Testing consistency of the LCDM model with Planck data

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CosKASI-ICG-NAOC-YITP joint workshop

Yukawa Institute for Theoretical Physics

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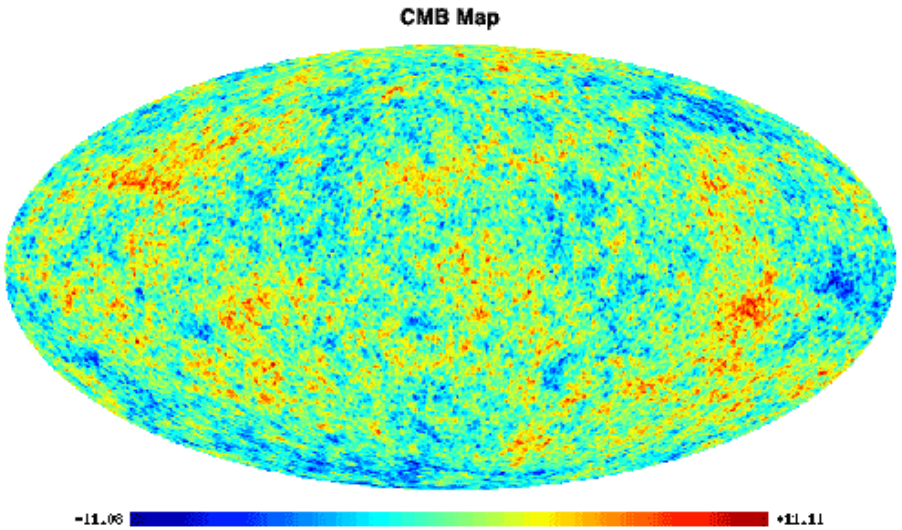
Statistics of CMB

CMB Anisotropy Sky map => Spherical Harmonic decomposition



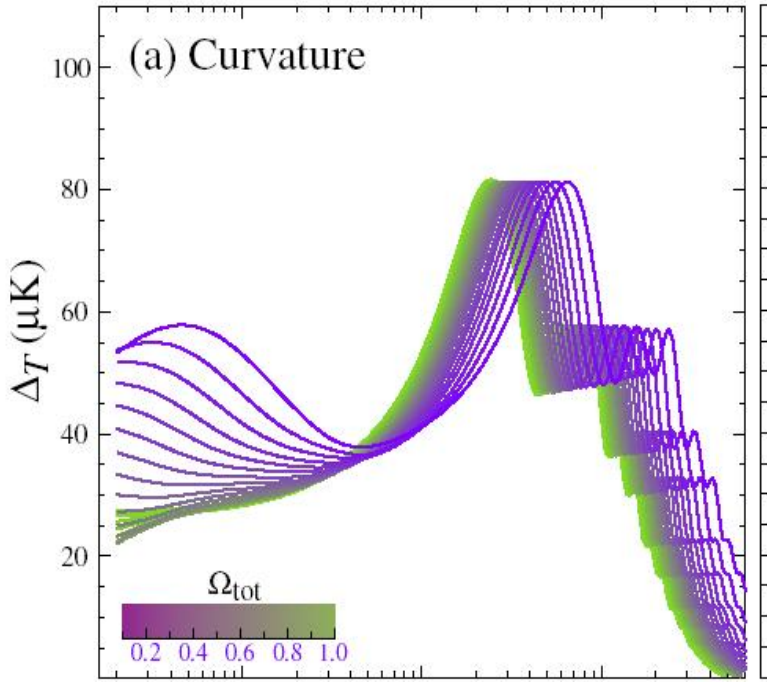
$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

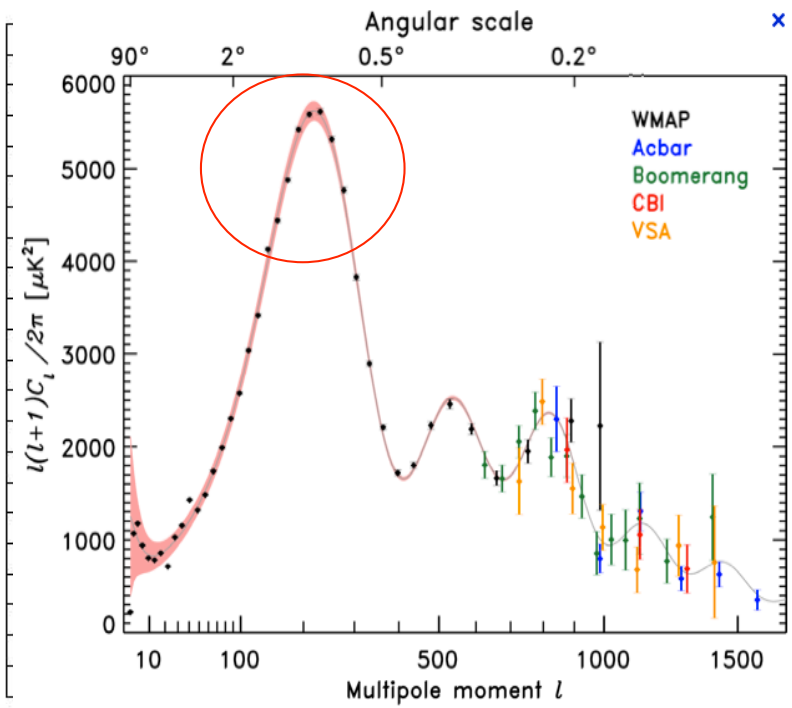
$$\boxed{\left\langle a_{lm}\, a^{*}_{l'm'} \right\rangle = C_l\ \delta_{ll'}\delta_{mm'}}$$

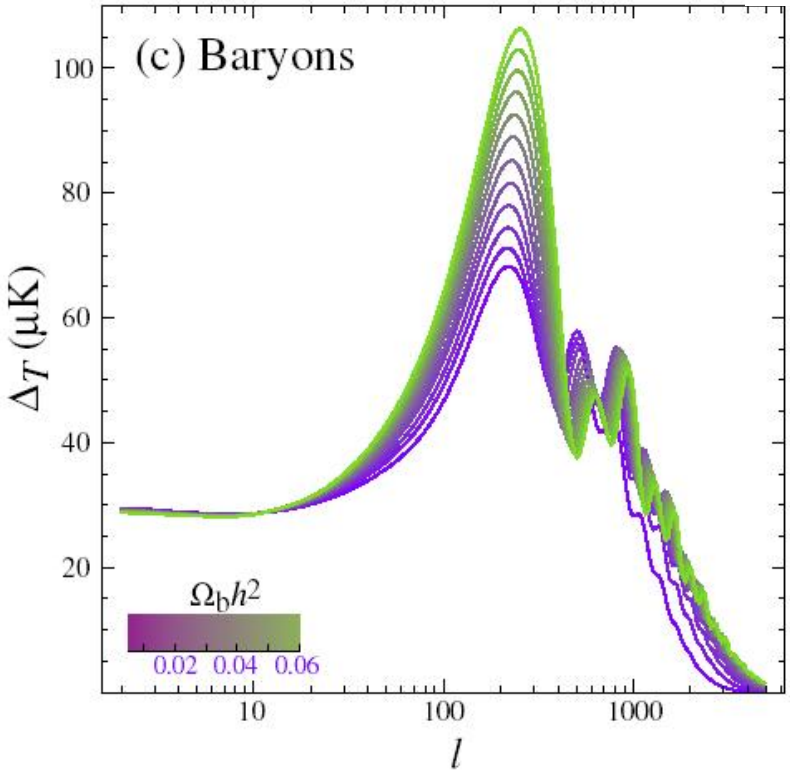
Gaussian Random field => Completely specified by

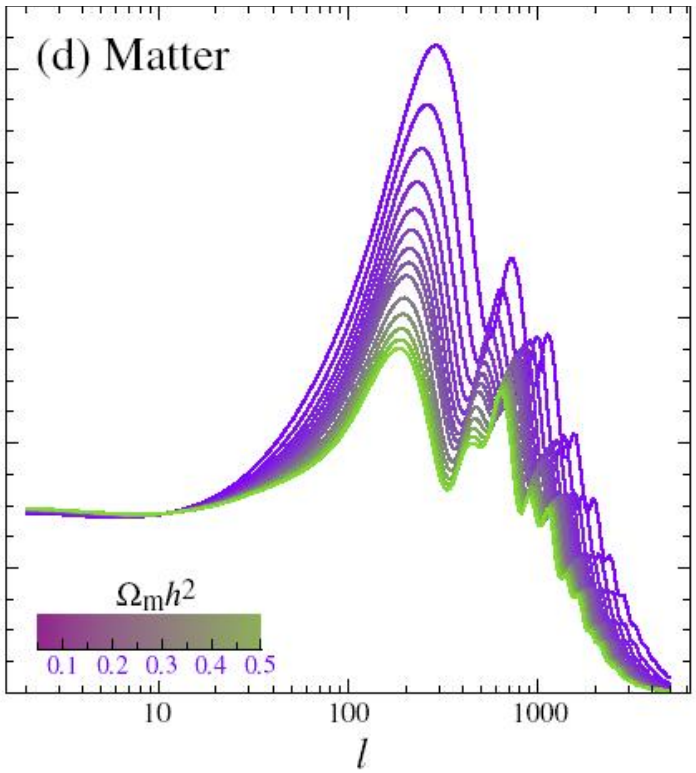
angular power spectrum $l(l+1)C_l$:

Power in fluctuations on angular scales of $\sim \pi/l$









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

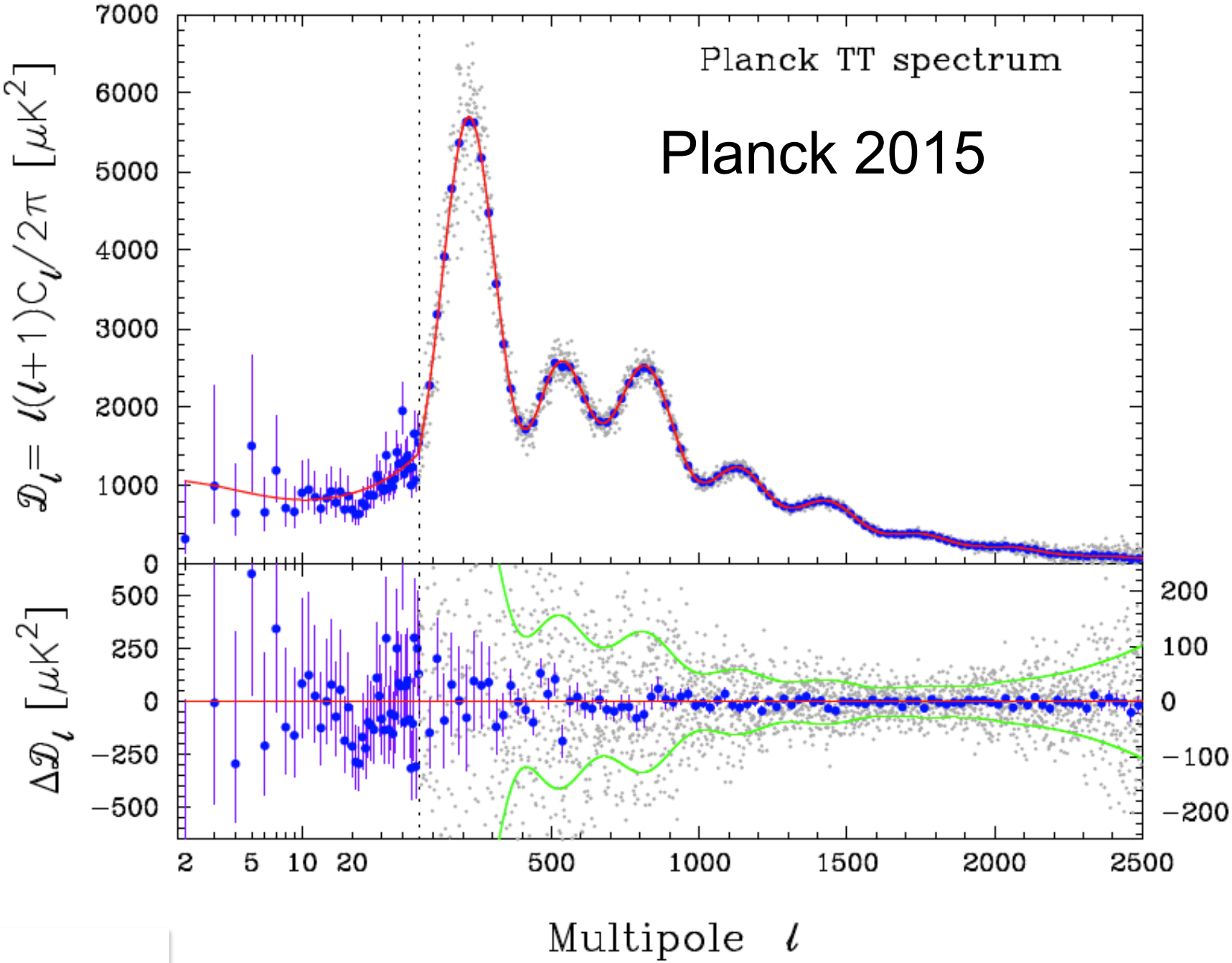
Total density

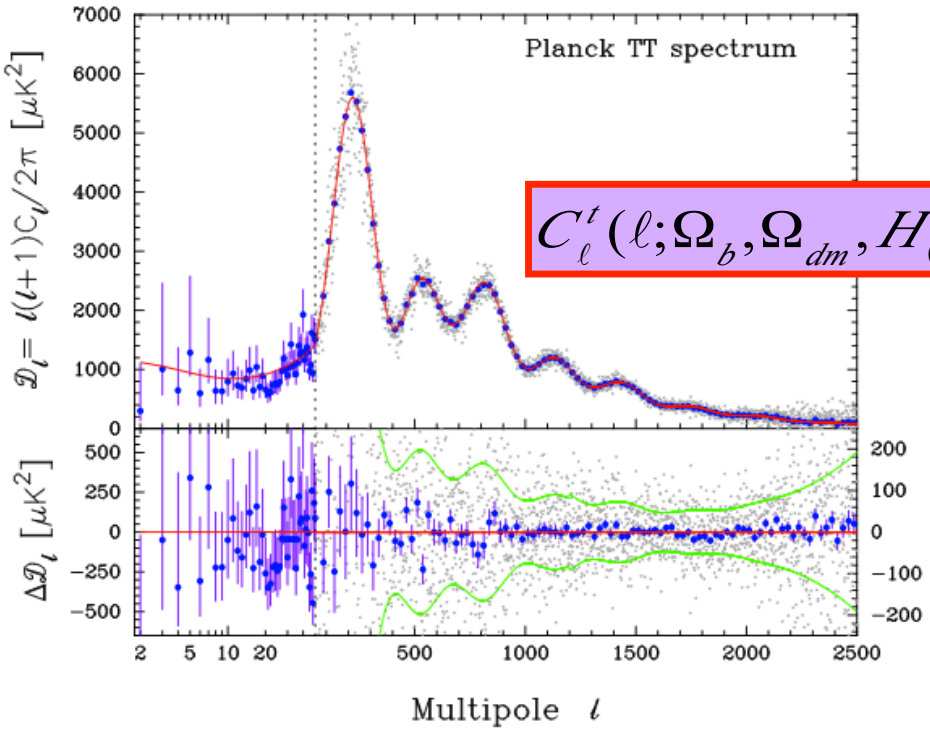
Dark Energy

Baryon density and

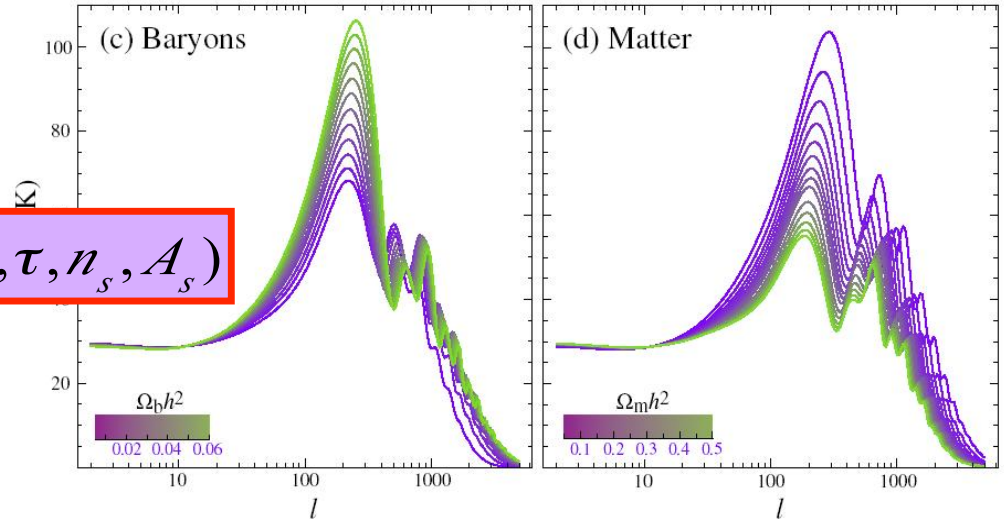
Matter density.

