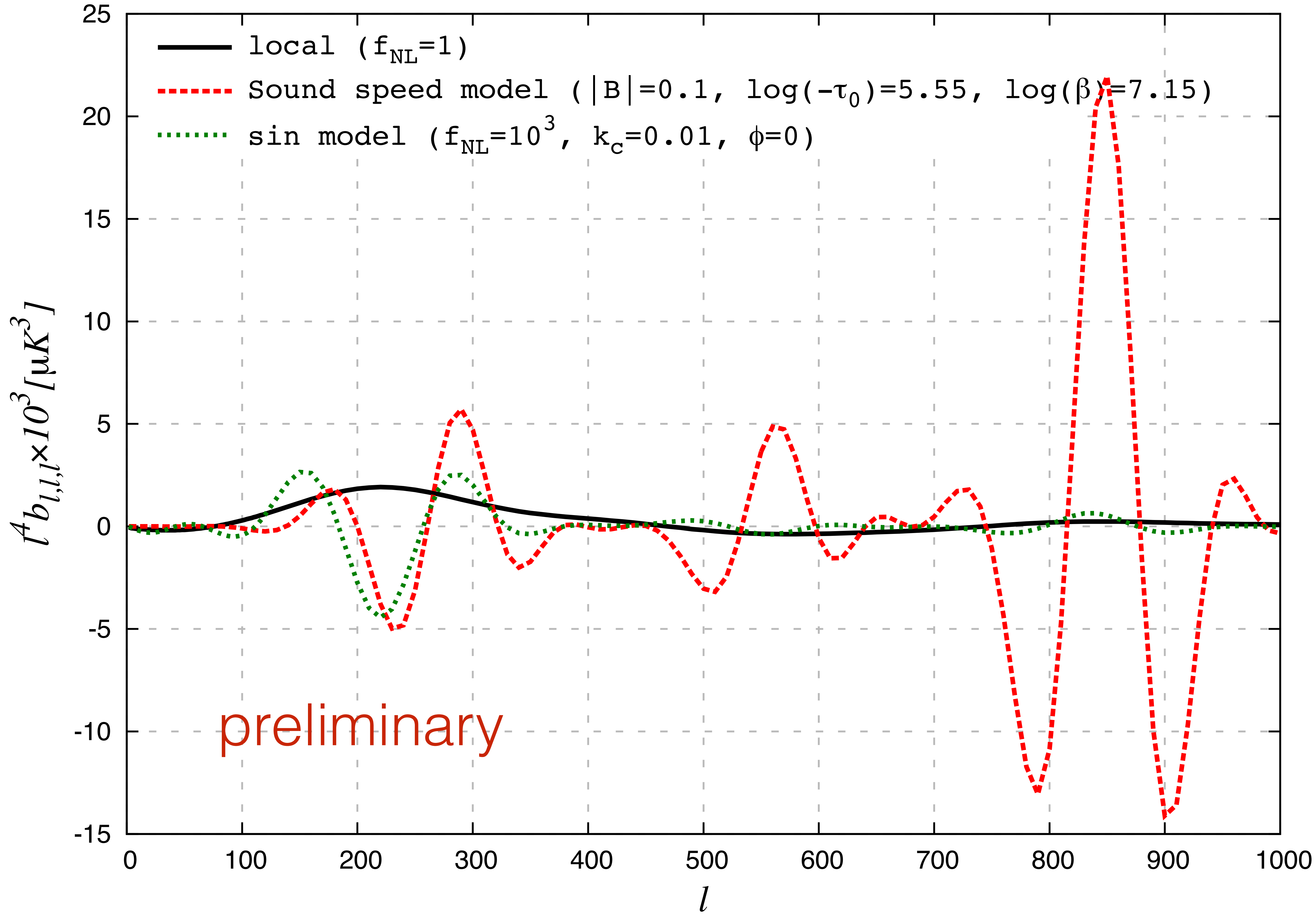
[Adshead et al. PhysRevD.84.043519], [Bartolo et al. JCAP 1310 (2013) 038]
[Miranda et al. Phys.Rev. D86 (2012)], [Park et al. Phys.Rev. D85 (2012)]
[Adshead et al. PhysRevD.84.043519], [Nakashima et al. Prog.Theor.Phys. 125 (2011)]
[Bean et al. JCAP 0803 (2008) 026], [Cannone et al. Phys.Rev. D89 (2014)]

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

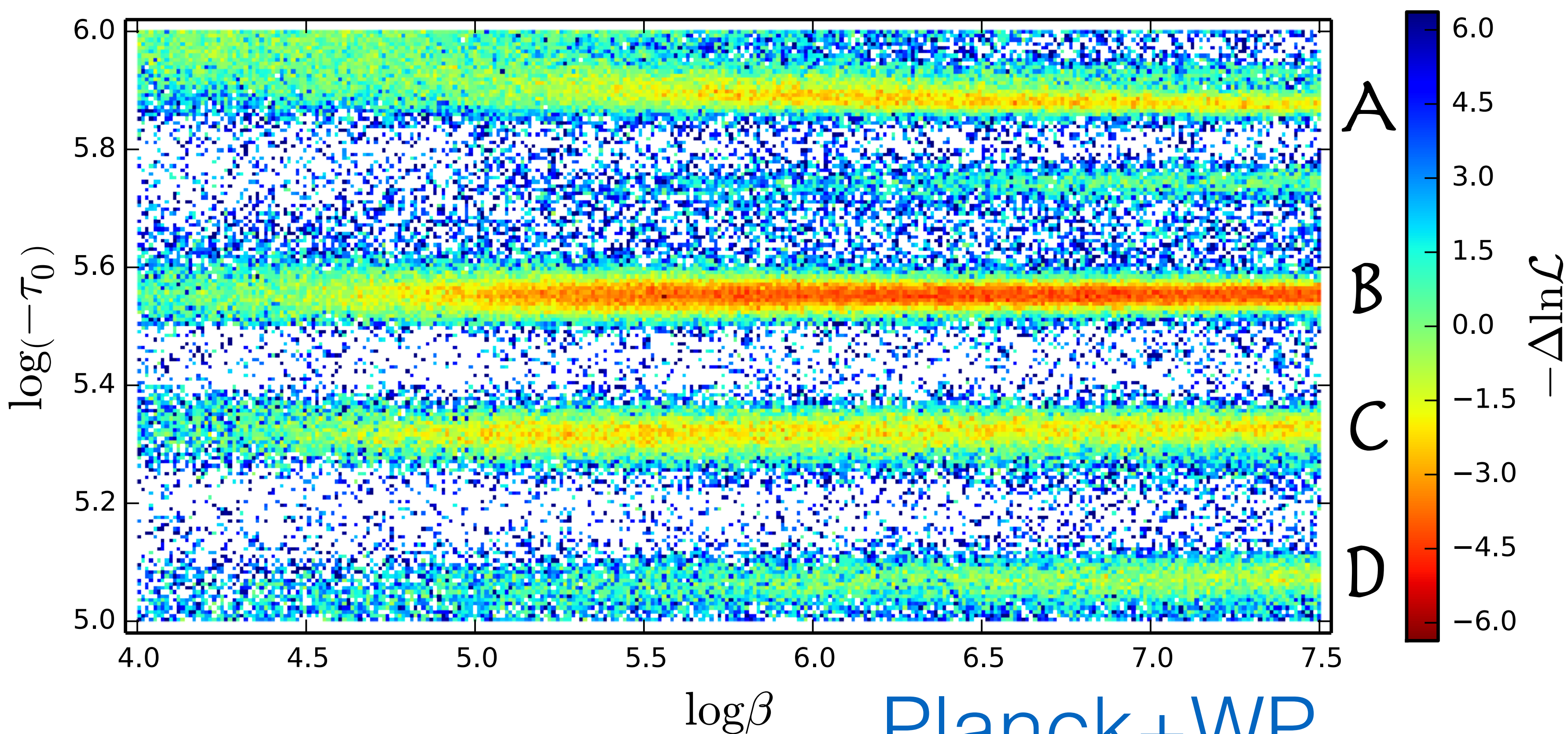
Danielsson (2002), Greene, Schalm, Shiu, v.d. Schaar (2004) Meerburg, v.d. Schaar, Corasaniti (2009), Jackson, Schaalm (2010), Gao, Langlois, Mizuno (2012, 2013), Saito, Takamizu (2013), Noumi, Yamaguchi (2013), Miranda, Hu, Dvorkin (2014), Cai, Chen, Ferreira, Quintin (2014) ...

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

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

3. Search with CMB map—TT spectrum

profile likelihood

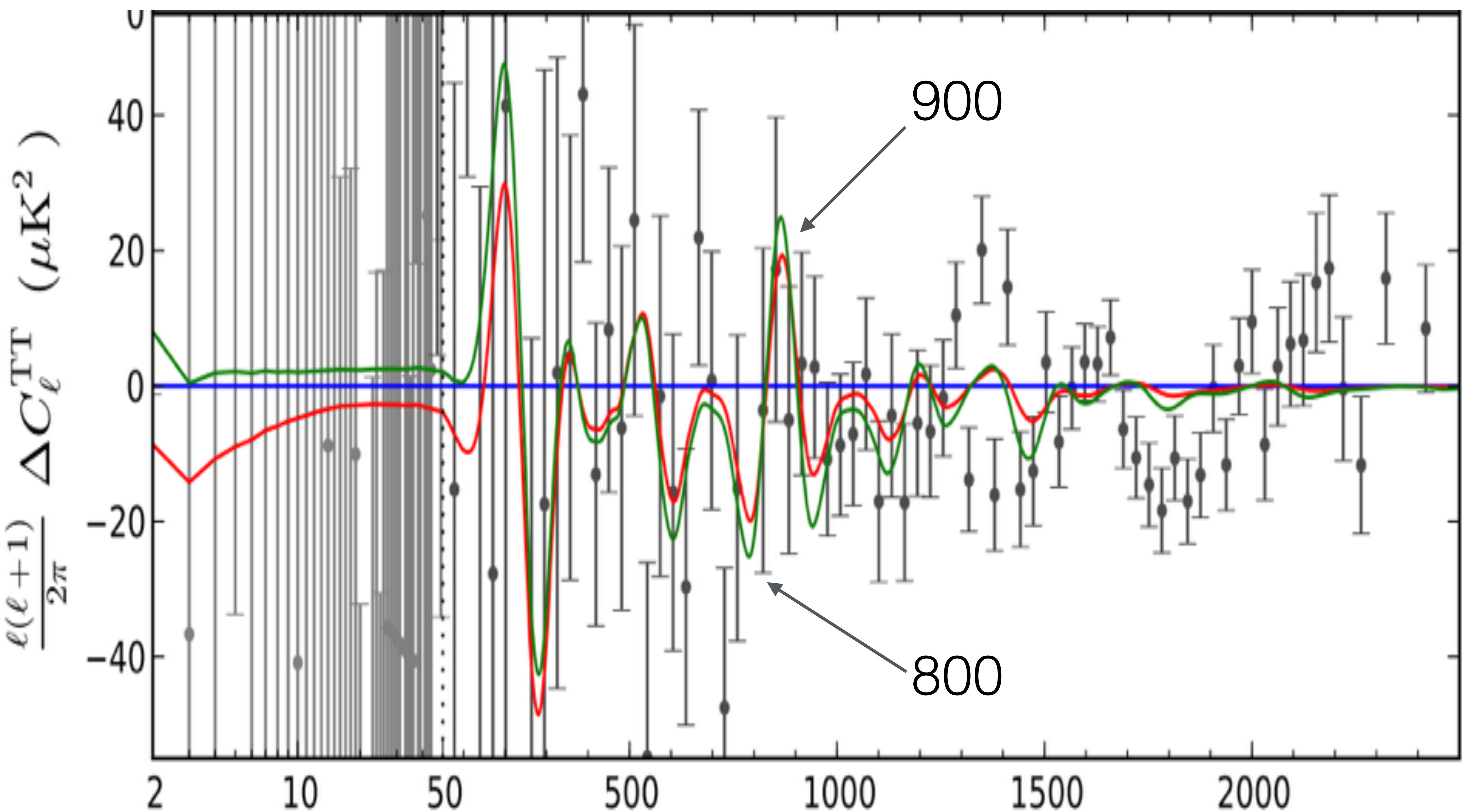


Planck+WP

#	$-B \times 10^2$	$\ln\beta$	$\ln(-\tau_0)$	$\Delta\chi^2$
$\mathcal{A}$	$(4.5)\, 3.7^{+1.6}_{-3.0}$	$(5.7)\, 5.7^{+0.9}_{-1.0}$	$(5.895)\, 5.910^{+0.027}_{-0.035}$	-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