From Hu & Dodelson, 2002

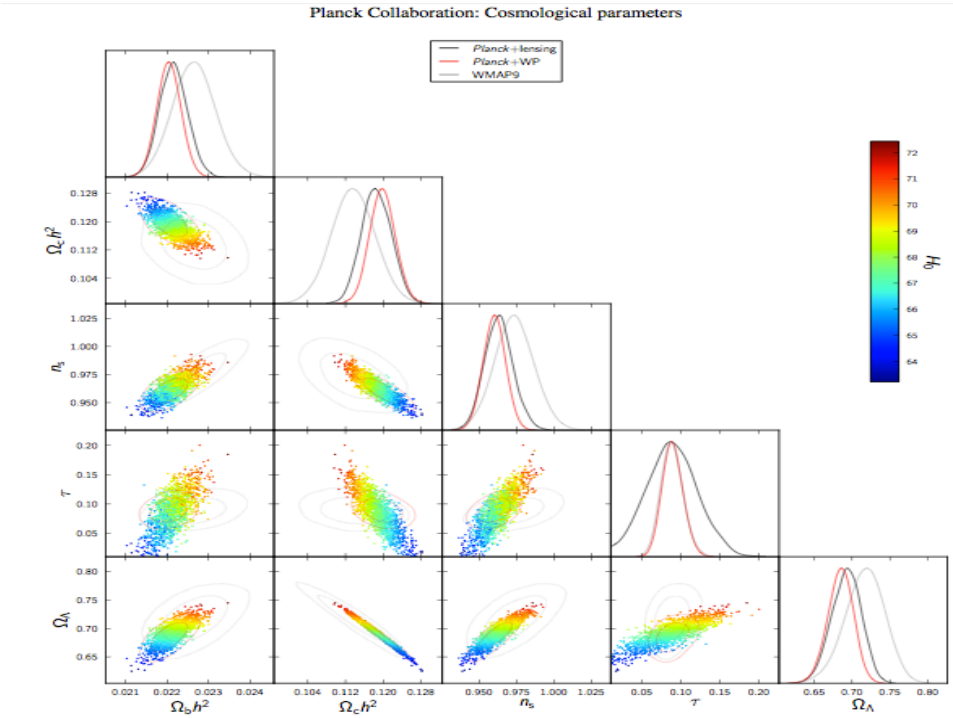

Planck TT spectrum
Planck 2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

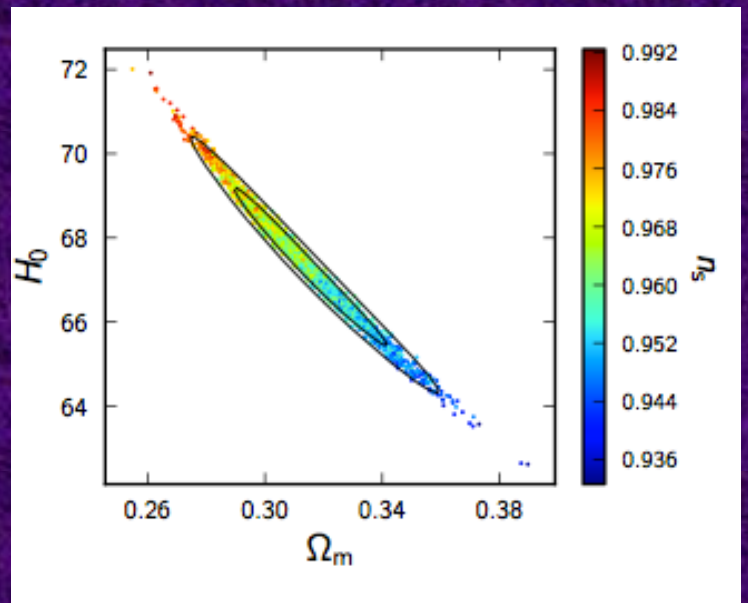


$$C_\ell^t(\ell;\Omega_b,\Omega_{dm},H_0,\tau,n_s,A_s)$$



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





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.

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 →

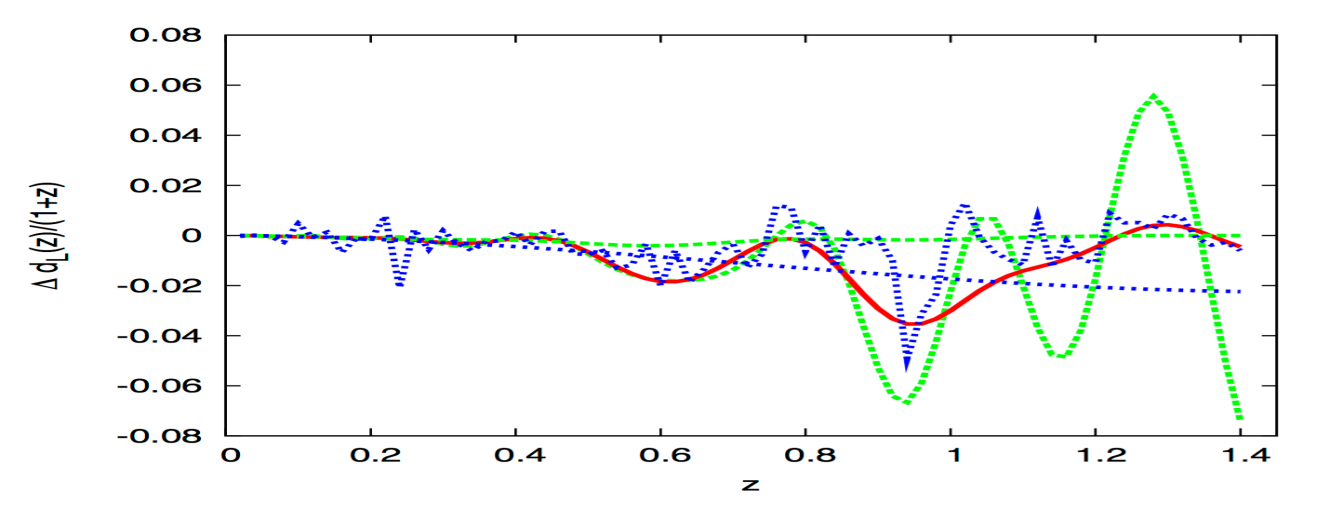
$$k(z,z') = \sigma_f^2 \exp\left(-\frac{|z-z'|^2}{2l^2}\right),$$

GP Hyper-parameters

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

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

GP Likelihood



Red : l=0.1, sig_f=0.001
Blue : l=0.01, sig_f=0.001
l=1.0, sig_f=0.001
Green : l=0.1, sig_f=0.1
l=0.1, sig_f=0.00001

Shafieloo, Kim & Linder, PRD 2012
Shafieloo, Kim & Linder, PRD 2013

Data **Mean Function**

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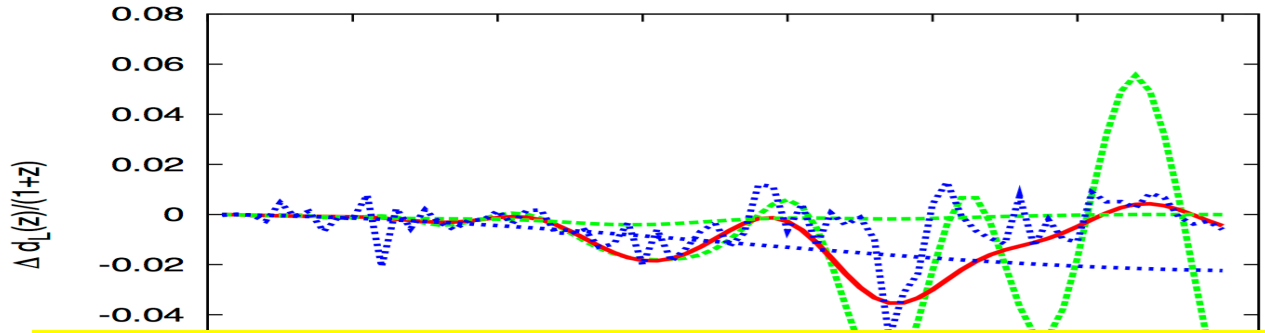
GP Likelihood



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Kim & Linder, PRD 2012
Kim & Linder, PRD 2013

WARNING:

DO NOT USE READY MADE GP PACKAGES FOR RECONSTRUCTION PURPOSES UNLESS YOU KNOW HOW GP WORKS IN DETAILS.

MOST IMPORTANTLY SINCE GP RECONSTRUCTIONS ARE SENSITIVE TO THE CHOICE OF THE MEAN FUNCTION.

Dat

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f} \\ \mathbf{f}' \\ \mathbf{f}'' \end{bmatrix} \sim$$

$$\Sigma_{\alpha\beta} = \frac{d^{(\alpha+\beta)}K}{dz_i^\alpha dz_j^\beta},$$

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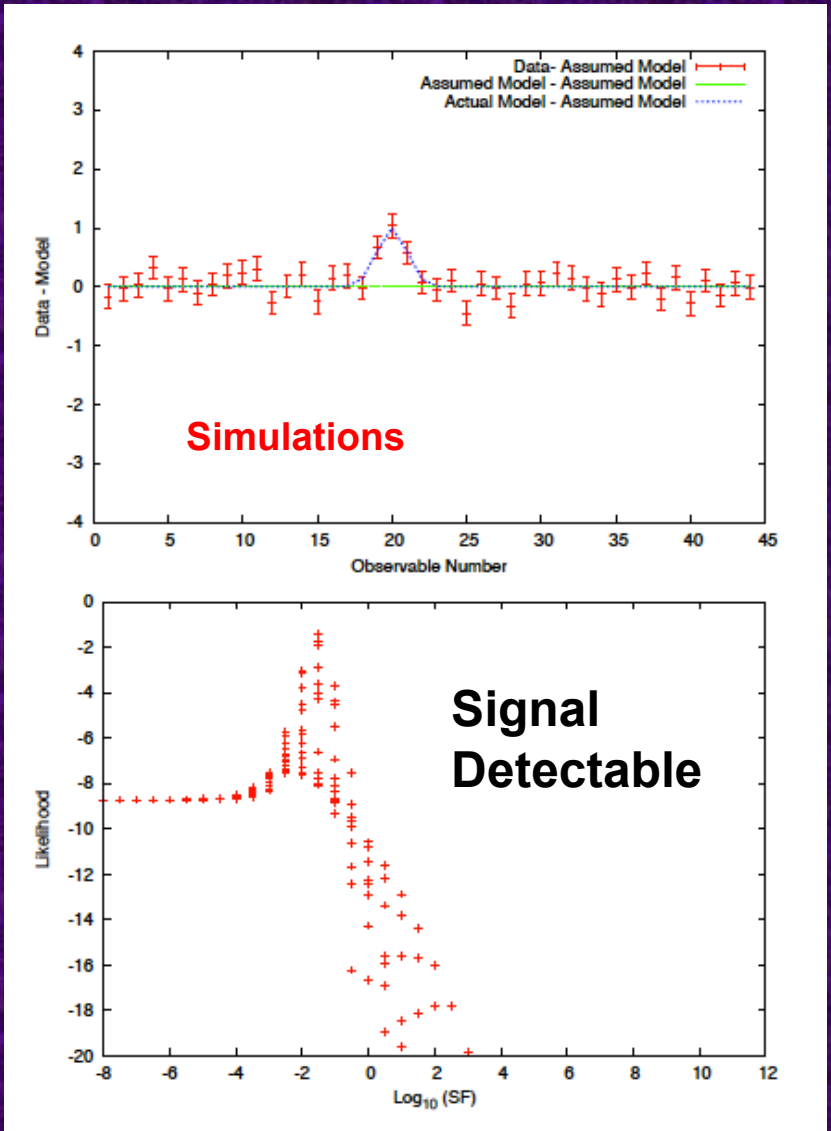
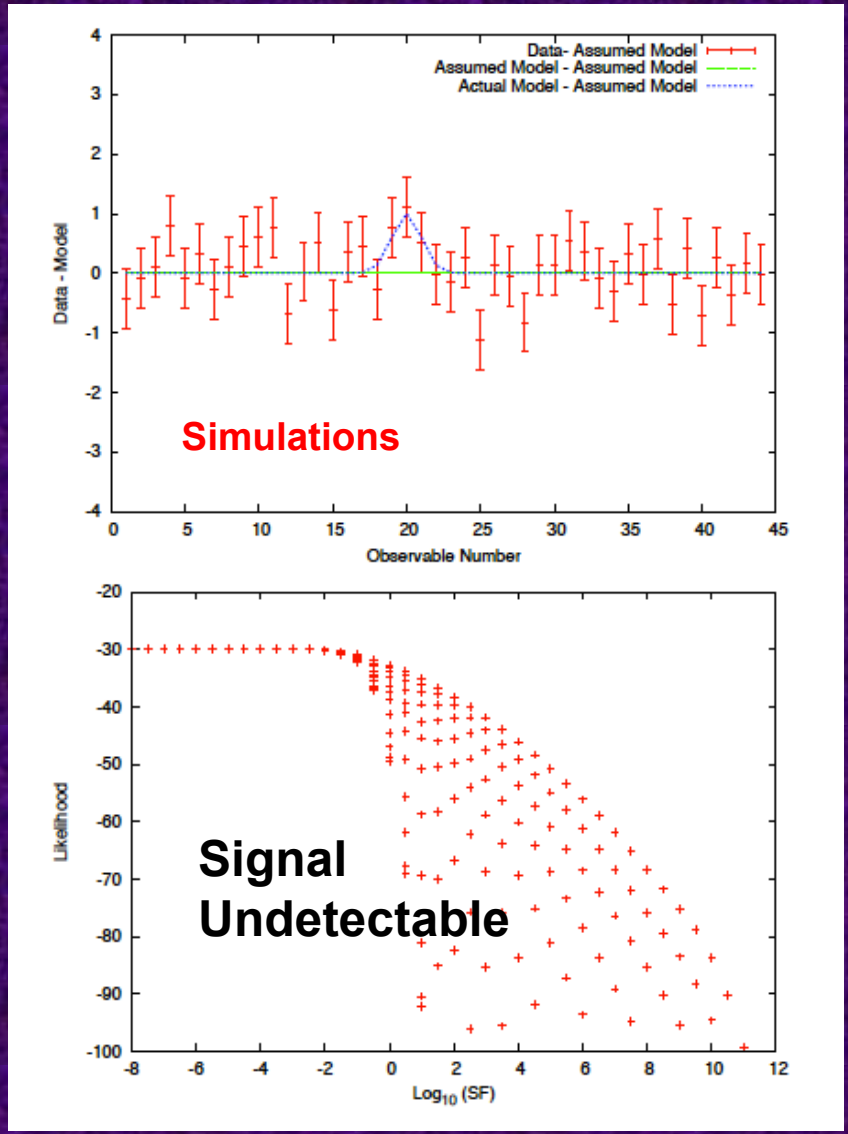
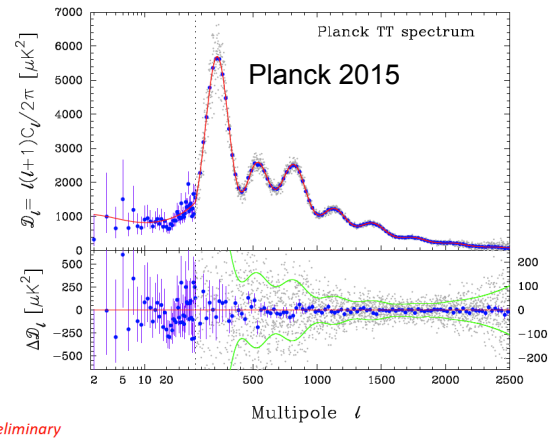
$$2\ln p(y|f) = -y^T \Sigma_{00}(Z, Z)^{-1} y - \ln\det \Sigma_{00}(Z, Z) - n\ln(2\pi)\,,$$

GP Likelihood

Detection of the features in the residuals



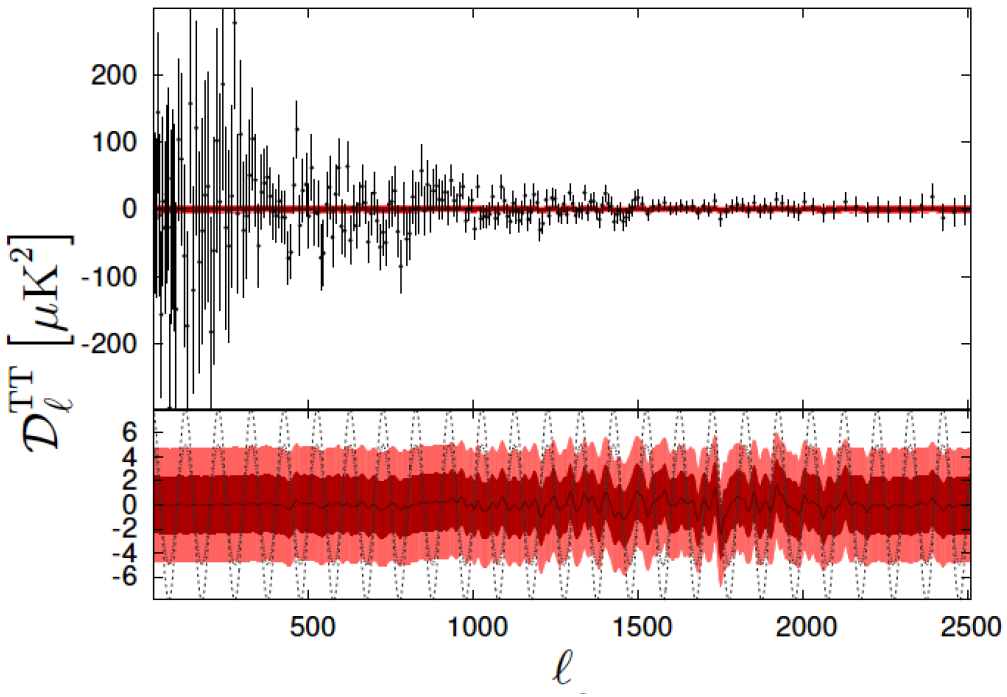


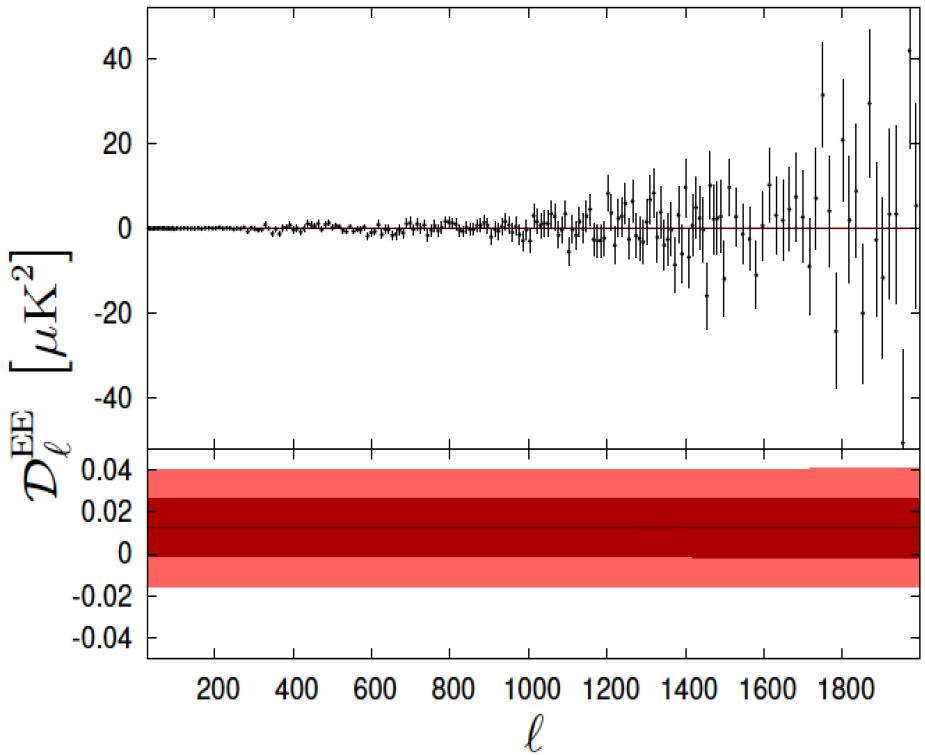


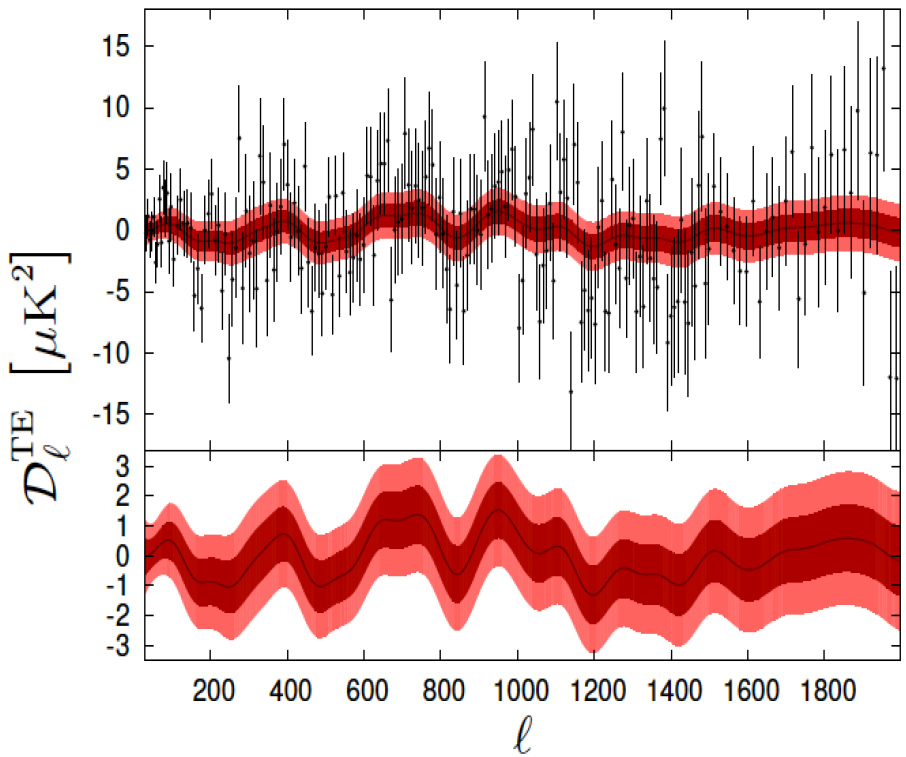
preliminary

GP Reconstruction of Planck TT, TE, EE spectra

Aghamousa, Hamann & Shafieloo, JCAP 2017

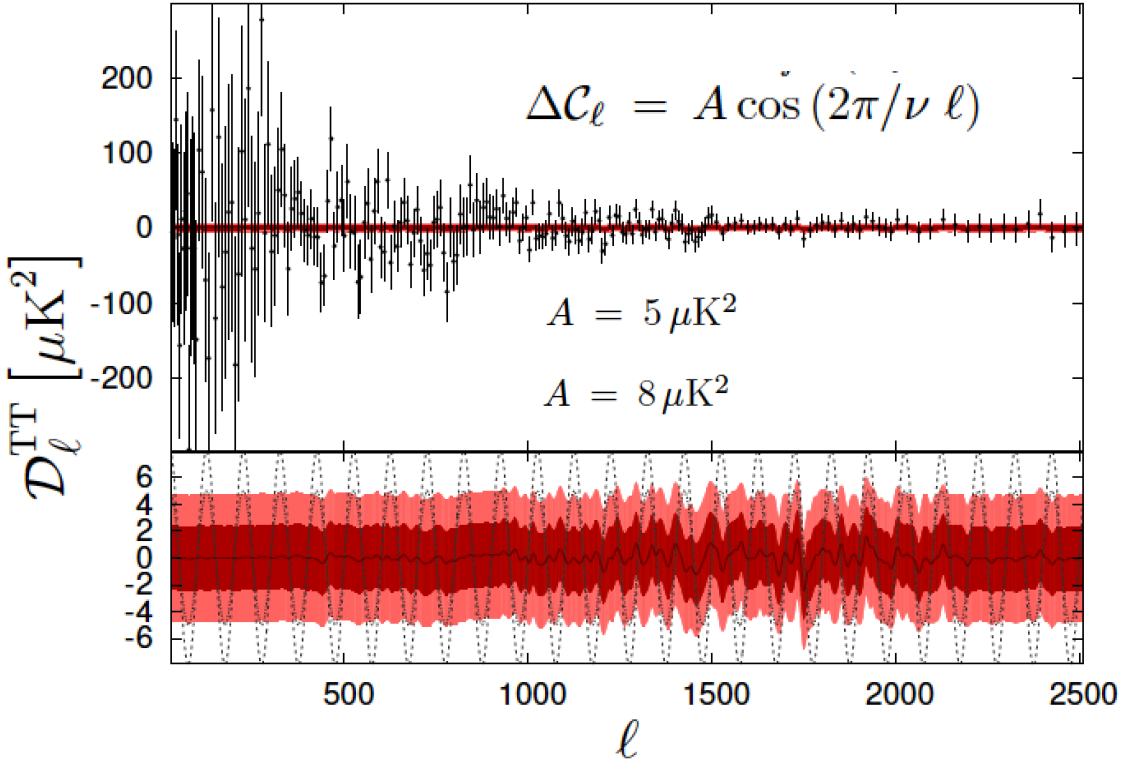


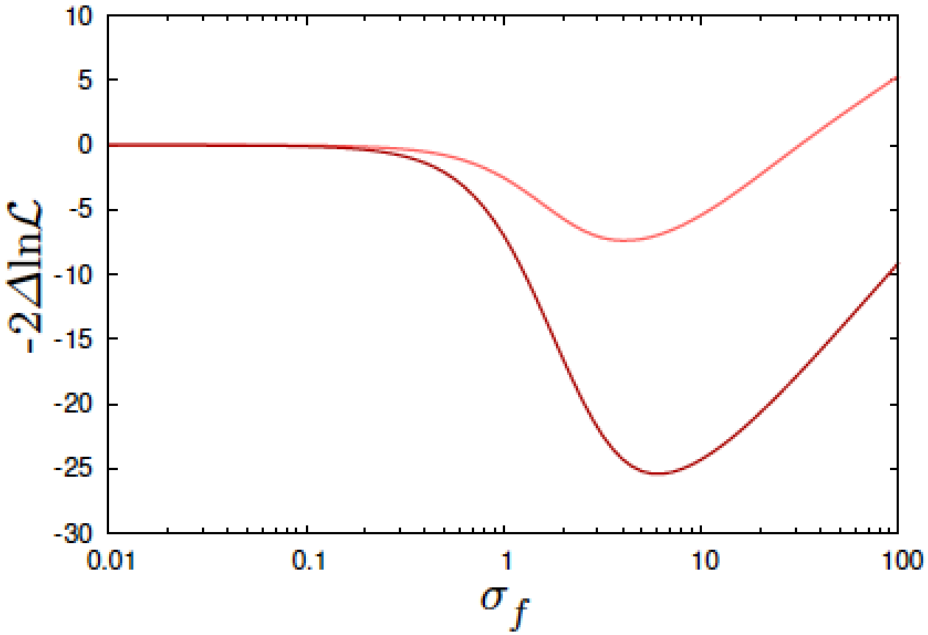


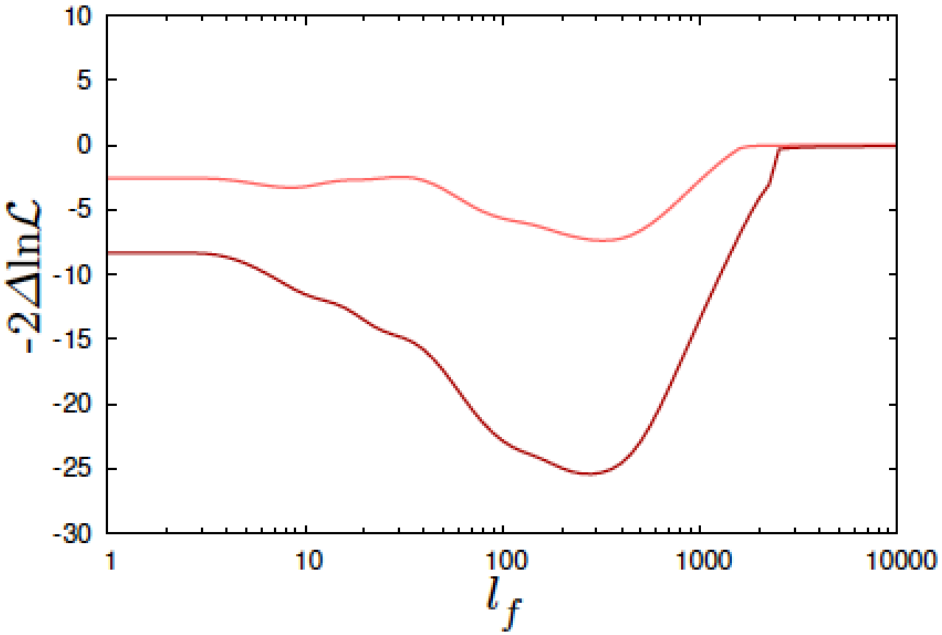


Testing GP

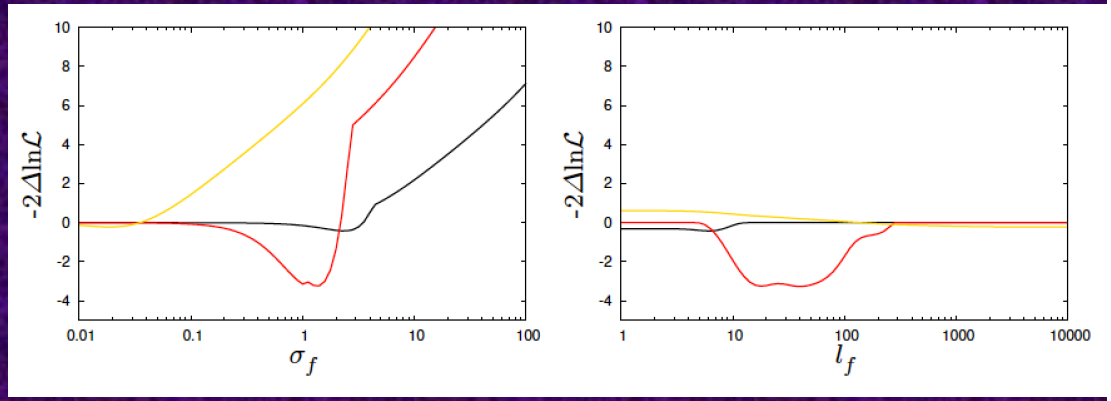
Aghamousa, Hamann & Shafieloo, JCAP 2017