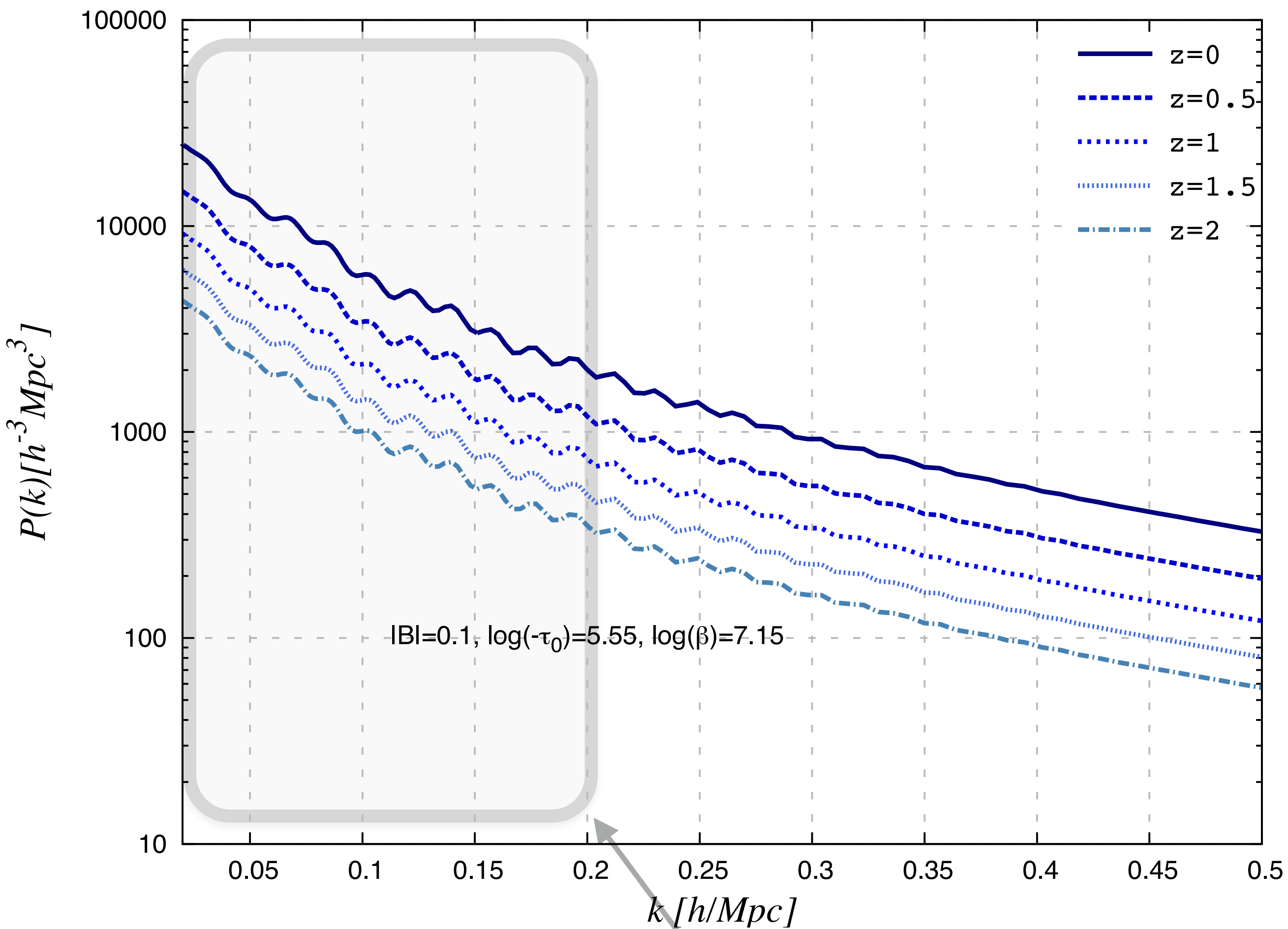
Also see Meerburg's talk

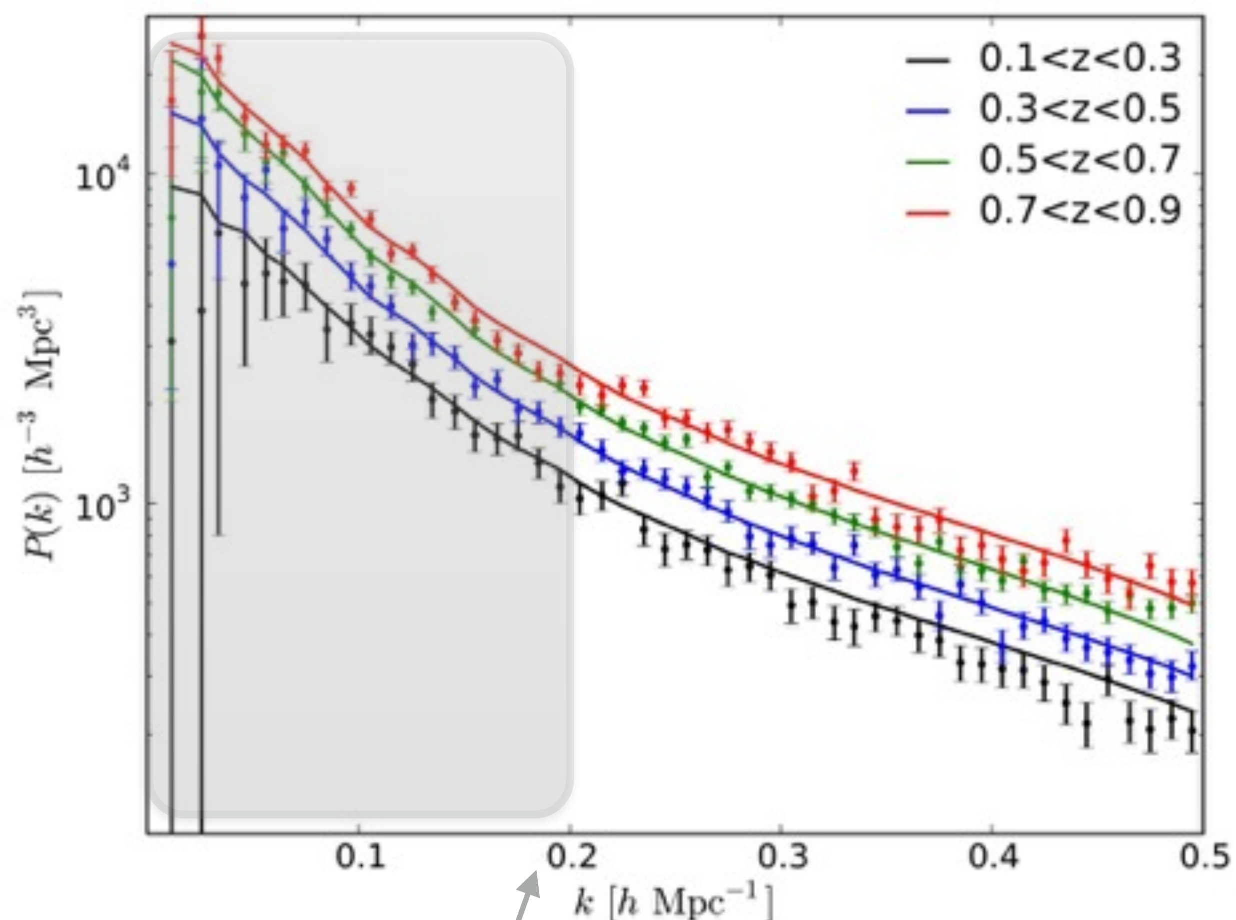
degeneracy of featured and vanilla parameters is negligible