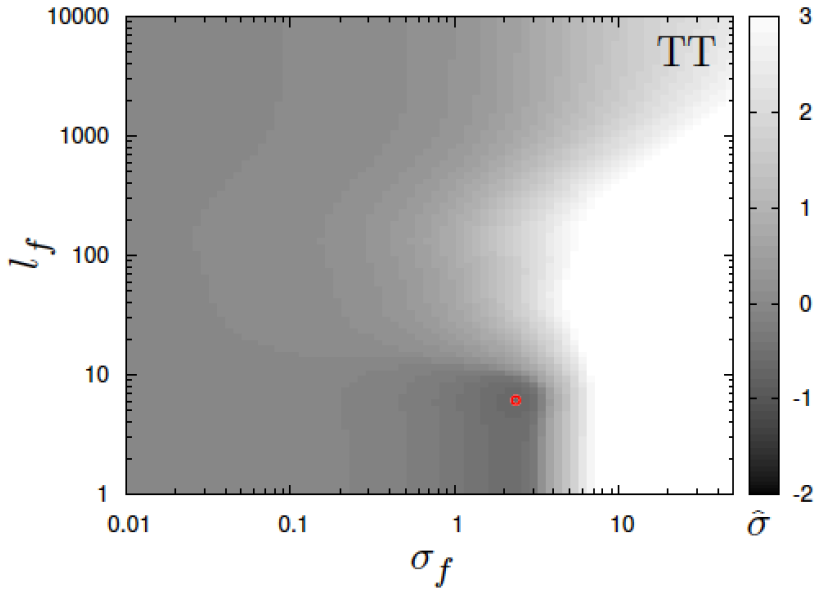


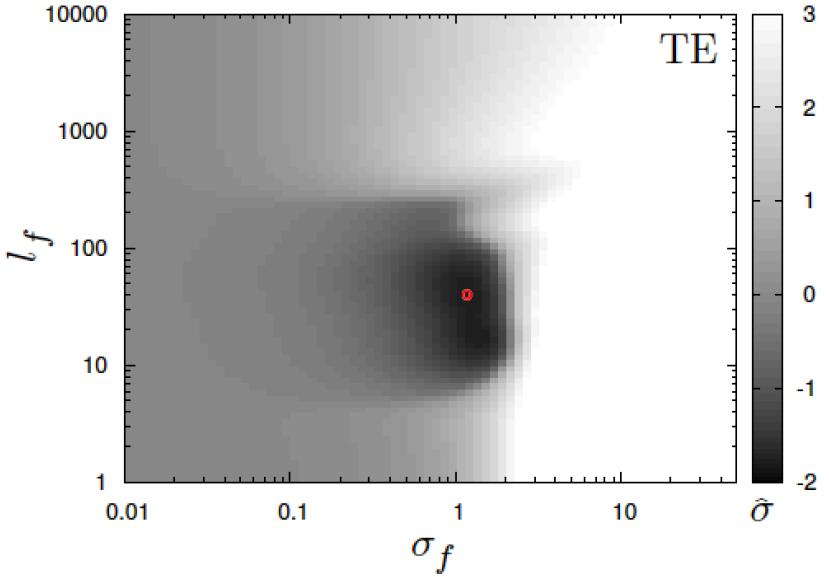


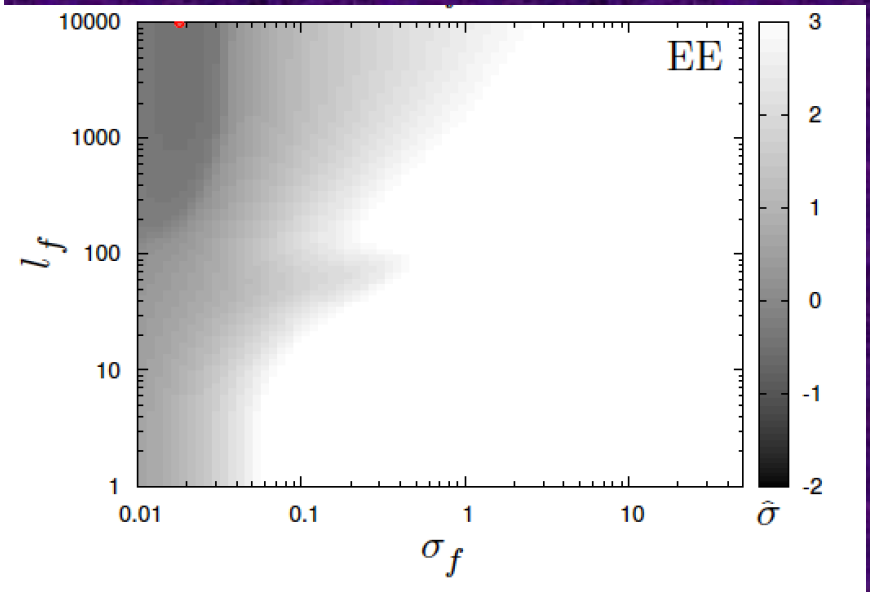


GP Reconstruction of Planck TT, TE, EE spectra





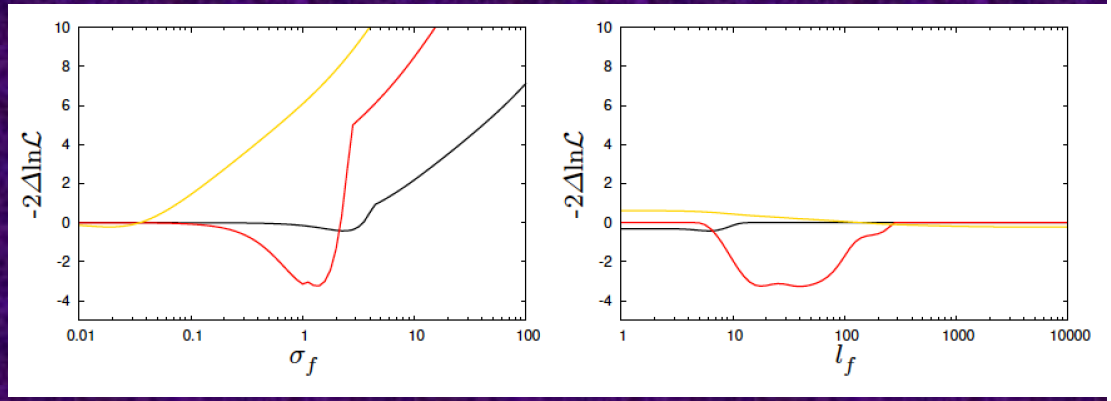


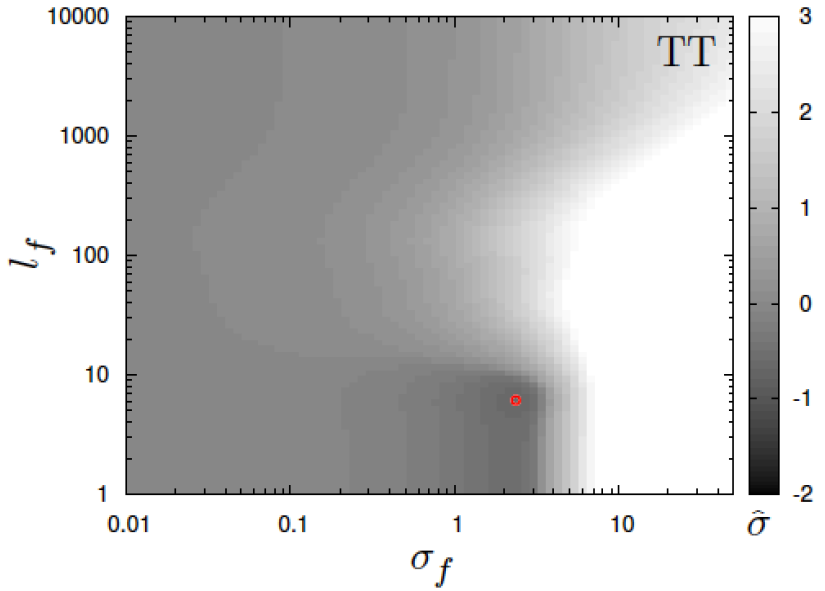


Aghamousa, Hamann & Shafieloo, JCAP 2017

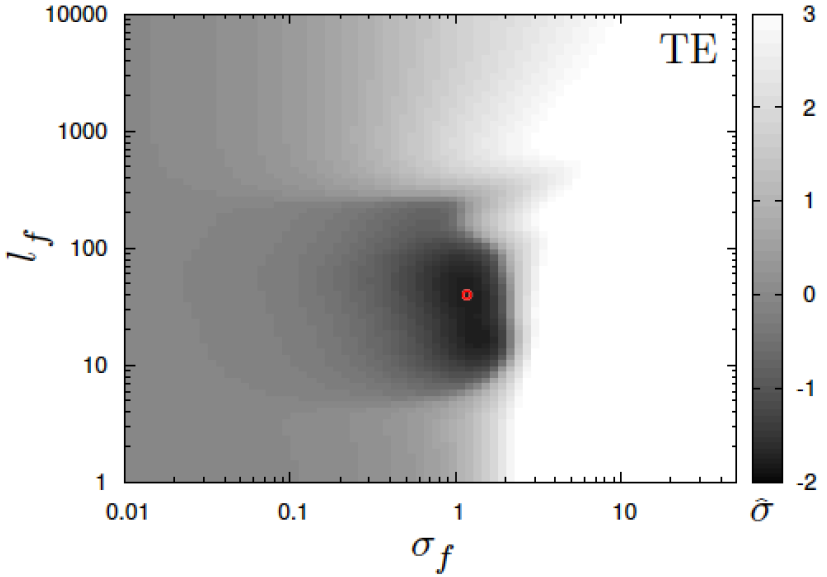
GP Reconstruction of Planck TT, TE, EE spectra

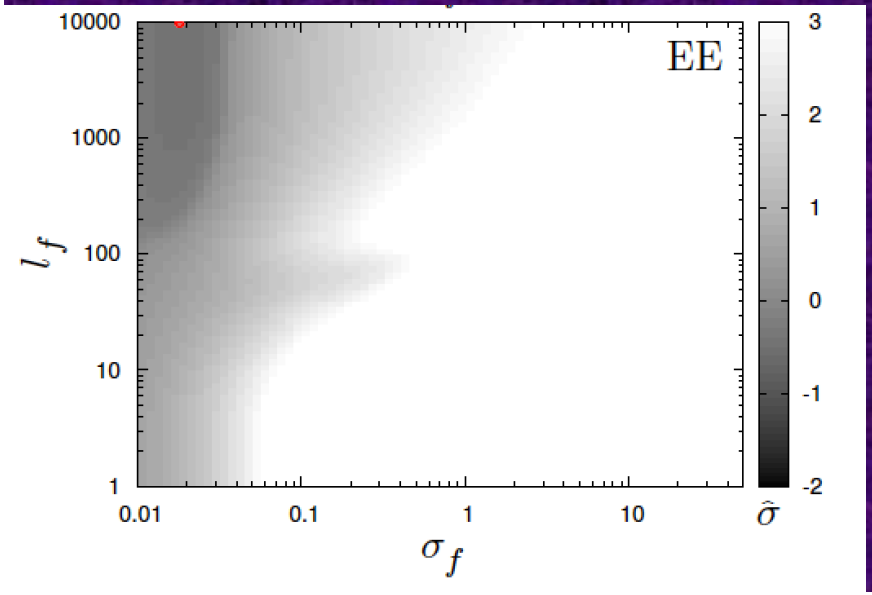
excellent agreement between Planck data and the best-fit LCDM





Aghamousa, Hamann & Shafieloo, JCAP 2017



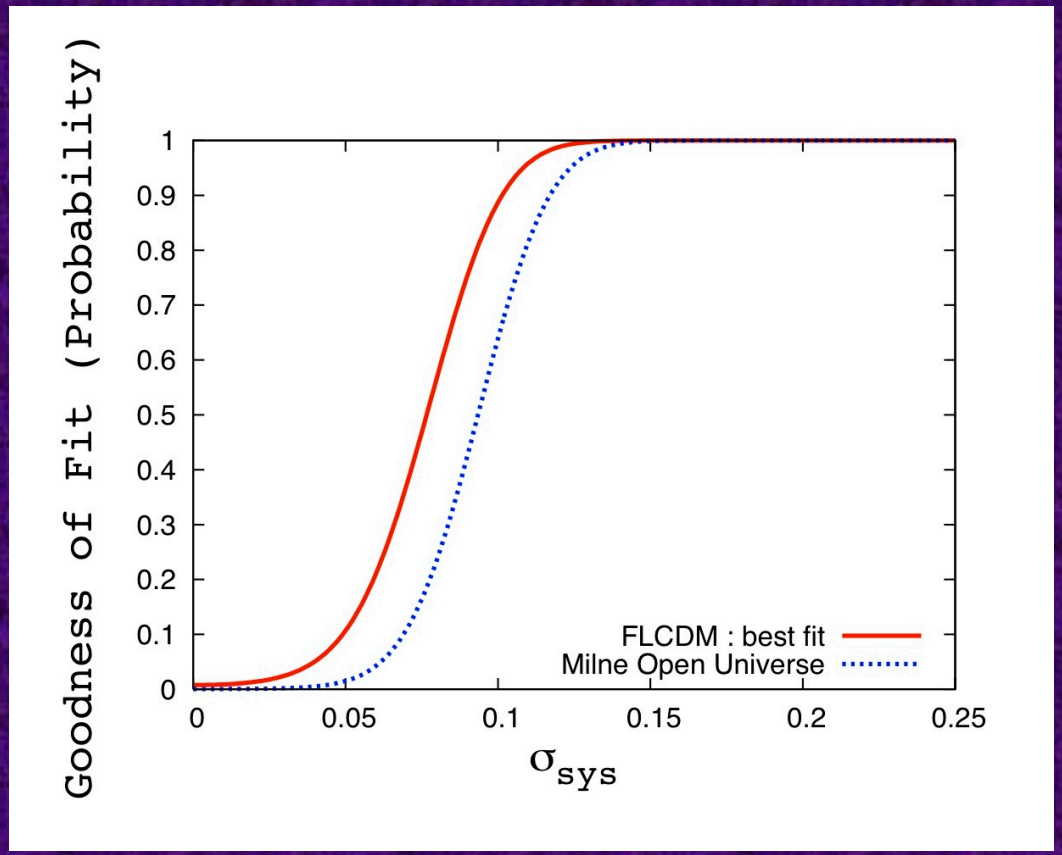


Crossing Statistic

- To deal with unknown uncertainties/ systematics in the data
- To go beyond averaging nature of Chi square statistic (as a core metric in most statistical analysis) extracting more information from the data.