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

4. Search with LSS survey—WiggleZ

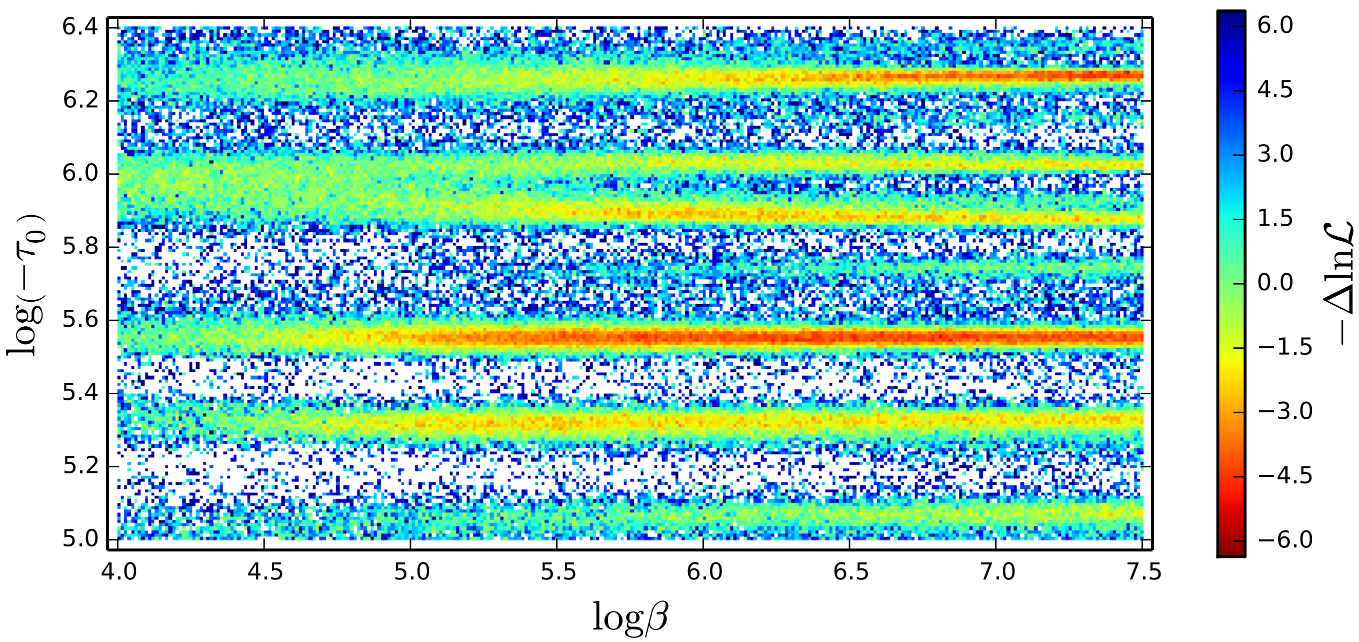




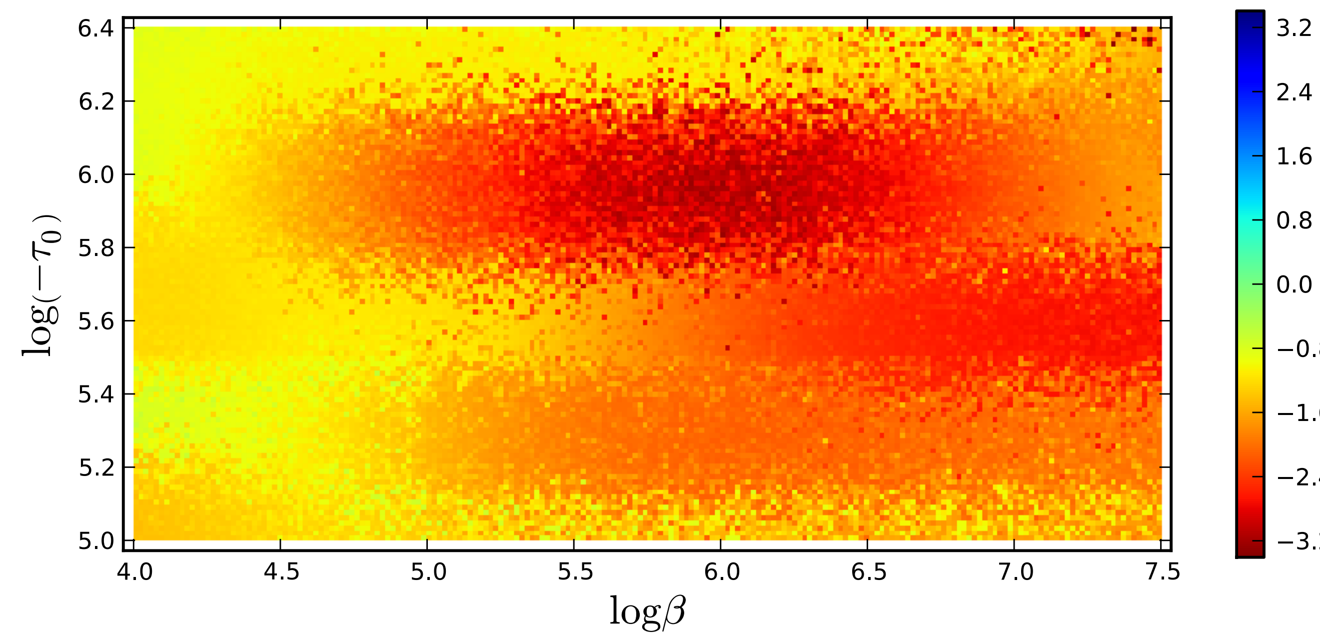
features shows around k~(0.1,0.2)

Search up to k=0.2

Independent search with different data

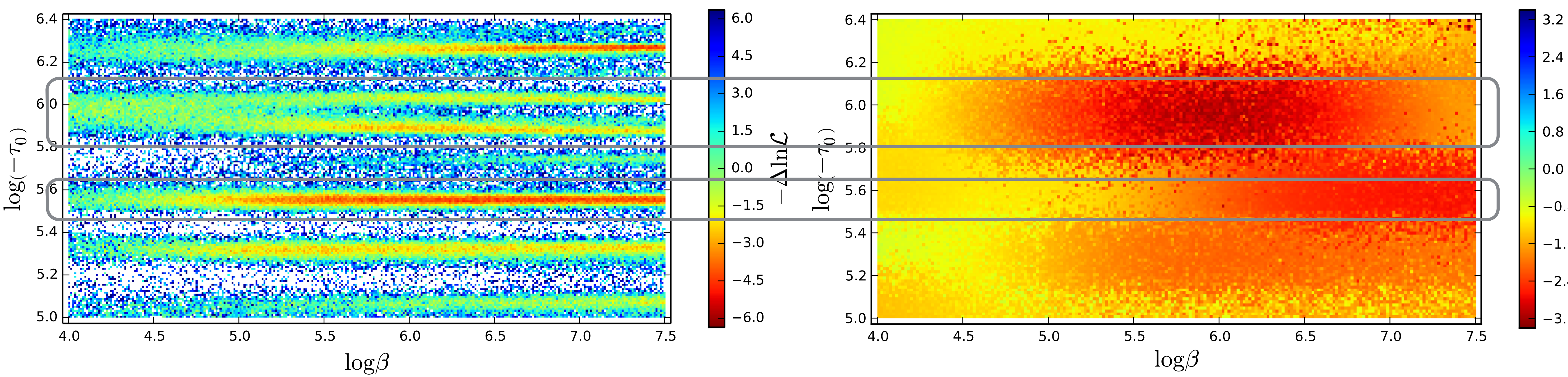


Planck+WP



WiggleZ

Independent search with different data

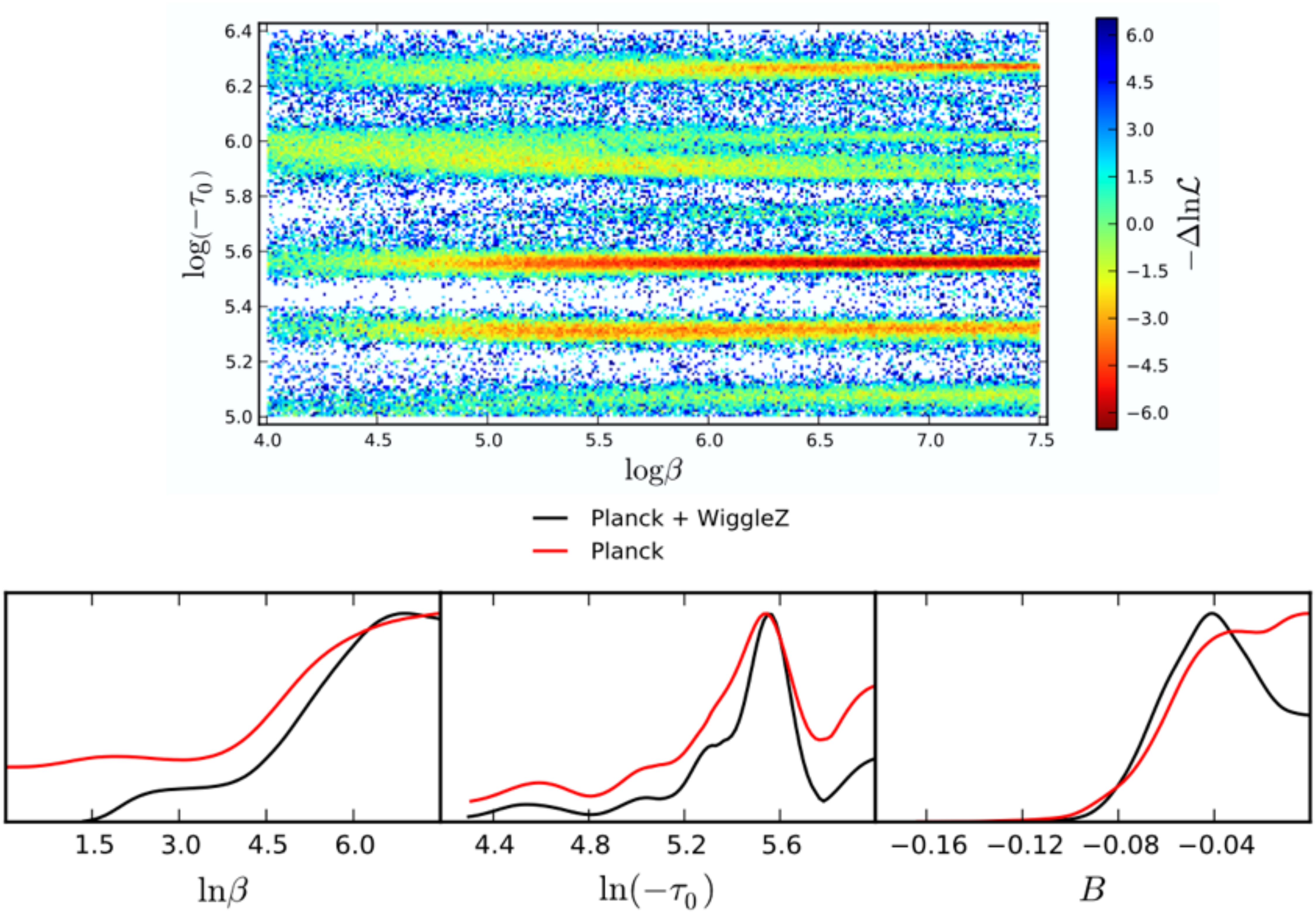


Planck+WP

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

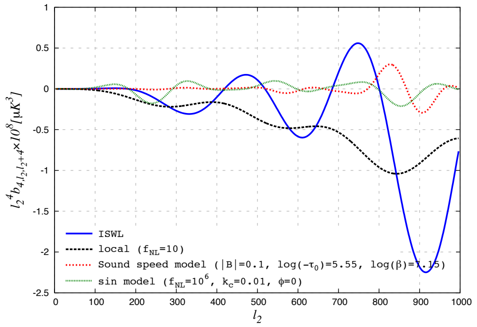
M_1 : Sound speed model

R<1: data faver M0

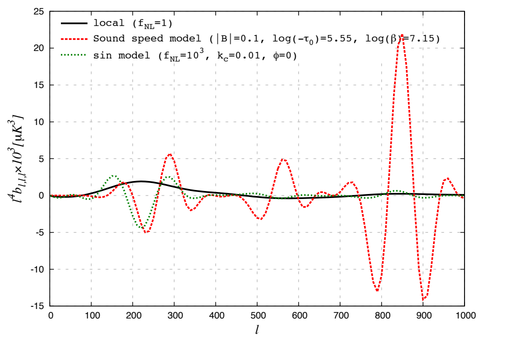
R>1: data faver M1

Model	Data set	$-2\ln\mathcal{L}$	$\ln\mathcal{Z}$	R
		posterior	evidence	Beyesian ratio
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



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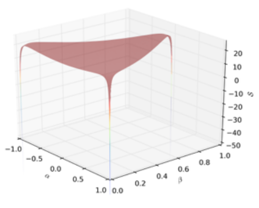
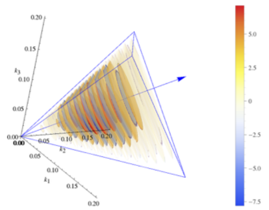
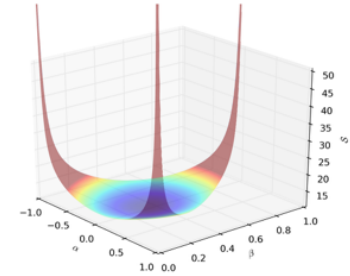