Shafieloo et al JCAP 2011
Shafieloo, JCAP 2012a
Shafieloo, JCAP 2012b

What if the actual size of the error bars are not known?



$$\chi^2 = \sum_i^N \frac{(\mu_i^t - \mu_i^e)^2}{\sigma_i^2},$$

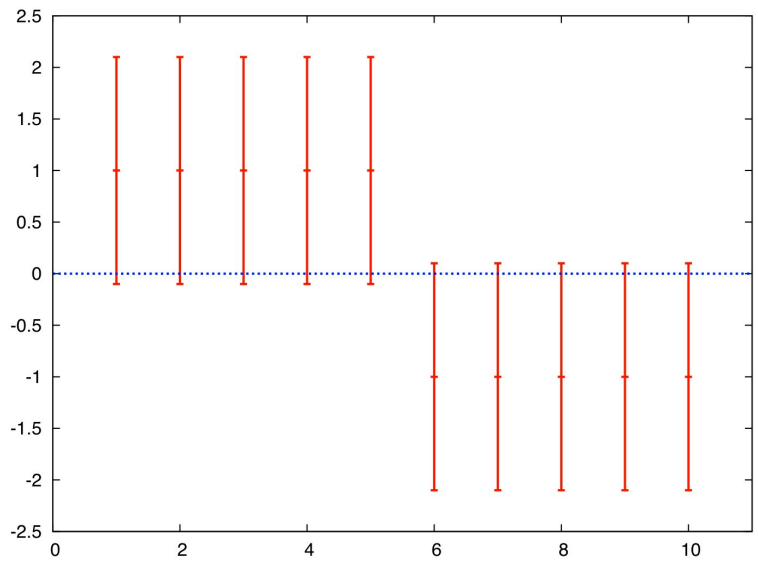
$$\sigma_i^2 = \sigma_{i(data)}^2 + \sigma_{(sys)}^2$$

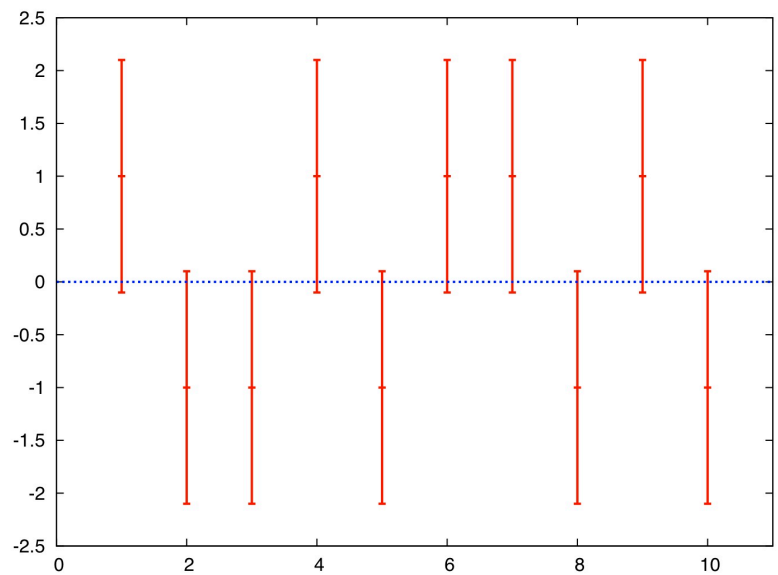
$$P(\chi^2; N) = \frac{2^{-N/2}}{\Gamma(N/2)} \chi^{N-2} e^{-\chi^2/2}$$

$$Prob(\chi^2; N) = \int_{\chi^2}^{\infty} P(\chi^2; N) d\chi'^2.$$

Constitution
Supernovae data
(2009)

Equal in being probable?!



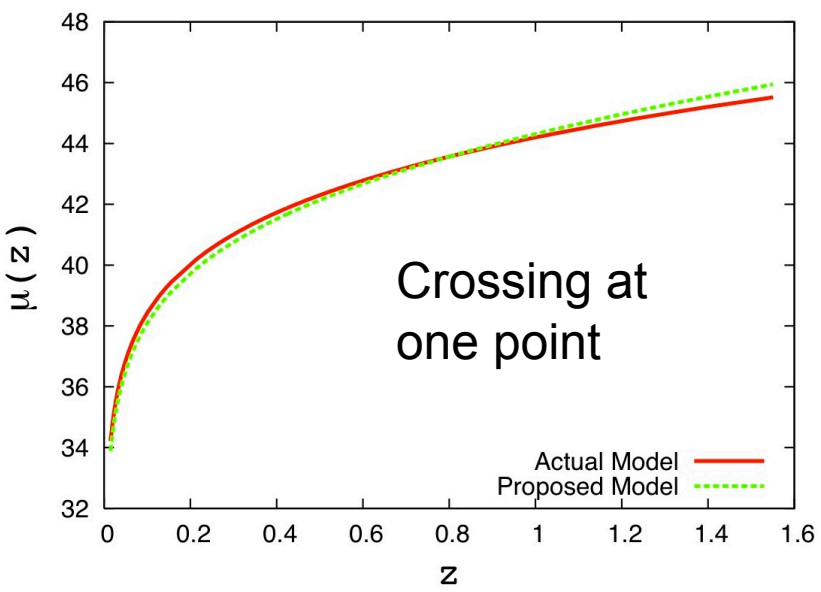


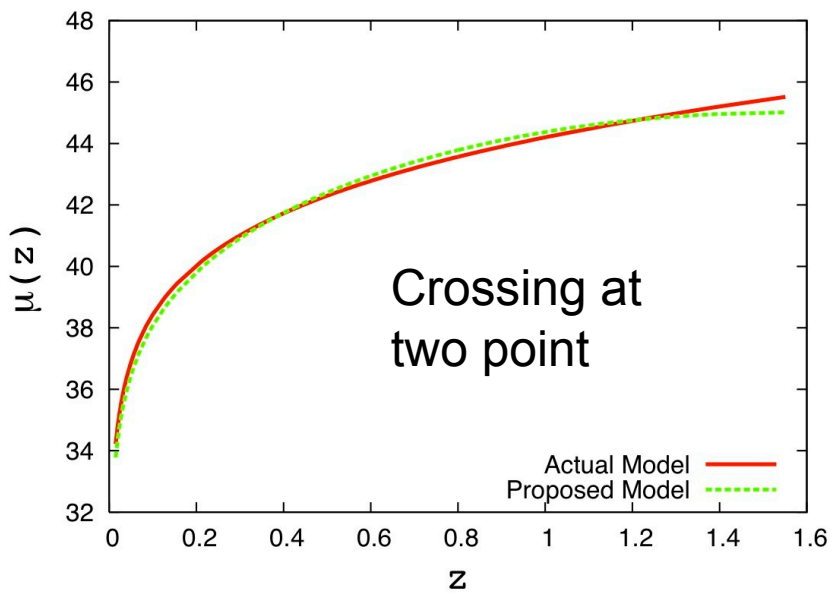
$$\chi^2 = \sum_i^N \frac{(\mu_i^t - \mu_i^e)^2}{\sigma_i^2},$$

Crossing Statistic

If a proposed model is different than the actual model, then they cross each other at one or two or three or … N points.

A. Shafieloo, T. Clifton & P. Ferreira, 2010





One point Crossing: T1

1. Assume a model
2. Construct the normalized residuals
3. Finding the crossing point and calculating T1 by maximizing T(n1):
4. Comparing the results with Monte Carlo simulations.

$$q_i(z_i) = \frac{\mu_i(z_i) - \bar{\mu}(z_i)}{\sigma_i(z_i)}.$$

$$T(n_1) = Q_1(n_1)^2 + Q_2(n_1)^2,$$

$$Q_1(n_1) = \sum_{i=1}^{n_1} q_i(z_i)$$

$$Q_2(n_1) = \sum_{i=n_1+1}^{N} q_i(z_i),$$

Two points Crossing: T2

1-2.....

3. Finding the crossing points and calculating T2 by maximizing T(n1,n2):

$$q_i(z_i) = \frac{\mu_i(z_i) - \bar{\mu}(z_i)}{\sigma_i(z_i)}.$$

$$T(n_1, n_2) = Q_1(n_1, n_2)^2 + Q_2(n_1, n_2)^2 + Q_3(n_1, n_2)^2,$$

4. Comparing the results with Monte Carlo simulations.

$$Q_1(n_1, n_2) = \sum_{i=1}^{n_1} q_i(z_i)$$

$$Q_2(n_1, n_2) = \sum_{i=n_1+1}^{n_2} q_i(z_i)$$

$$Q_3(n_1, n_2) = \sum_{i=n_2+1}^{N} q_i(z_i).$$

And so on we can derive T3, T4,…

Important Features:

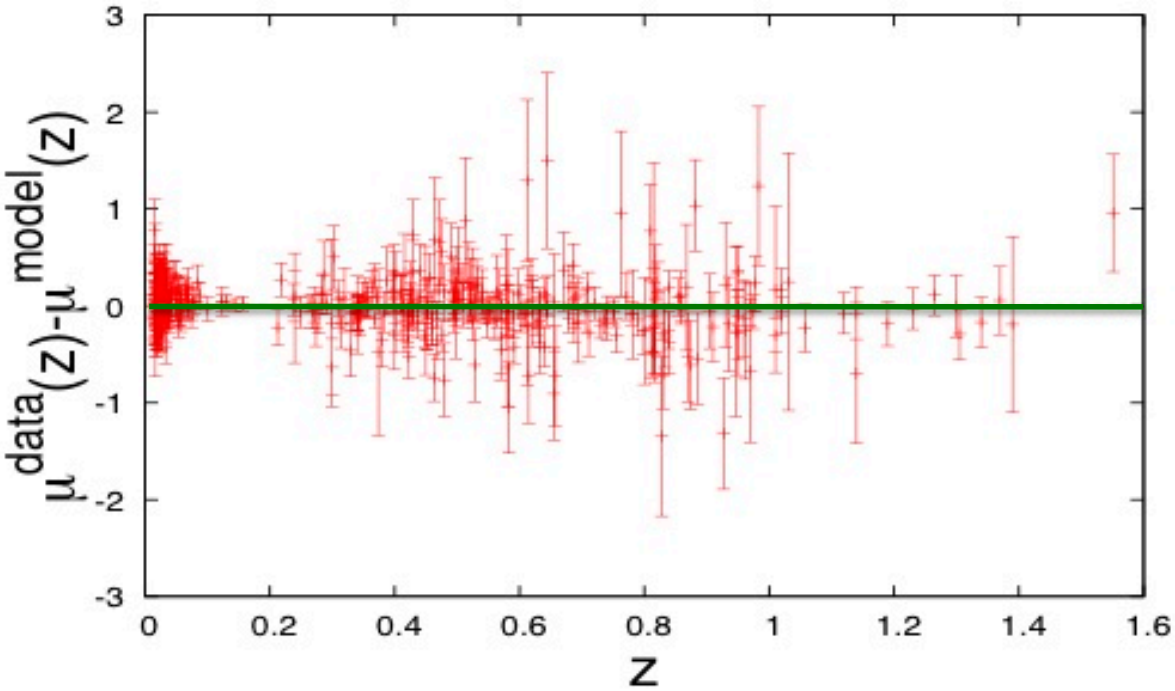
For N data points, **the last mode of Crossing Statistic** is T(N-1) which **is identical to Chi Square Statistic**

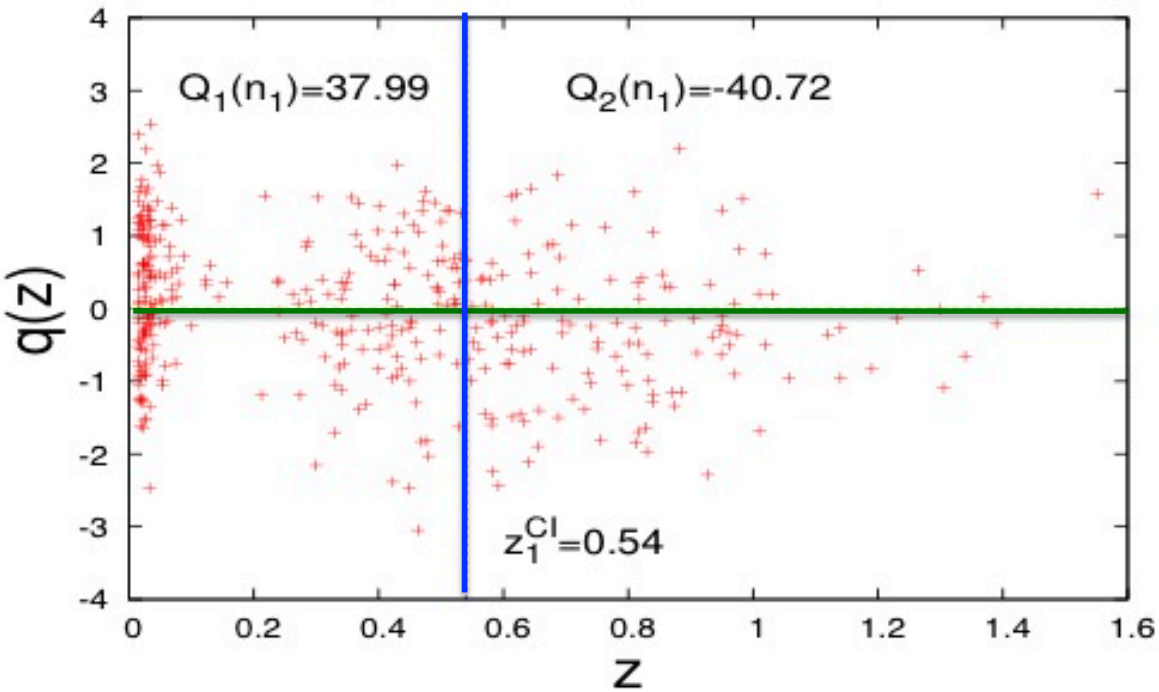
$$T_{N-1} = \sum_{i}^{N} (q_i)^2 = \chi^2$$

The zero mode of Crossing Statistic is similar to Median Statistic

$$T_0 = (\sum_{i}^{N} q_i)^2$$

not only should the whole sample of residuals have a Gaussian distribution around the mean, but so should any continuous subsample.





Assumed model is consistent with the data using chi square

Data:
Flat LCDM $\Omega_{0m}^{true} = 0.27$

Assumed Model:
Flat LCDM $\Omega_{0m}^{erroneous} = 0.22$

Assumed model is ruled out at 99% CL using T1

Comparing Two Statistics

	T1	**Chi Square**
Ruling out by 99% CL	1% (Correct Model) 28.5% (Incorrect Model)	1% (Correct Model) 1.9% (Incorrect Model)
Ruling out by 99% CL Assuming extra (0.05) intrinsic dispersion	0.5% (Correct Model) 26.4% (Incorrect Model)	0% (Correct Model) 0% (Incorrect Model)

$$\sigma_i^2 = \sigma_{i(data)}^2 + \sigma_{(sys)}^2$$

Correct Model: Flat LCDM with $\Omega_{0m}^{true} = 0.27$

Incorrect Model: Flat LCDM with $\Omega_{0m}^{erroneous} = 0.22$

Simulated data similar to Constitution compilation

Bayesian Interpretation of Crossing Statistics

Theoretical Model Crossing Function

$$\mathcal{C}_\ell^{\rm TT}\,|^{N}_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\,|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H}_0,\tau,{\rm A_s},{\rm n_s}} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$

$$\begin{aligned}
T_0(C_0, x) &= C_0 \\
T_{\rm I}(C_0, C_1, x) &= T_0(C_0, x) + C_1\ x \\
T_{\rm II}(C_0, C_1, C_2, x) &= T_{\rm I}(C_0, C_1, x) + C_2(2x^2 - 1) \\
T_{\rm III}(C_0, C_1, C_2, C_3, x) &= T_{\rm II}(C_0, C_1, C_2, x) + C_3(4x^3 - 3x) \\
T_{\rm IV}(C_0, C_1, C_2, C_3, C_4, x) &= T_{\rm III}(C_0, C_1, C_2, C_3, x) + C_4(8x^4 - 8x^2 + 1) \\
T_{\rm V}(C_0, C_1, C_2, C_3, C_4, C_5, x) &= T_{\rm IV}(C_0, C_1, C_2, C_3, C_4, x) + C_5(16x^5 - 20x^3 + 5x).
\end{aligned}$$

$$x = \ell/\ell_{\rm max} \qquad \ell_{\rm max} = 2500.$$

Shafieloo et al JCAP 2011
Shafieloo, JCAP 2012a
Shafieloo, JCAP 2012b

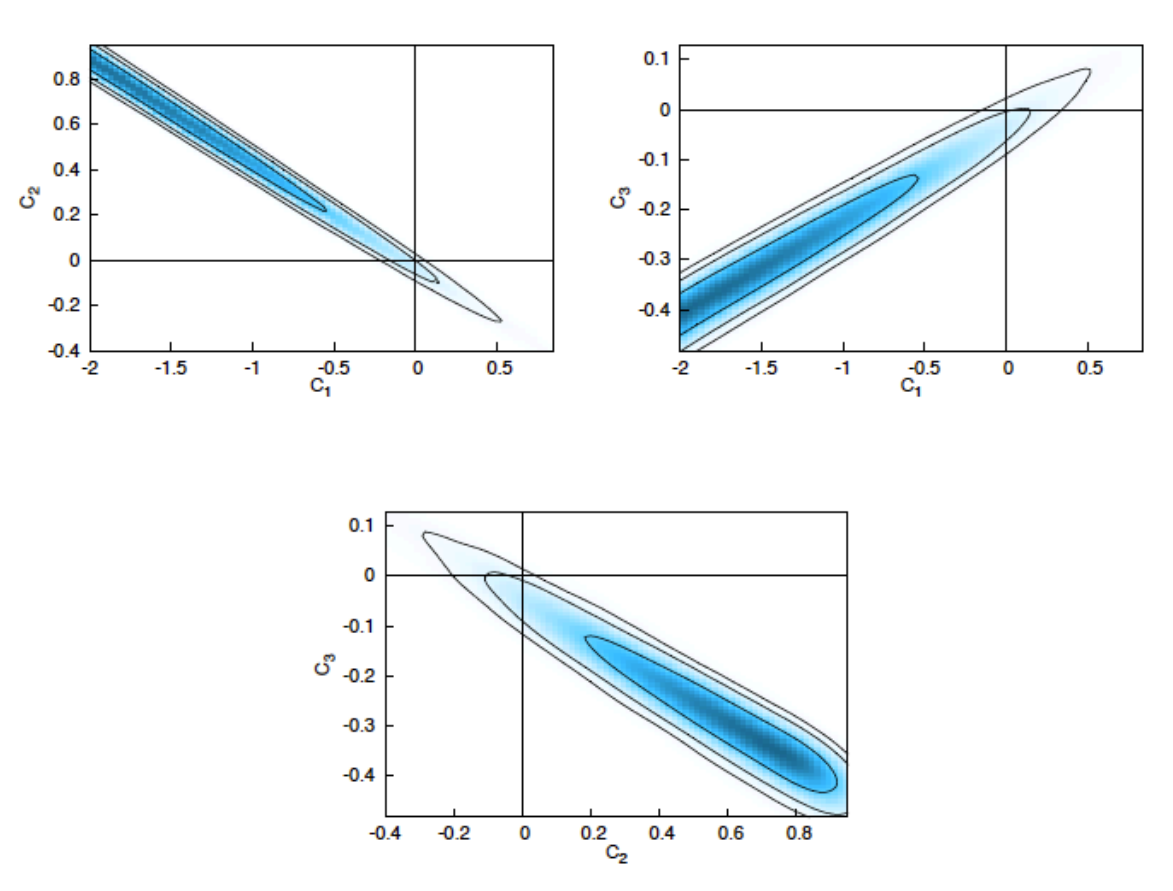
Chebychev polynomials have the properties of orthogonality and convergence within the limited range of -1 < x < 1.

Theoretical Model Crossing Function

$$\mathcal{C}_\ell^{\mathrm{TT}}\,|^{N}_{\mathrm{modified}} = \mathcal{C}_\ell^{\mathrm{TT}}\,|_{\Omega_{\mathrm{b}},\Omega_{\mathrm{CDM}},\mathrm{H}_0,\tau,\mathrm{A_s},\mathrm{n_s}} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$

$$T_{\mathrm{III}}(C_0, C_1, C_2, C_3, x) = C_0 + C_1\, x + C_2(2x^2 - 1) + C_3(4x^3 - 3x)$$

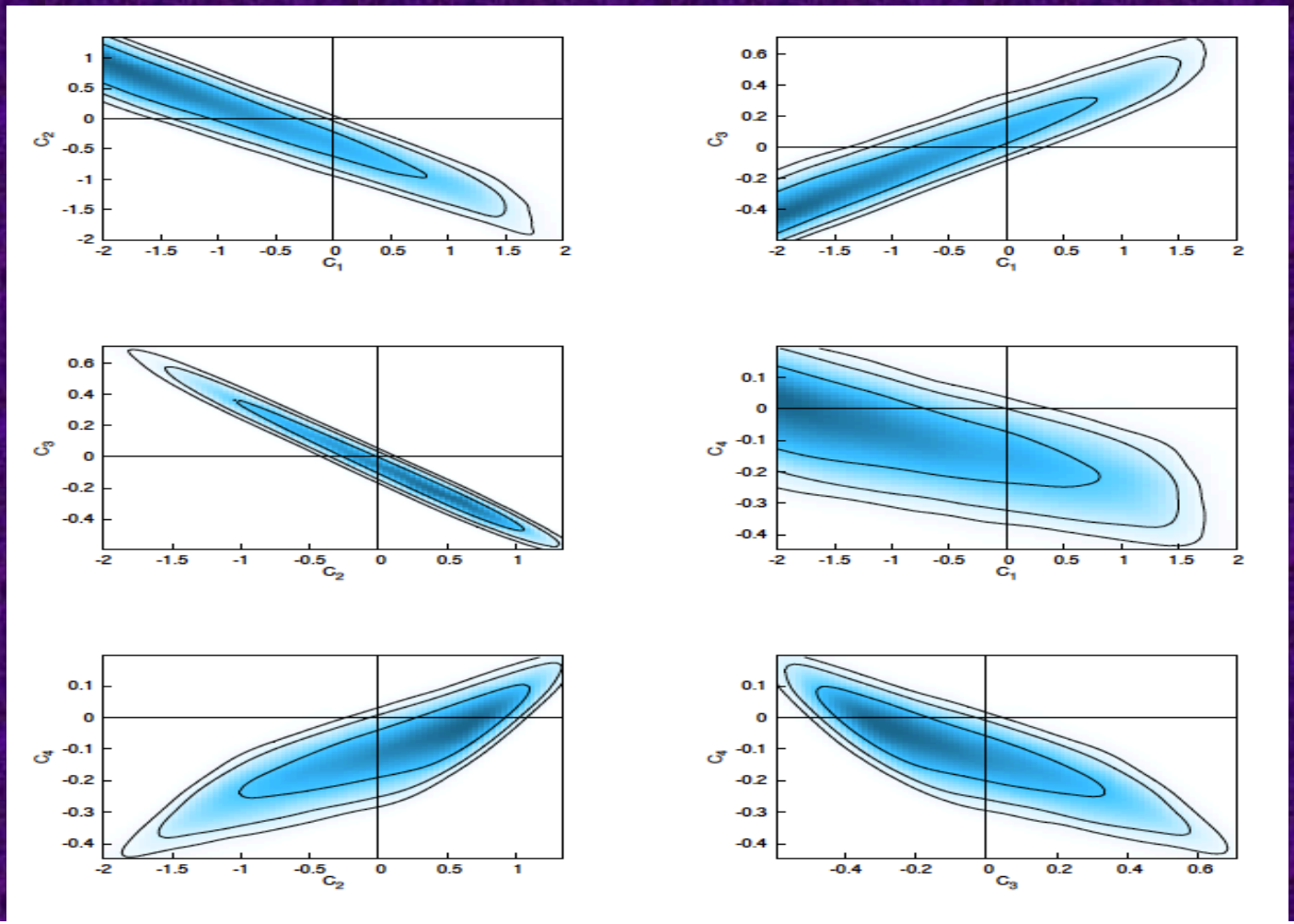
Planck 2013



Theoretical Model Crossing Function

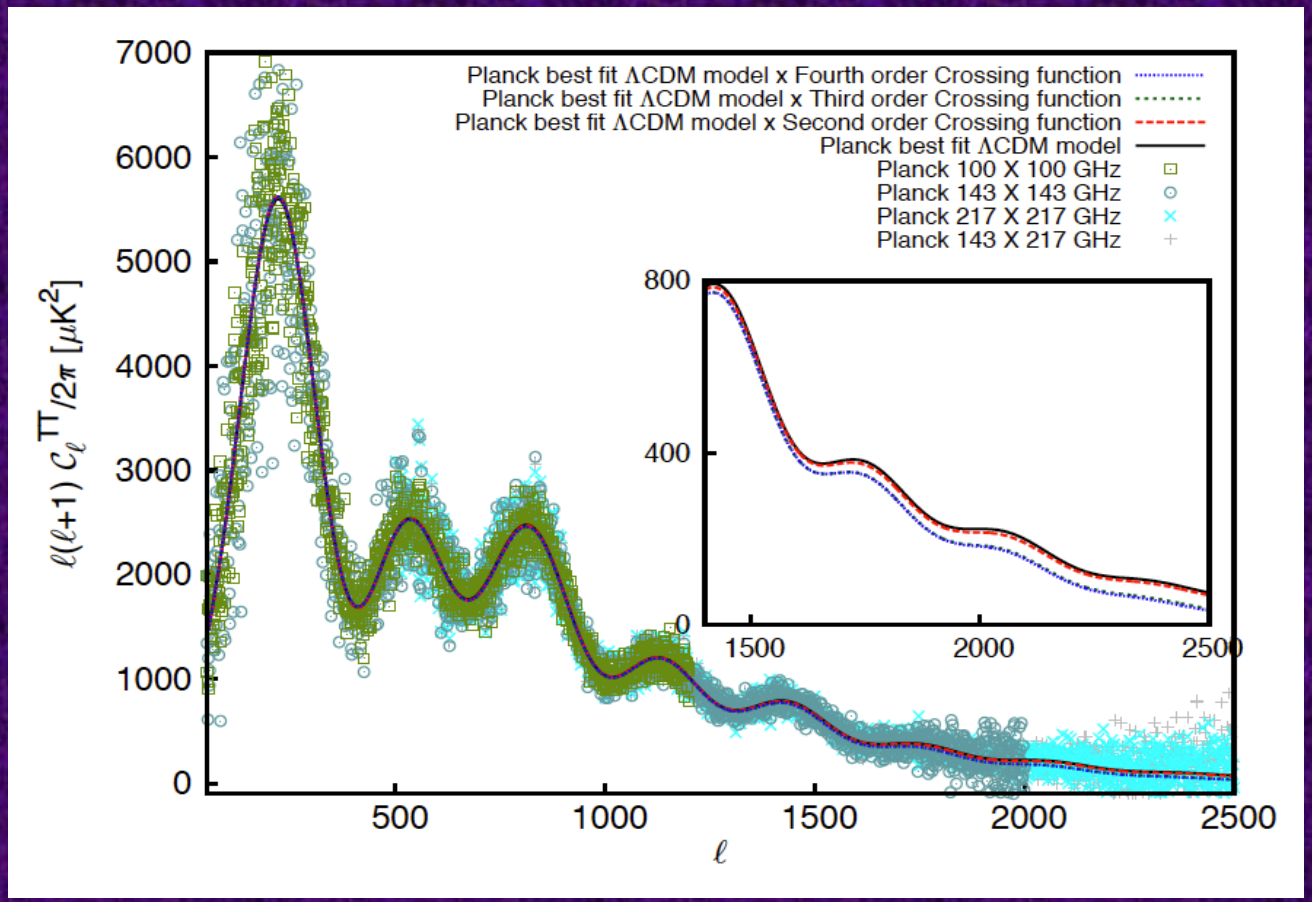
$$\mathcal{C}_\ell^{\mathrm{TT}}\,|^{N}_{\mathrm{modified}} = \mathcal{C}_\ell^{\mathrm{TT}}\,|_{\Omega_b,\Omega_{\mathrm{CDM}},H_0,\tau,A_s,n_s} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$

$$T_{\mathrm{IV}}(C_0, C_1, C_2, C_3, C_4, x) = C_0 + C_1\, x + C_2(2x^2 - 1) + C_3(4x^3 - 3x) + C_4(8x^4 - 8x^2 + 1)$$