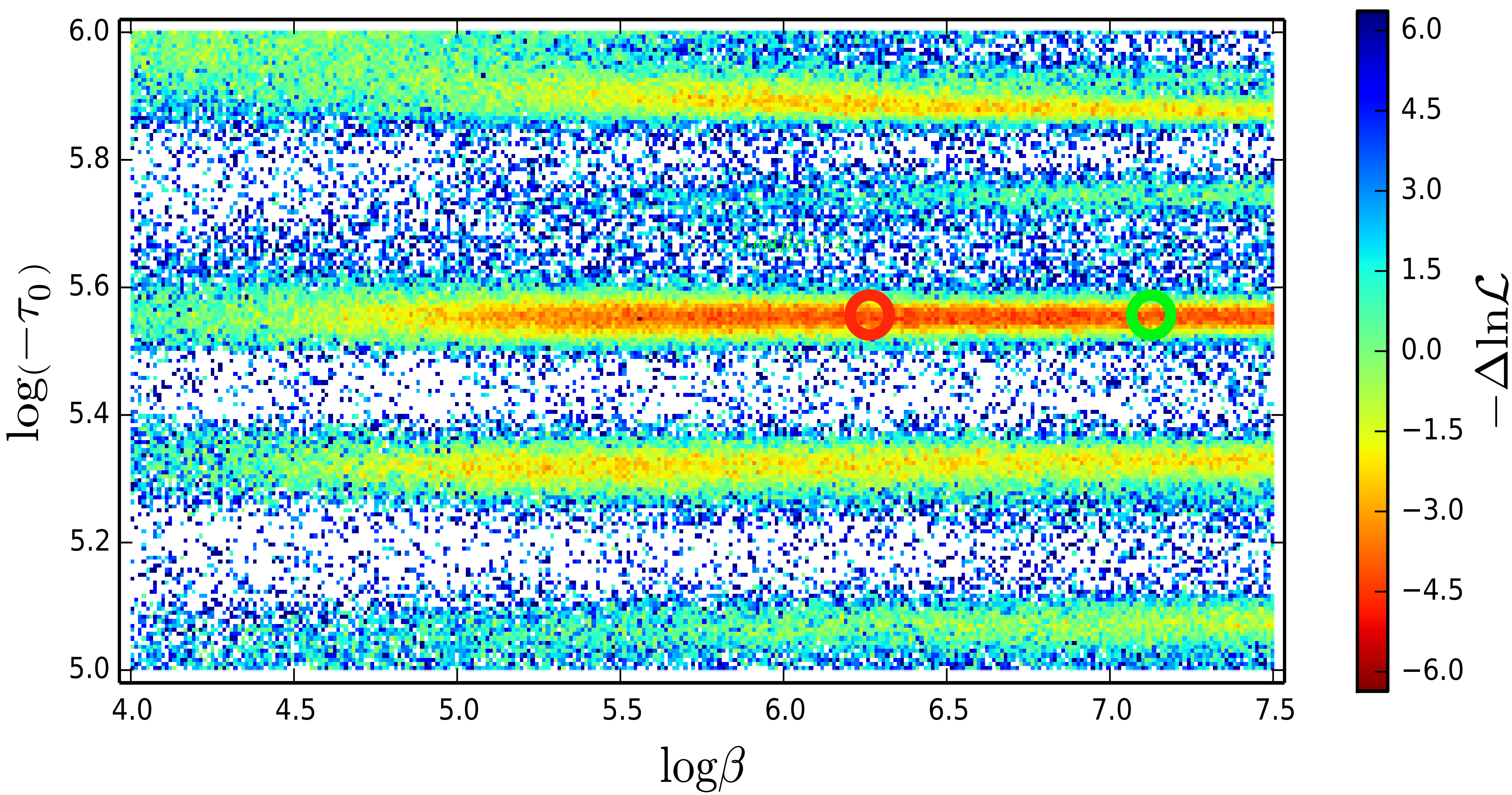


Thanks for your attention!

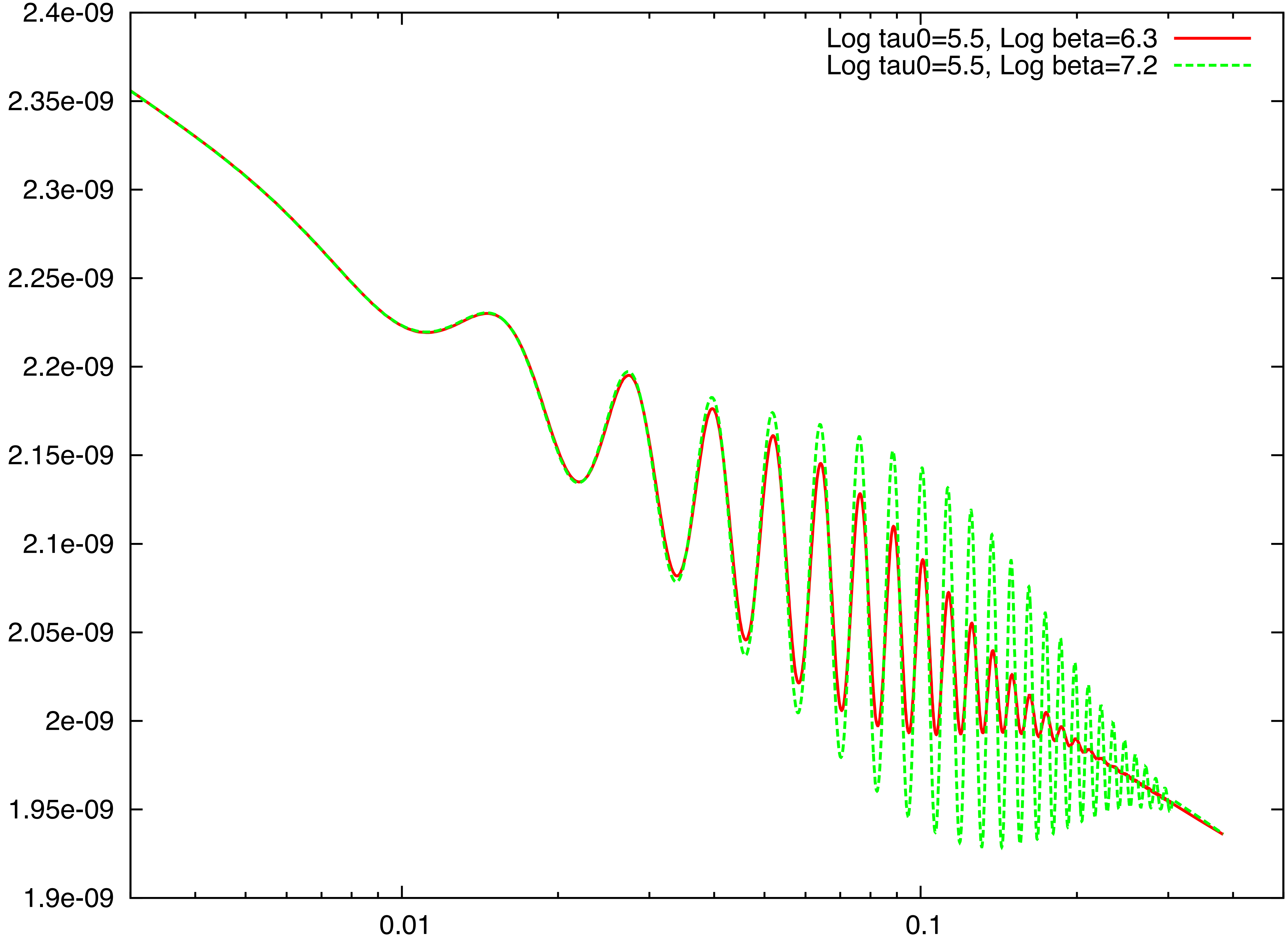
Merry Xmas to Planck!

bonus slide

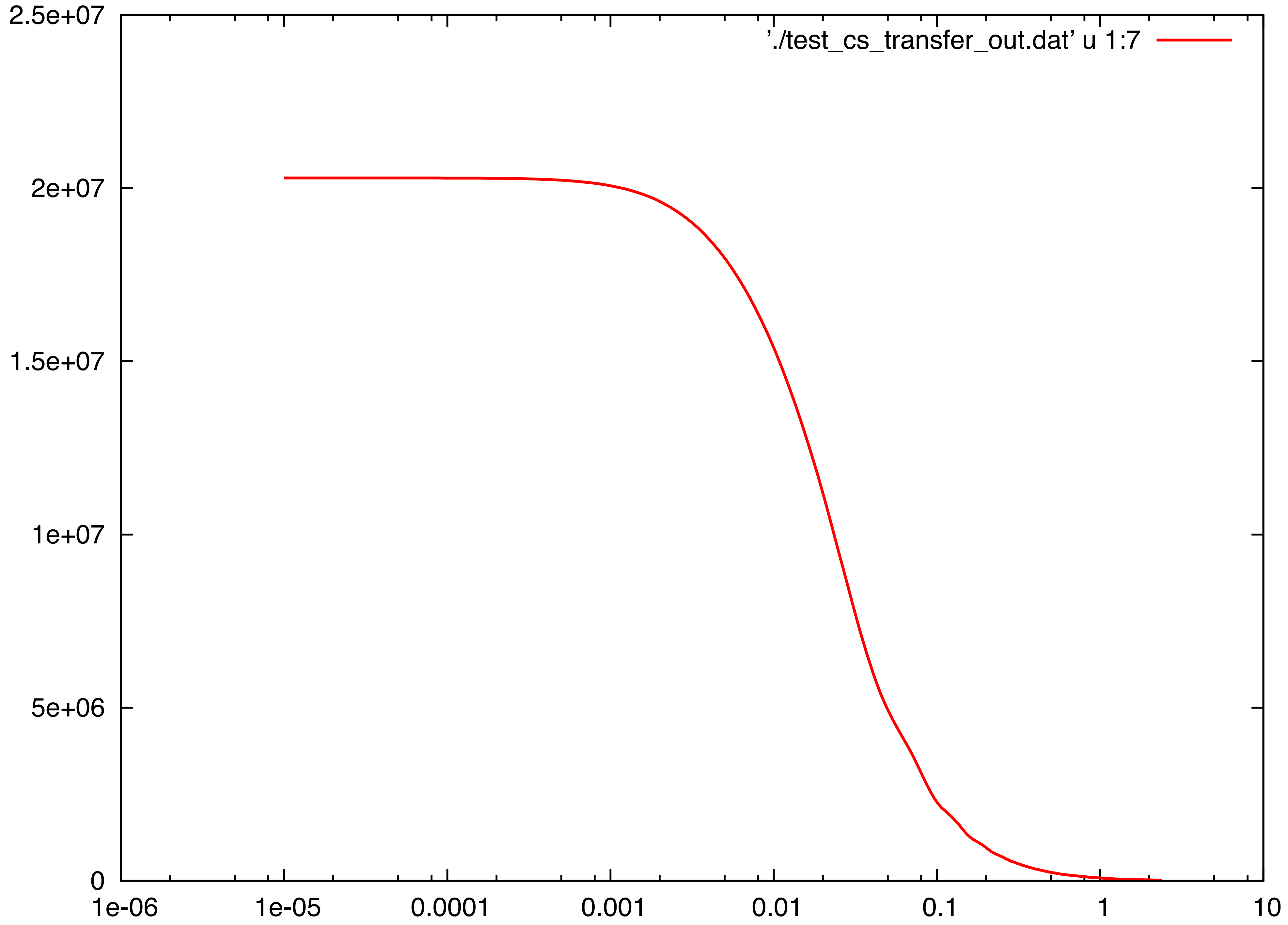
Two mode with the same frequency $Log(-\tau_0) = 5.5$ but with different location $Log(\beta) = 6.3$ (red) $Log(\beta) = 7.2$ (green)