Theoretical Model Crossing Function

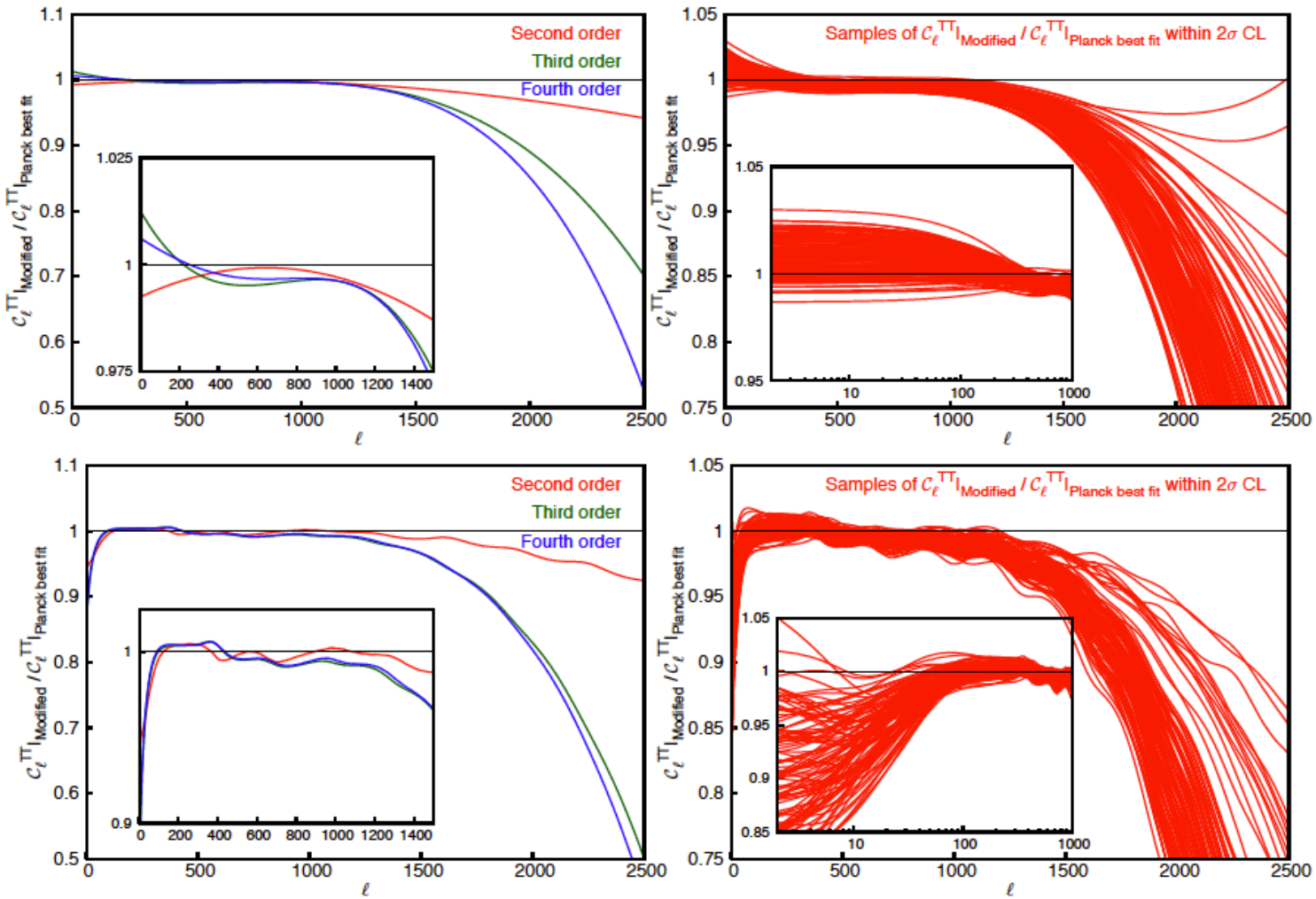
$$\mathcal{C}_\ell^{\rm TT}\,|^{N}_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\,|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H}_0,\tau,{\rm A_s},{\rm n_s}} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$



Data	ΛCDM	T_0	$T_{\rm I}$	$T_{\rm II}$	$T_{\rm III}$	$T_{\rm IV}$	$T_{\rm V}$
Planck low-ℓ (ℓ=2-49)	-6.3	-7	-8.5	-8.6	-9.8	-9.7	-9.7
Planck high-ℓ (ℓ=50-2500)	7794.9	7793.8	7793.8	7789.6	7785.9	7785.7	7784.7
Total	7788.6	7786.8	7785.3	7781	7776.1	7776	7775
$\chi^2_{\rm Model}$ - $\chi^2_{\Lambda\rm CDM}$	-	-1.8	-3.3	-7.6	-12.5	-12.6	-13.6

Theoretical Model Crossing Function

$$\mathcal{C}_\ell^{\rm TT}\,|^{N}_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\,|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H}_0,\tau,{\rm A_s},{\rm n_s}} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$

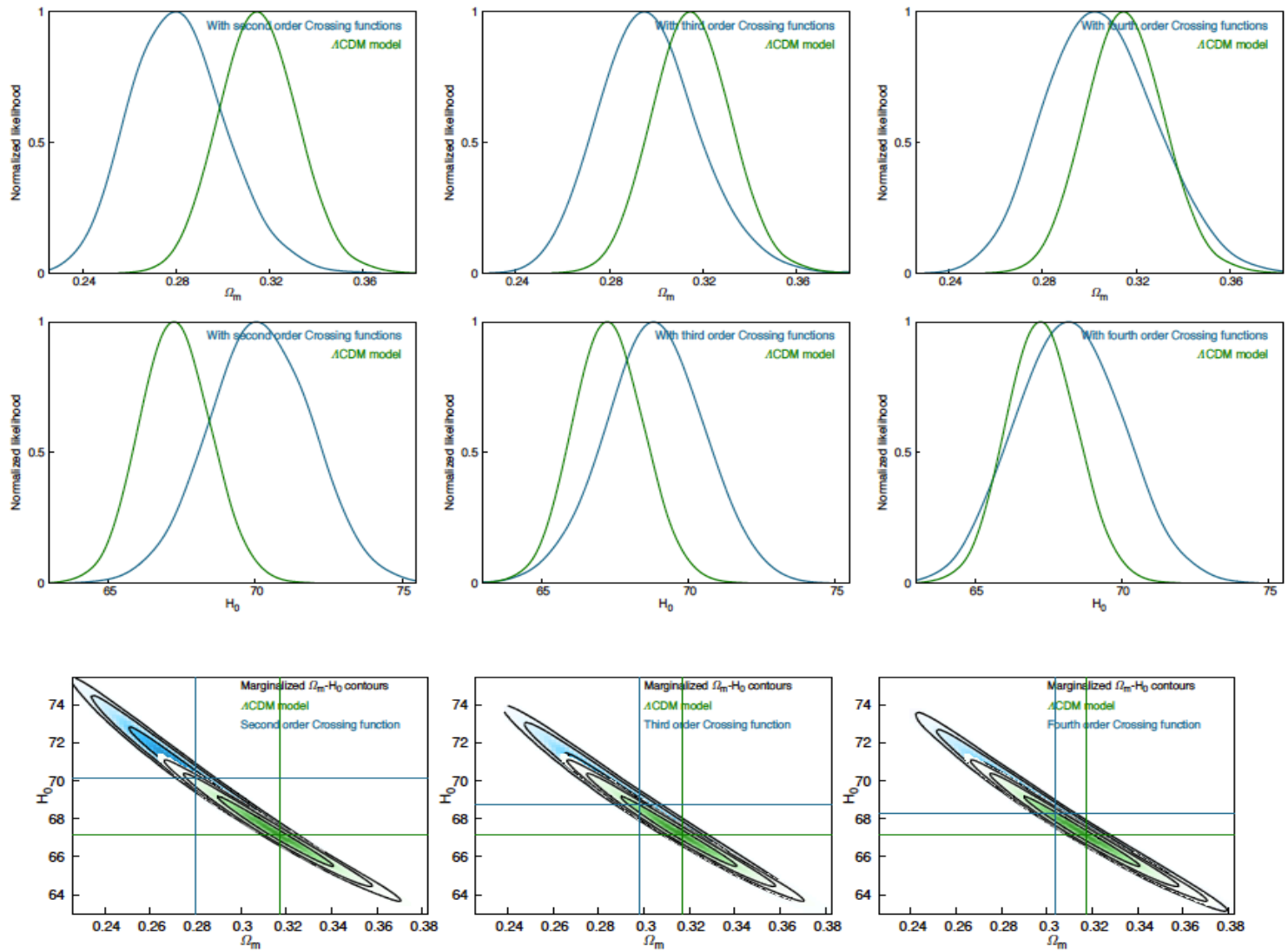


Data suggests substantial suppressions are required at both low and high multiples.

Hazra & Shafieloo, JCAP 2014

Theoretical Model Crossing Function

$$\mathcal{C}_\ell^{\rm TT}\,|^{N}_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\,|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H}_0,\tau,{\rm A_s},{\rm n_s}} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$



Cosmological parameters while considering Crossing functions.

Hazra & Shafieloo, JCAP 2014

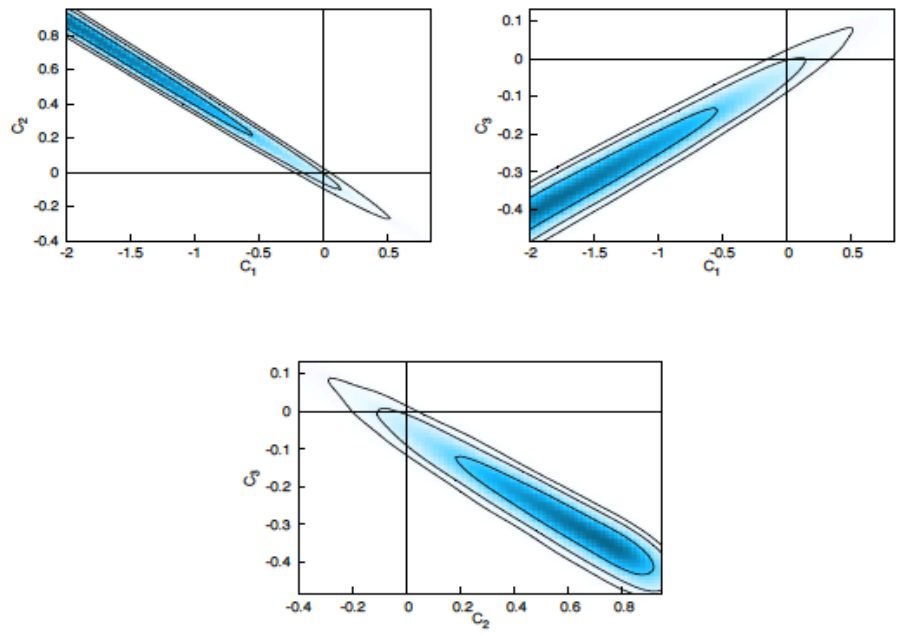
Crossing Statistic (Bayesian Interpretation)

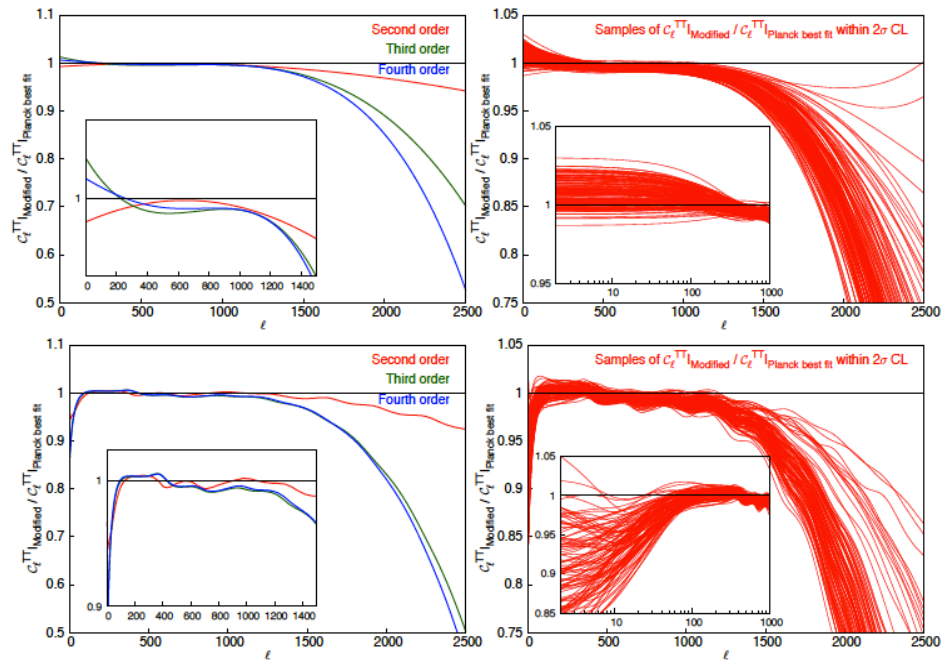
Theoretical model Crossing function

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

Confronting the concordance model of cosmology with Planck data

Consistent only at 2~3 sigma CL





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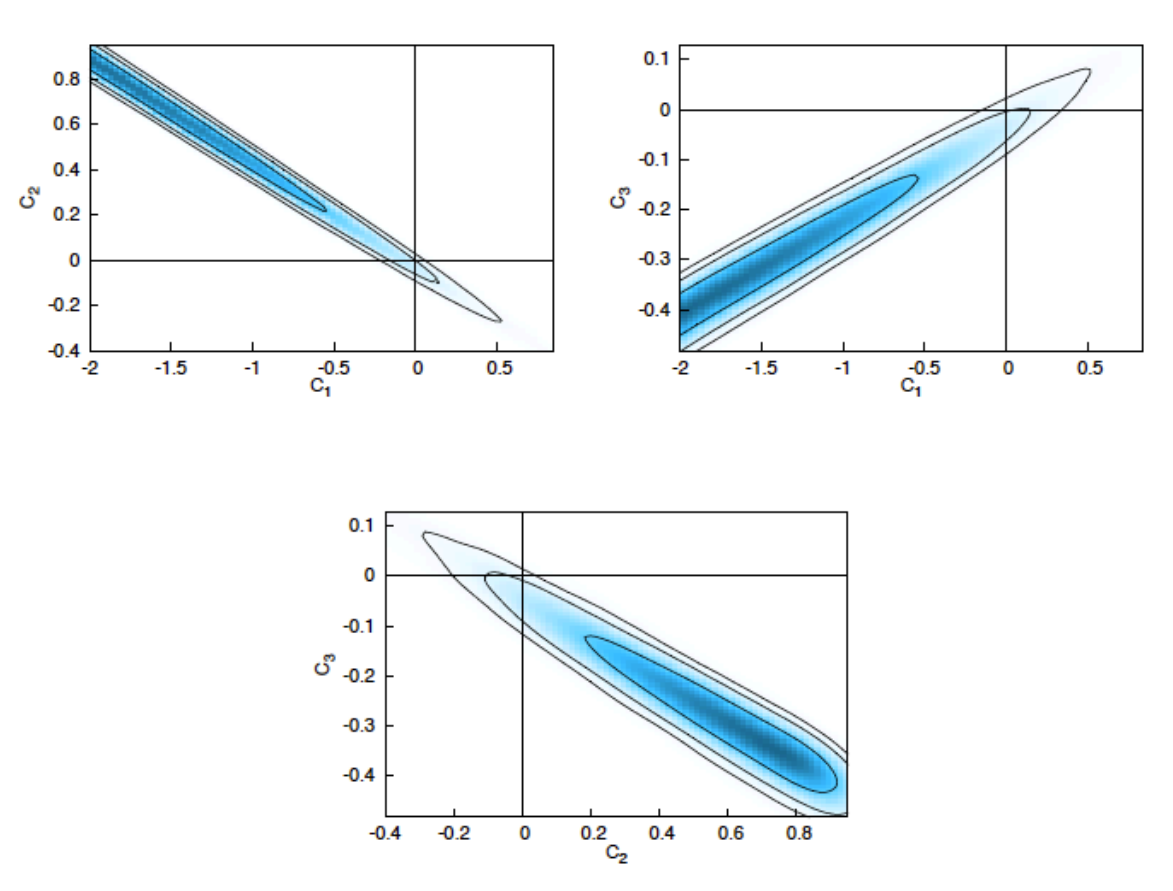
Hazra and Shafieloo, JCAP 2014