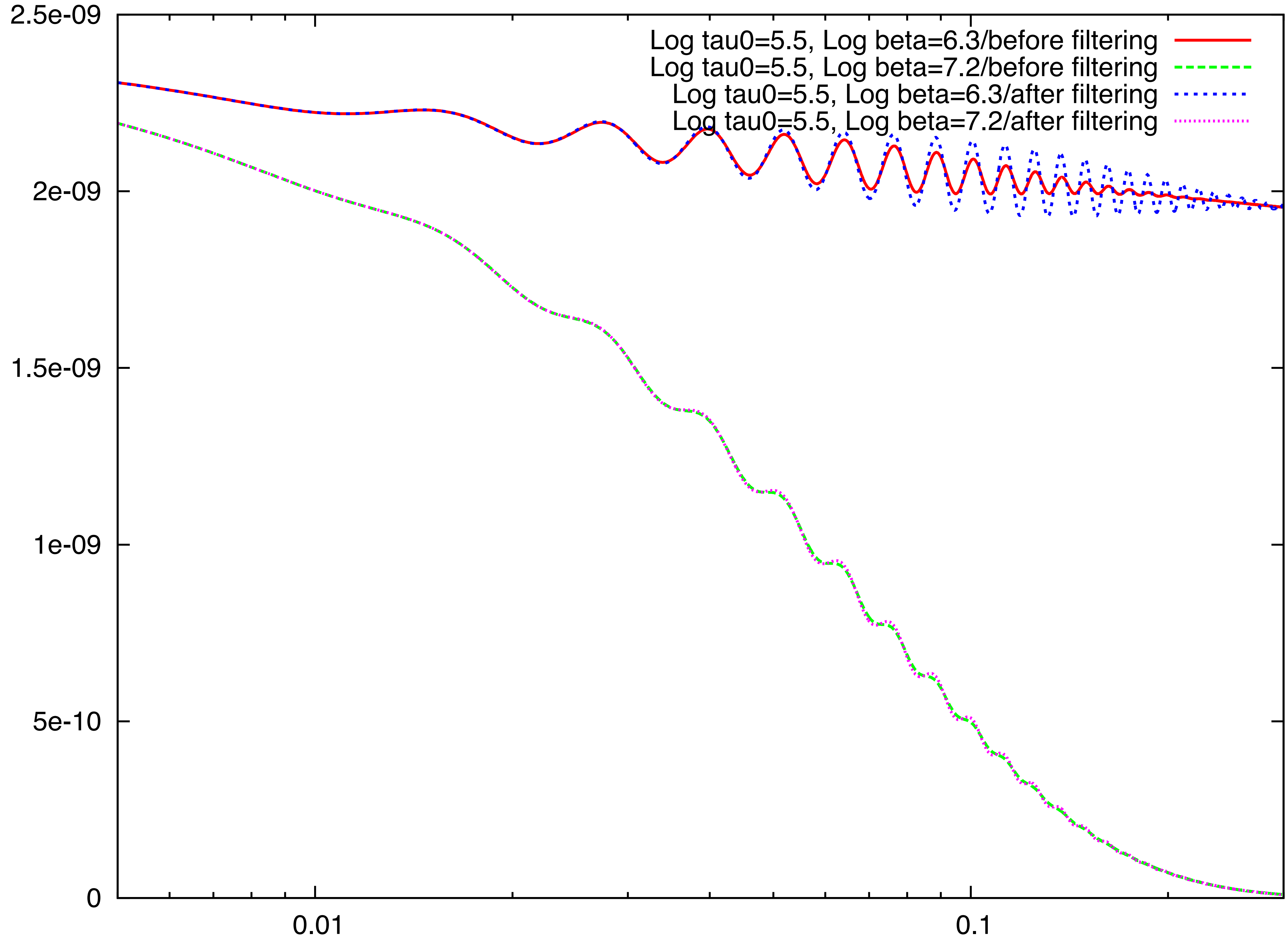
Primordial power spectrum



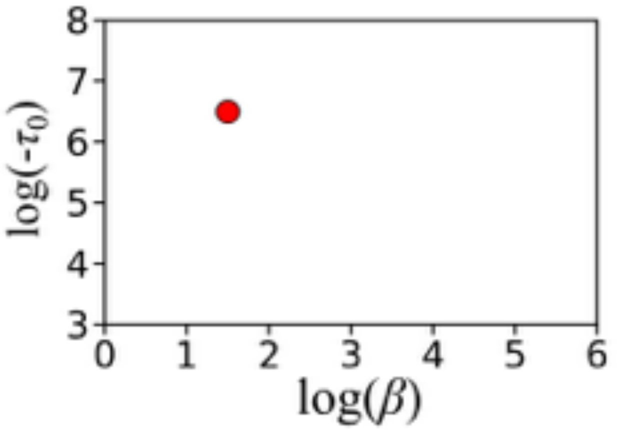
Transfer function

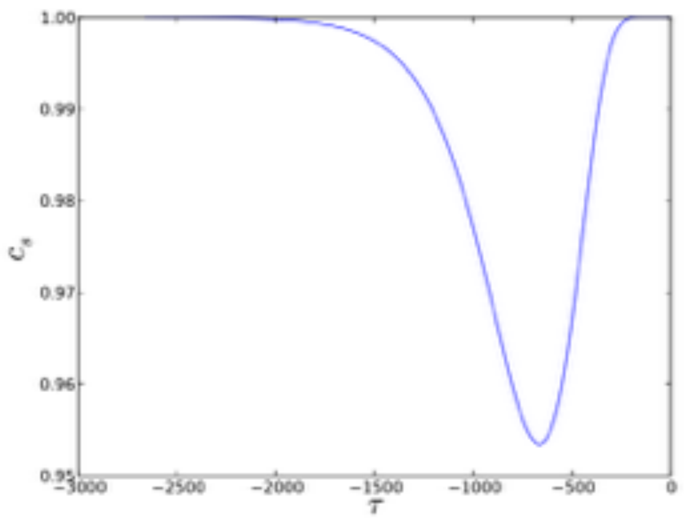


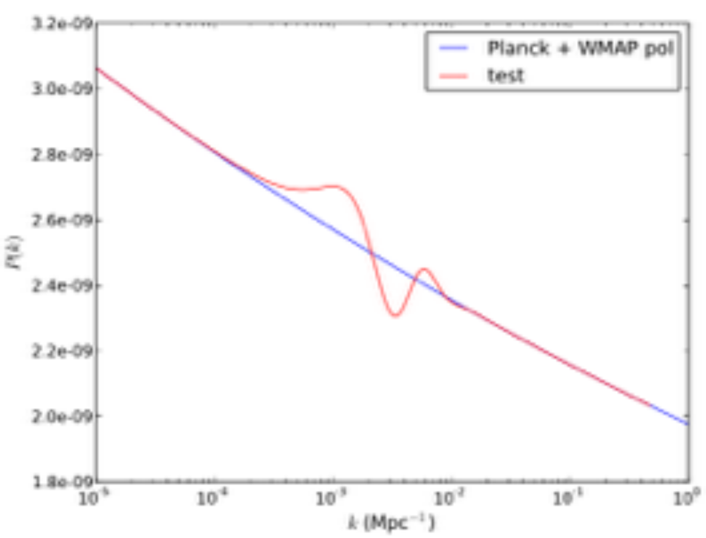
After convolving with transfer function they looks similar, due to the damping effect on small scale

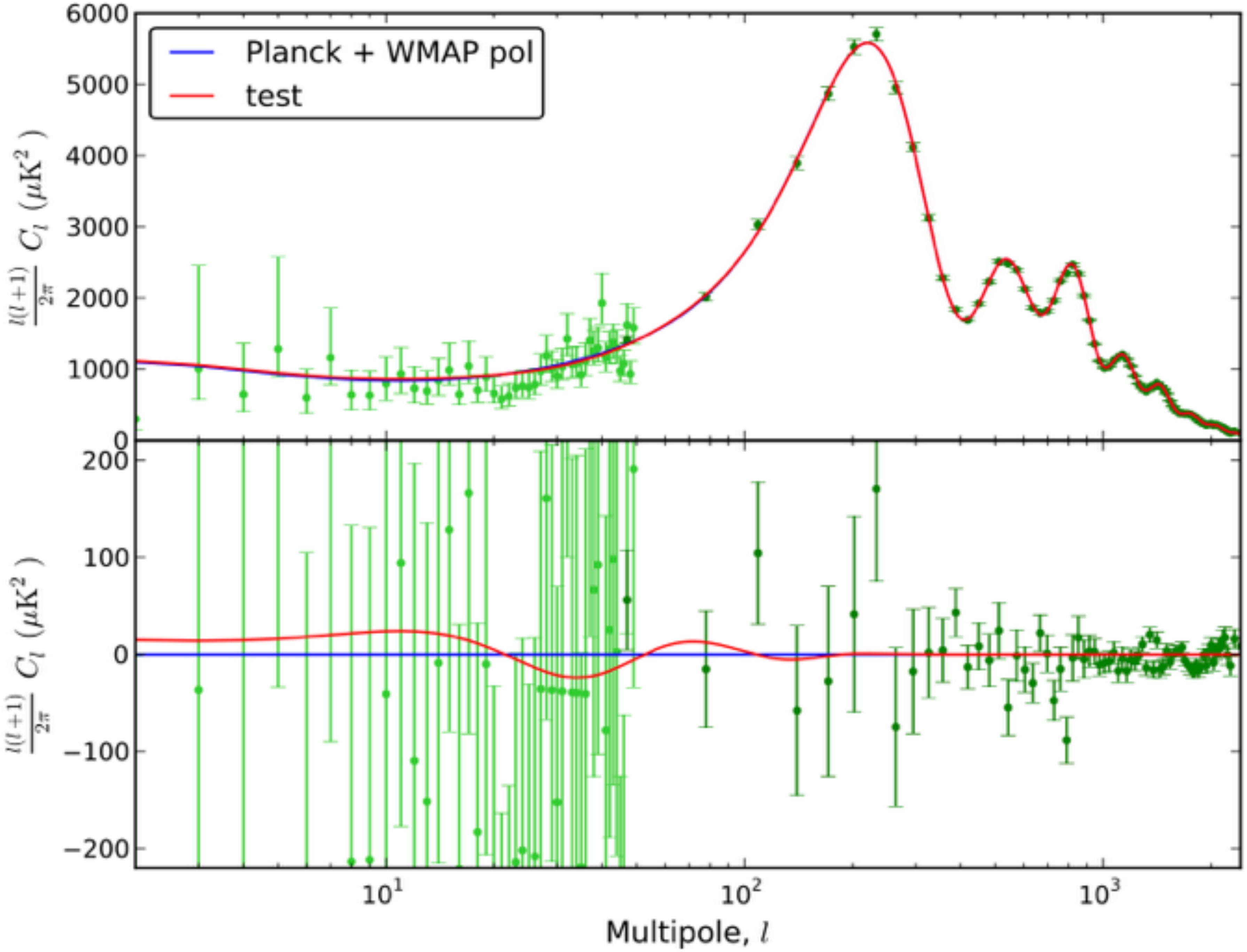


Some examples ($B = -0.1$)

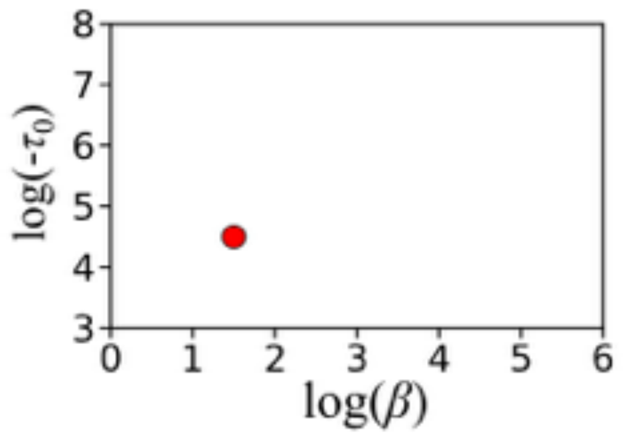


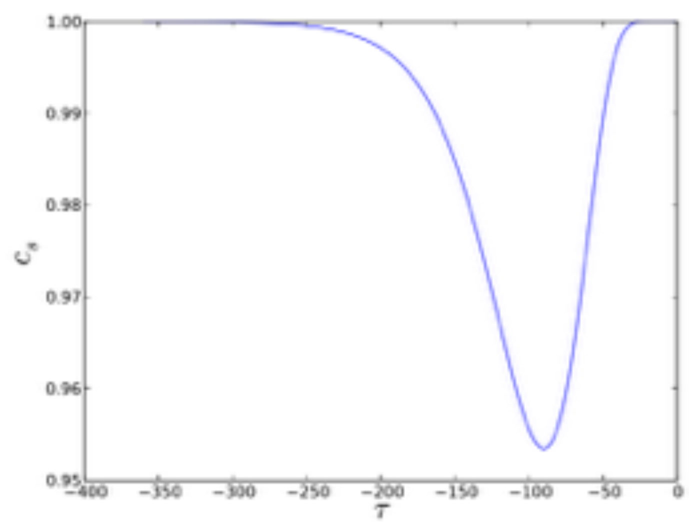


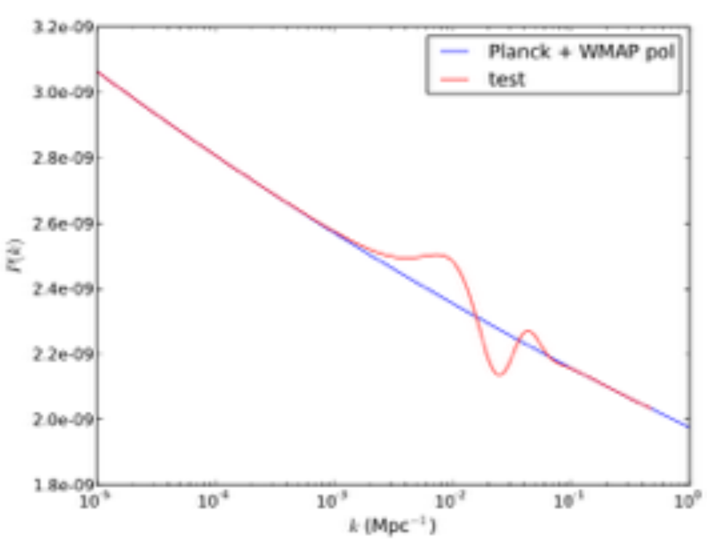


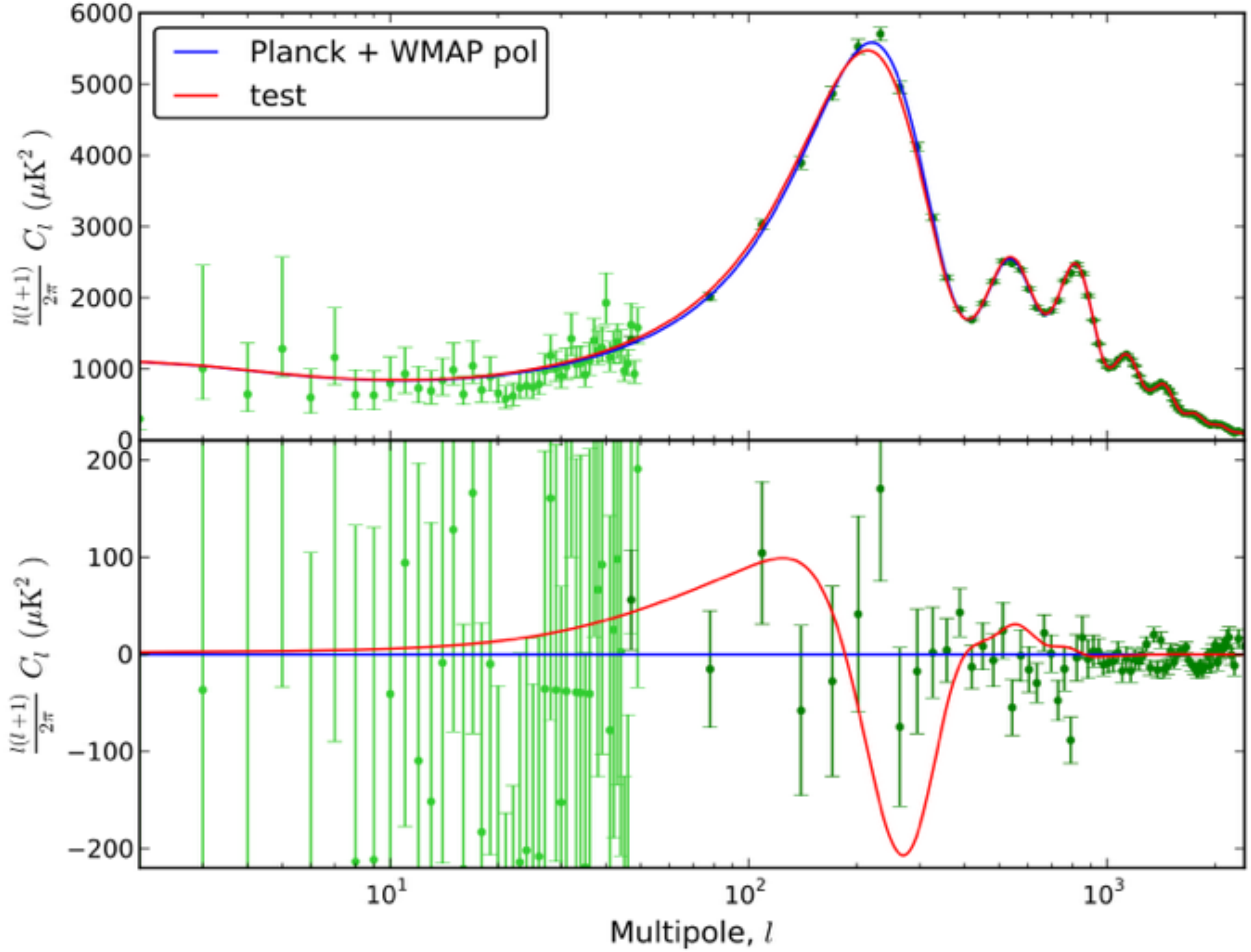


Some examples ($B = -0.1$)

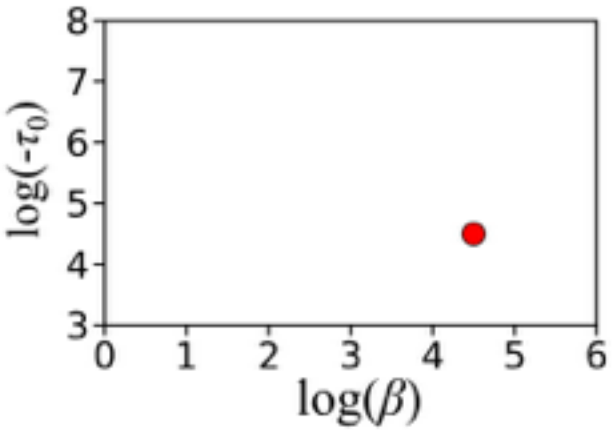


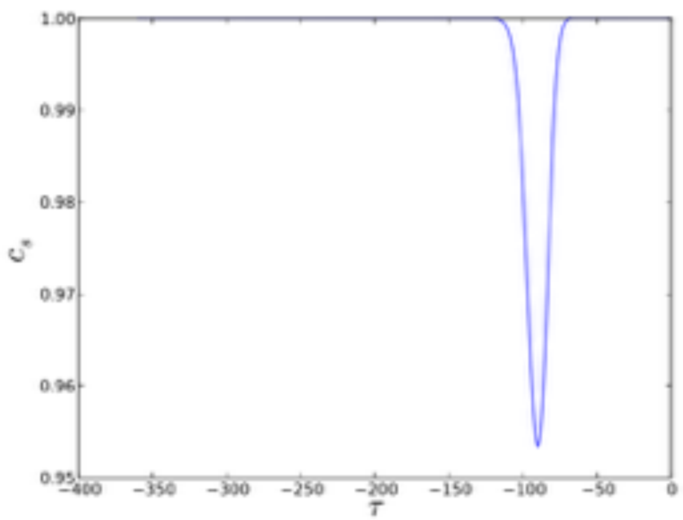


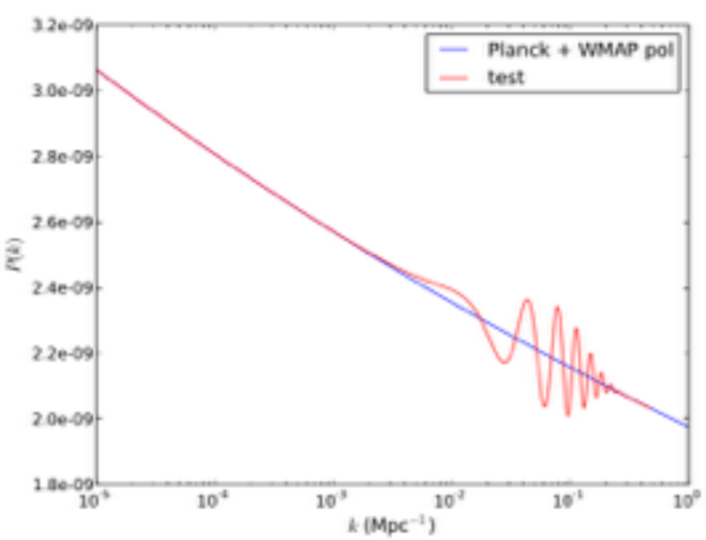


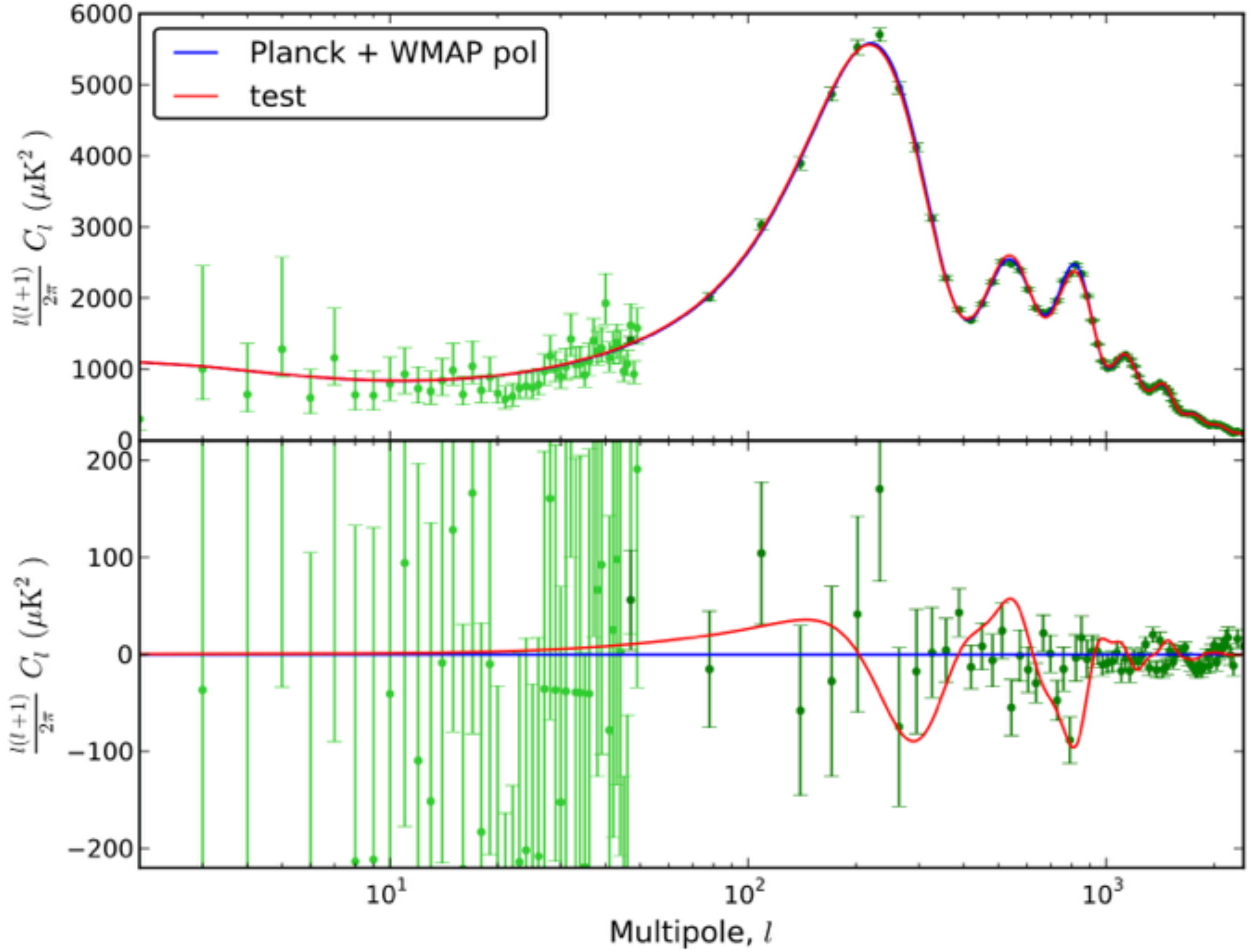


Some examples ($B = -0.1$)



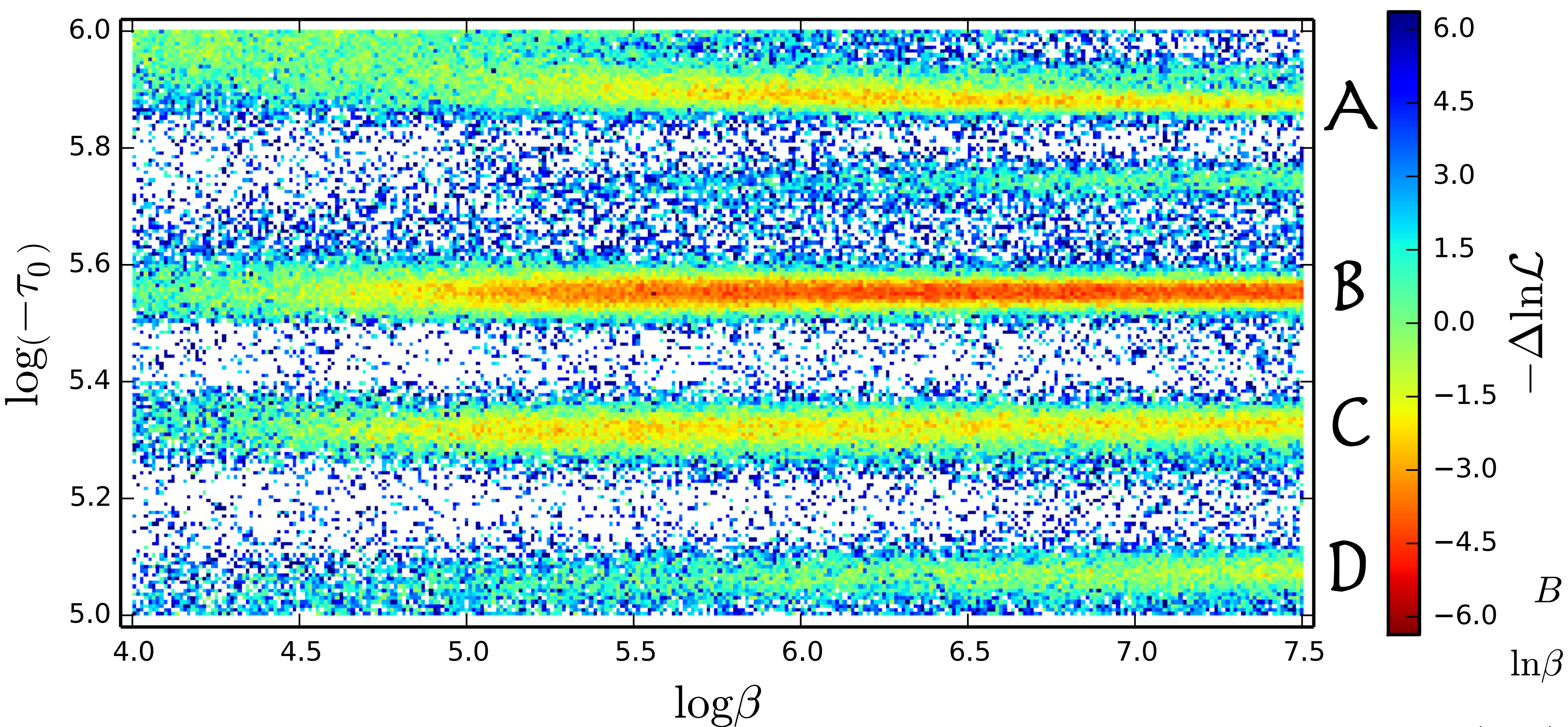






3. Search with CMB map—TT spectrum

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

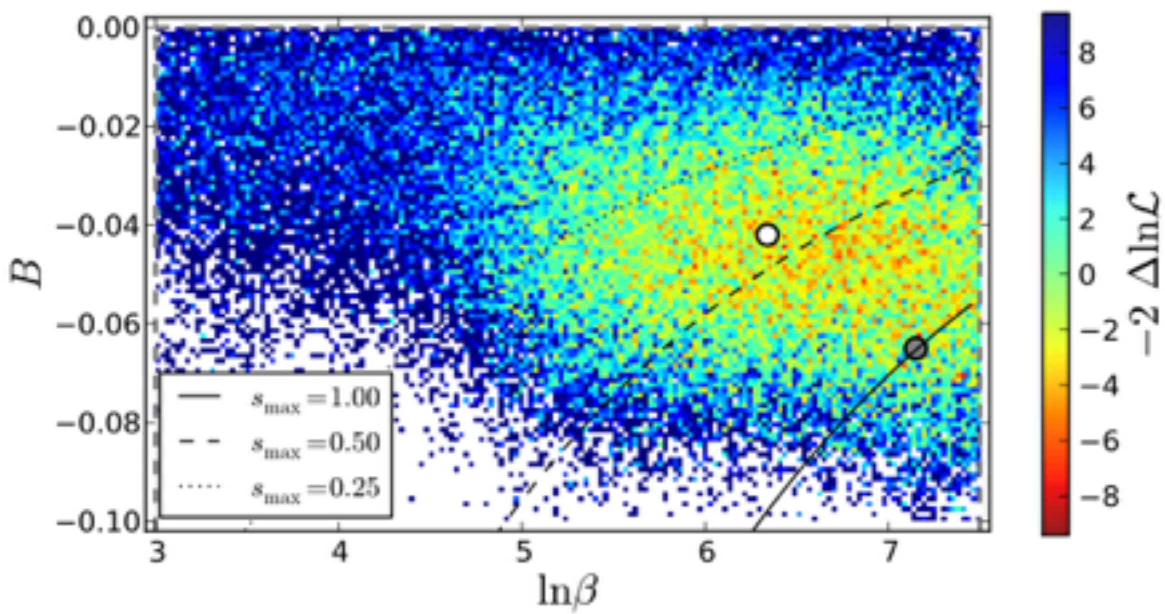
Planck+WP

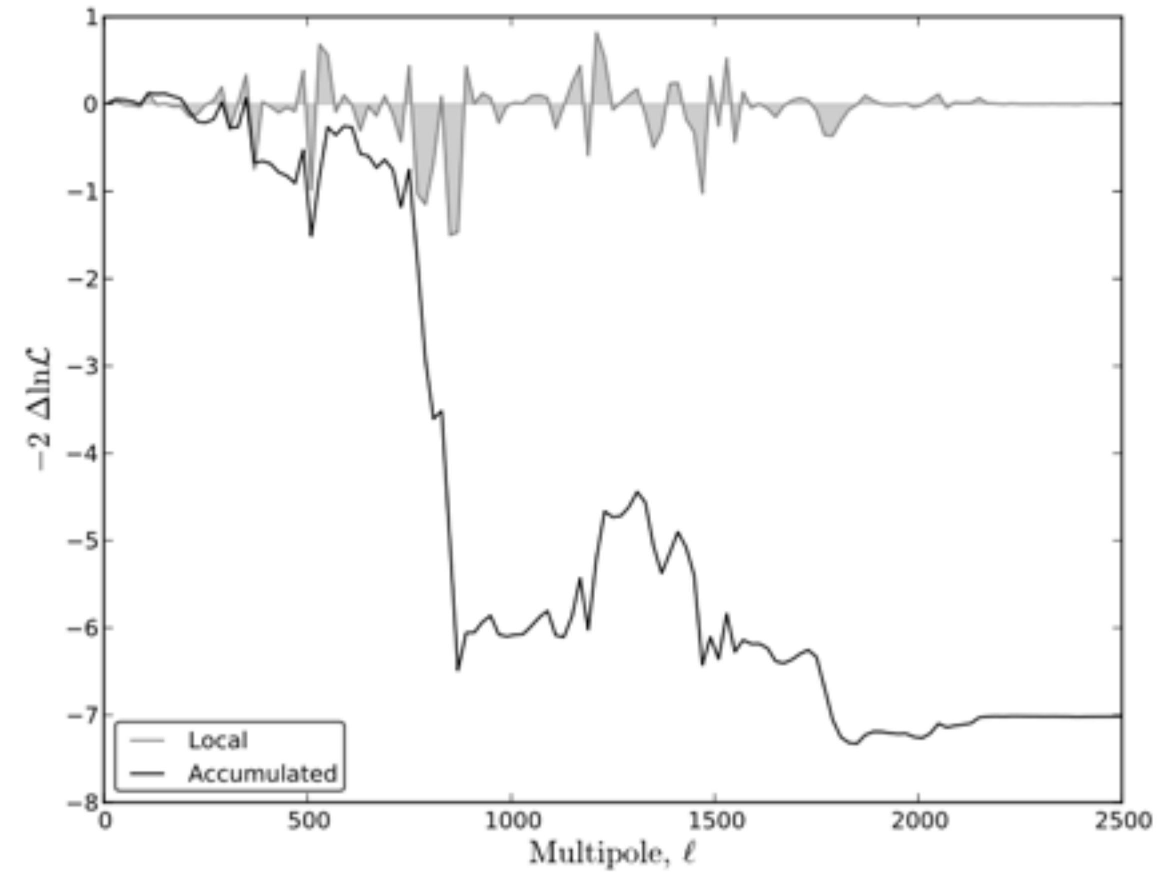
degeneracy with vanilla parameter is negligible

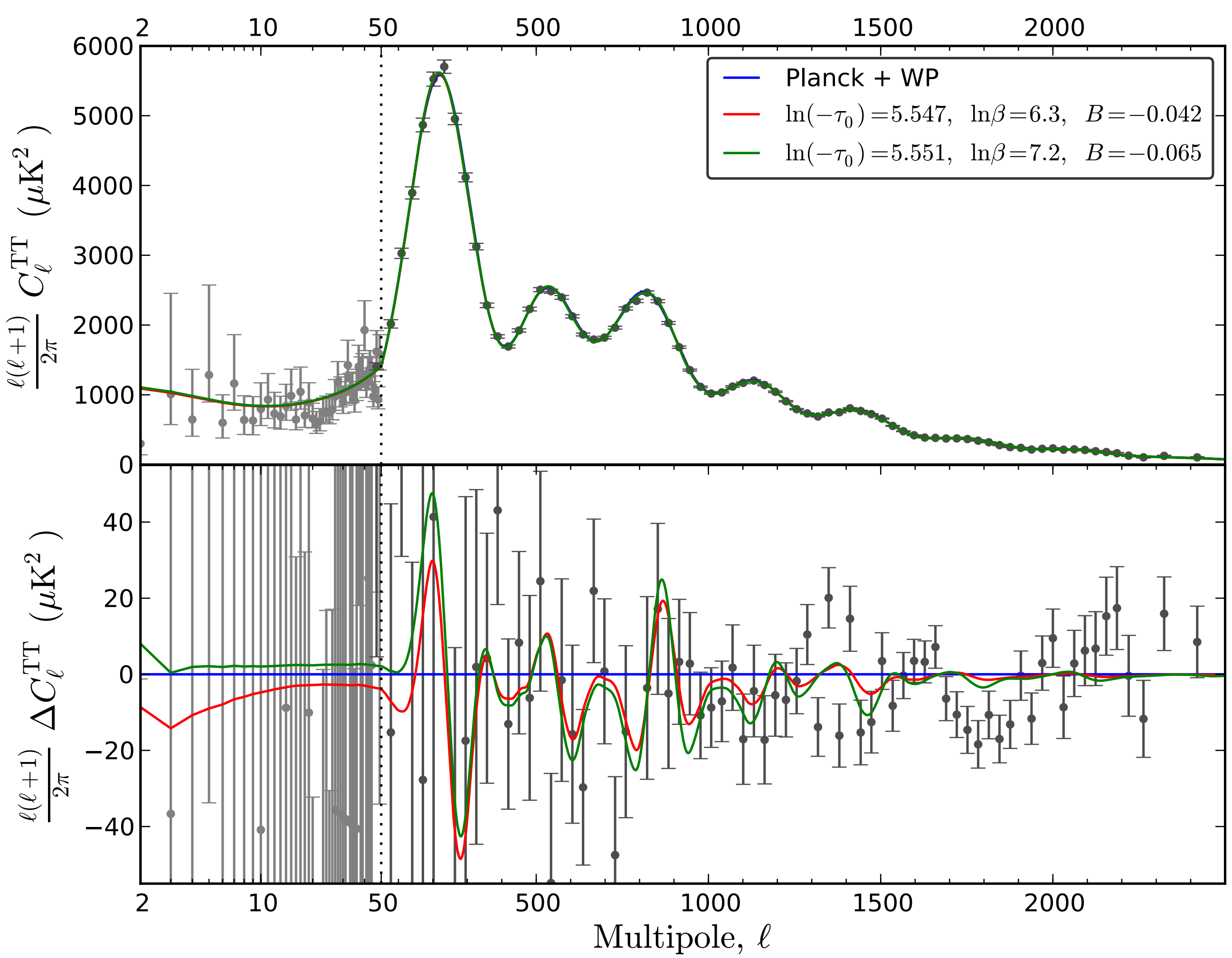
CoV Mat

	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

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

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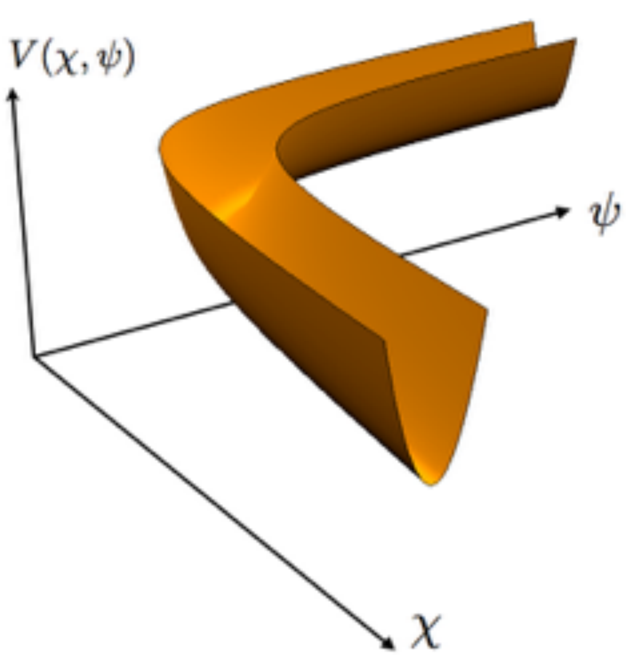
$$\phi^a(t,\boldsymbol{x}) = \phi_0^a(t+\pi) + N^a(t+\pi)\mathcal{F}$$

light adiabatic — heavy isocurvature

integrating out heavy field

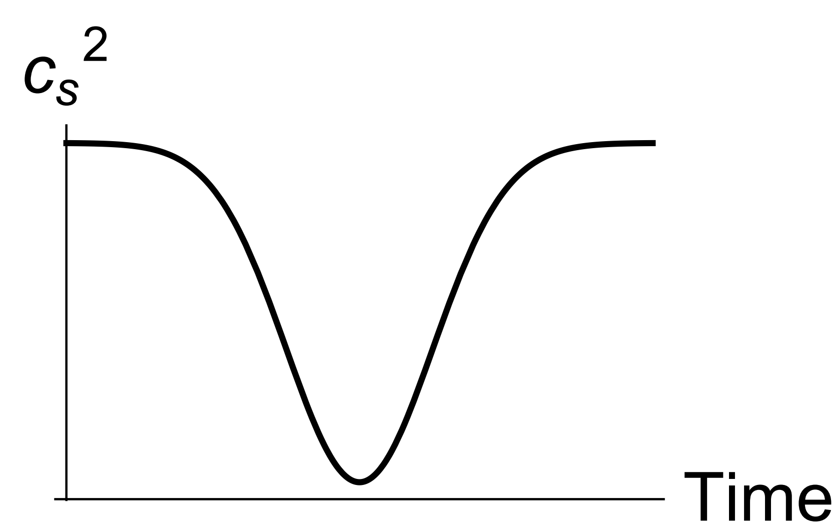
effective action:

$$S = \frac{1}{2}\int d^4x\dot{\phi}_0^2\Big\{c_s^{-2}\dot{\pi}^2 - (\nabla\pi)^2 + \left(\frac{1}{c_s^2}-1\right)\dot{\pi}\left[\dot{\pi}^2 - (\nabla\pi)^2\right] + \left(\frac{1}{c_s^2}-1\right)^2\frac{\dot{\pi}^3}{2}$$
$$+ 2\frac{\ddot{\phi}_0}{\dot{\phi}_0}\left[\frac{\dot{\pi}^2}{c_s^2} - (\nabla\pi)^2\right]\pi - 2\frac{\dot{c}_s}{c_s^3}\dot{\pi}^2\pi\Big\},$$

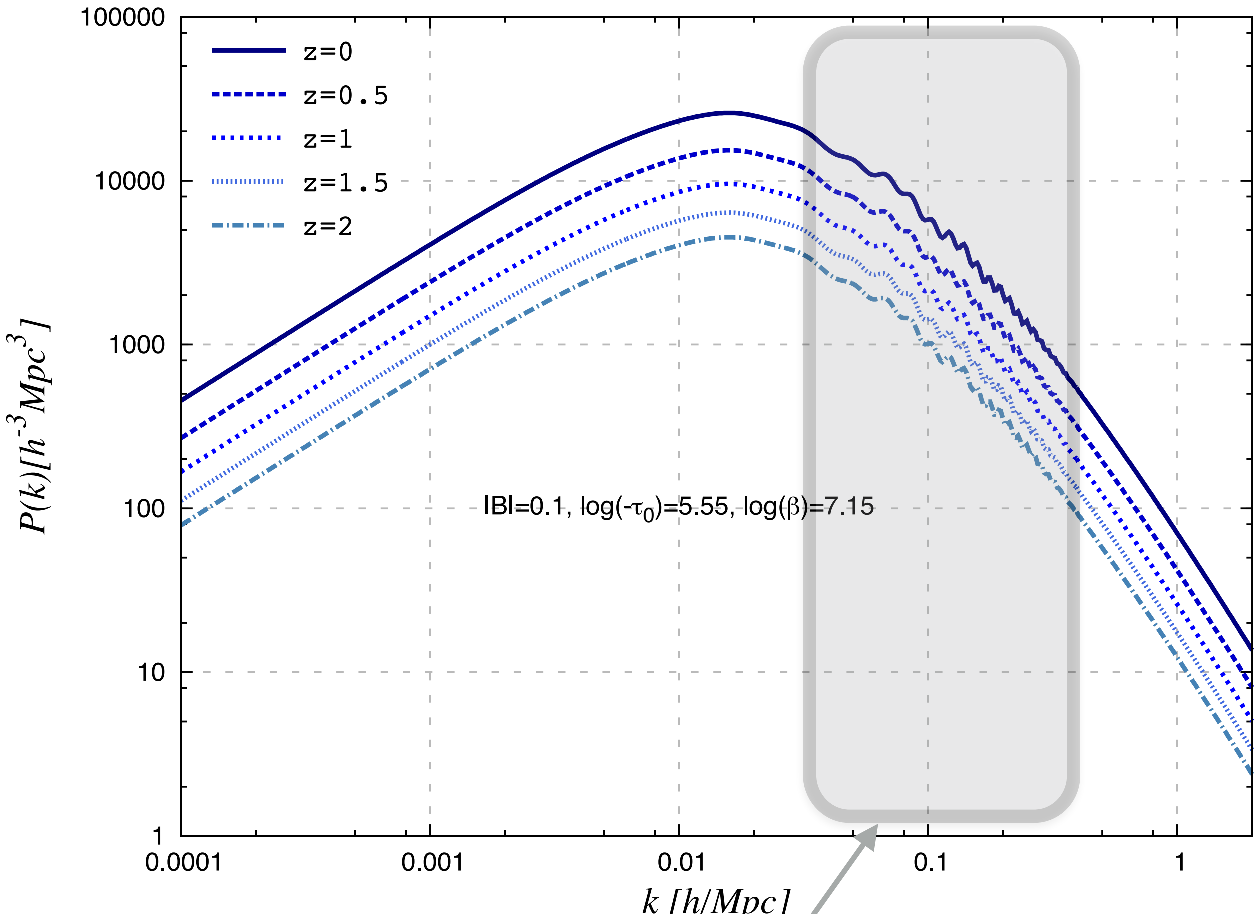


turn

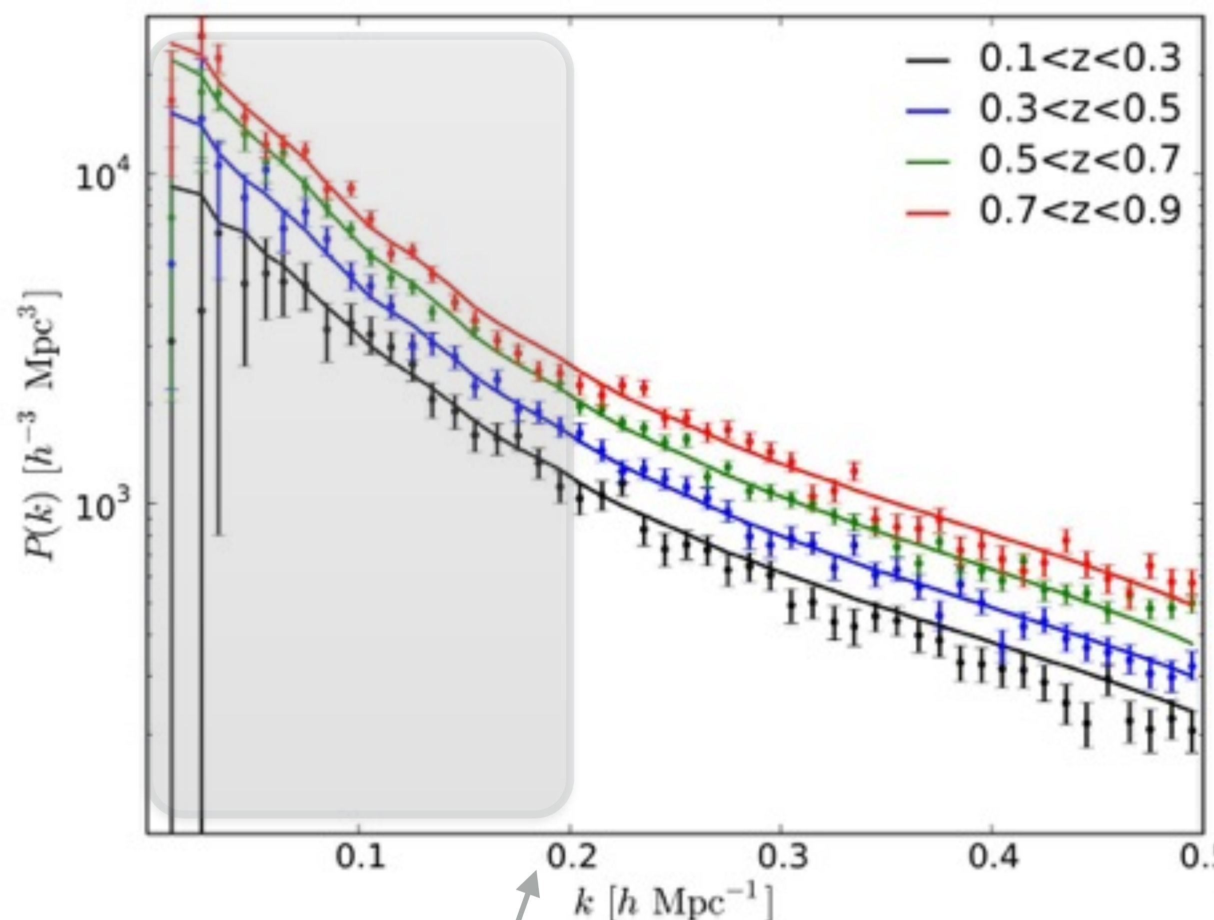
sound speed reduced



4. Search with LSS survey—WiggleZ



features shows around k~(0.1,0.2)



Search up to k=0.2