Theoretical Model Crossing Function

$$\mathcal{C}_\ell^{\mathrm{TT}}\,|^{N}_{\mathrm{modified}} = \mathcal{C}_\ell^{\mathrm{TT}}\,|_{\Omega_{\mathrm{b}},\Omega_{\mathrm{CDM}},\mathrm{H}_0,\tau,\mathrm{A_s},\mathrm{n_s}} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$

$$T_{\mathrm{III}}(C_0, C_1, C_2, C_3, x) = C_0 + C_1\, x + C_2(2x^2 - 1) + C_3(4x^3 - 3x)$$

With 217 GHz x 217 GHz

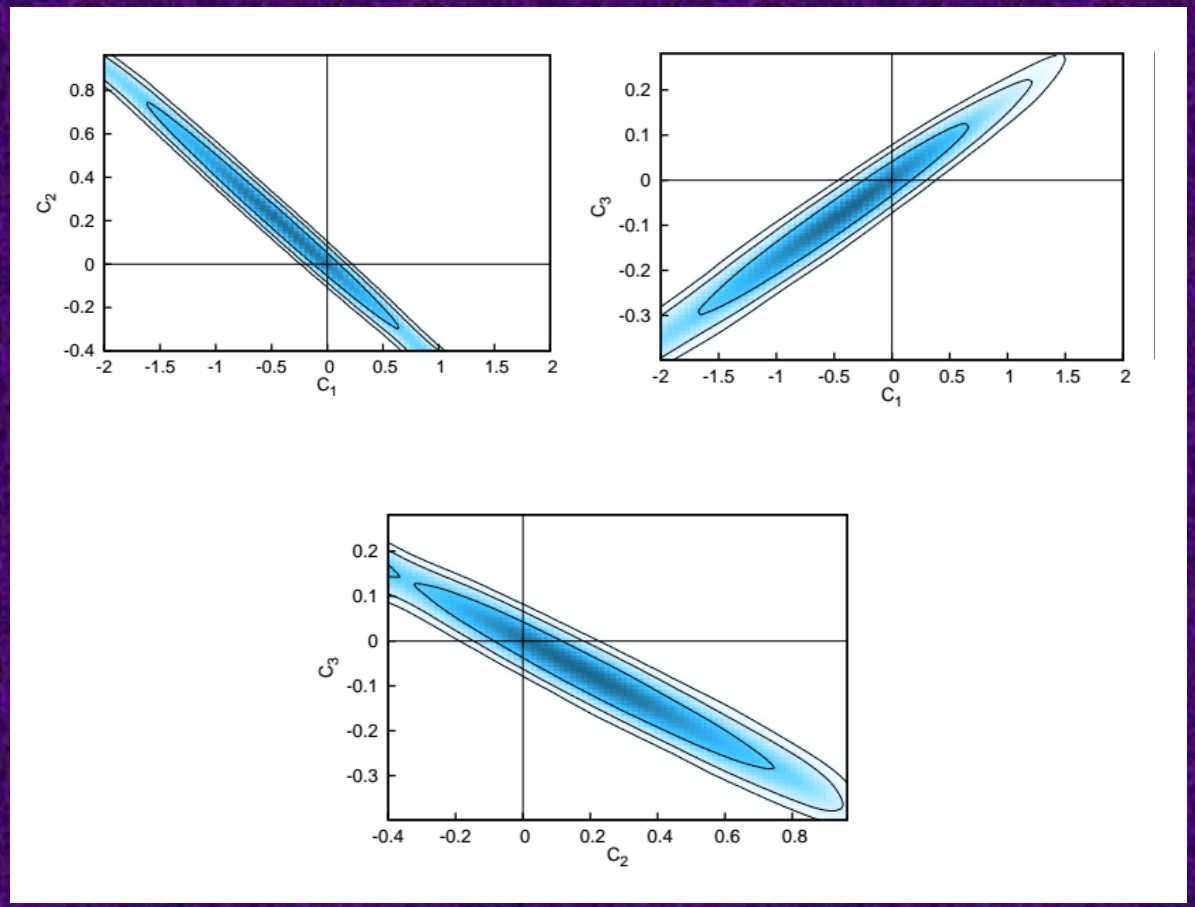


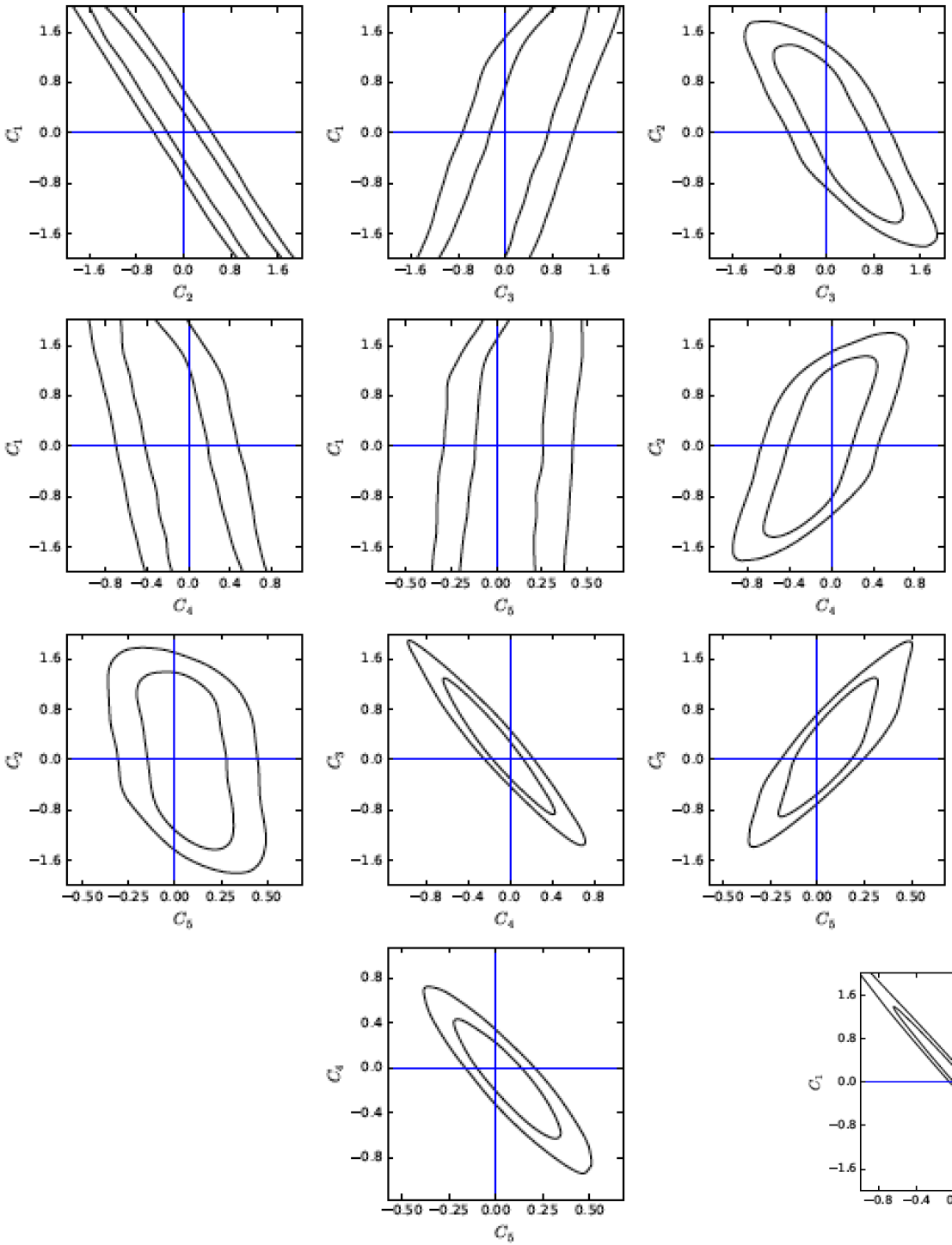
Theoretical Model Crossing Function

$$\mathcal{C}_\ell^{\mathrm{TT}}\,|^{N}_{\mathrm{modified}} = \mathcal{C}_\ell^{\mathrm{TT}}\,|_{\Omega_b,\Omega_{\mathrm{CDM}},H_0,\tau,A_s,n_s} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$

$$T_{\mathrm{III}}(C_0, C_1, C_2, C_3, x) = C_0 + C_1\, x + C_2(2x^2 - 1) + C_3(4x^3 - 3x)$$

Without 217 GHz x 217 GHz

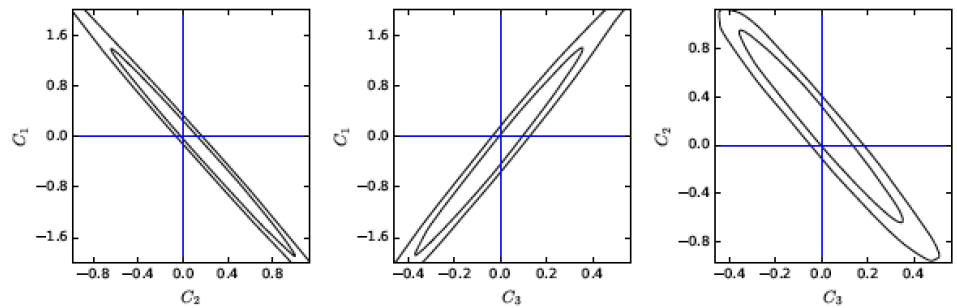


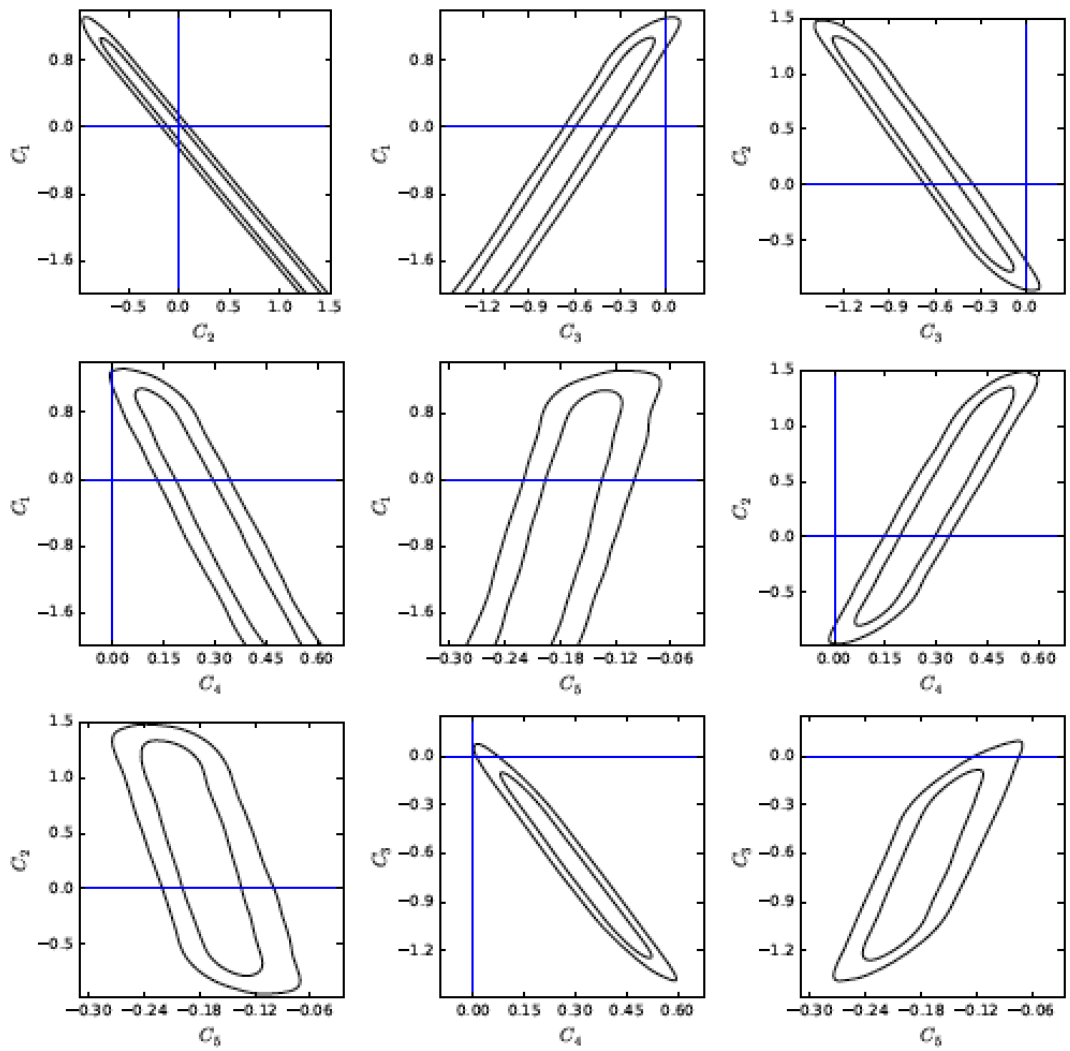


Test of consistency between temperature and polarization data from Planck 2015

Well consistent

Best fit (LCDM) TT power spectrum to EE data using 3rd anf 5th order Crossing functions

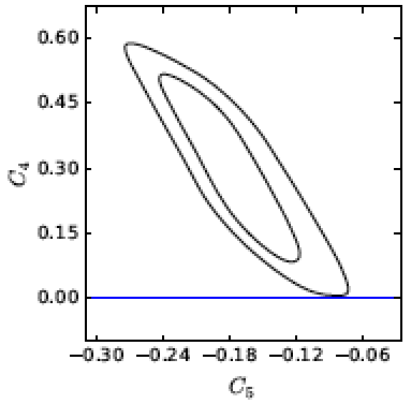


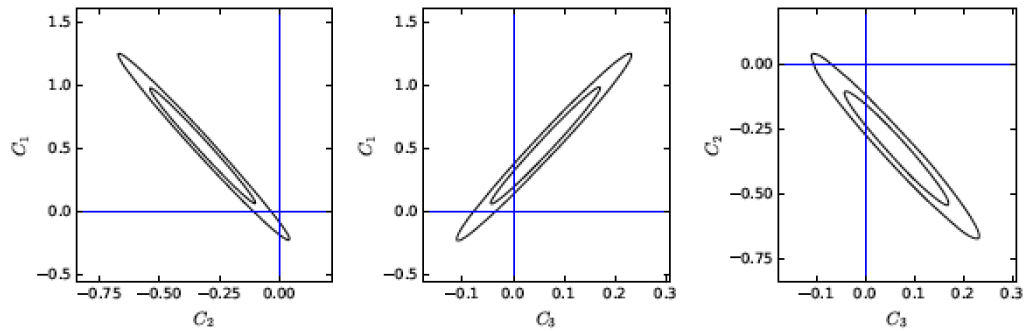


Test of consistency between temperature and polarization data from Planck 2015

Not consistent

Best fit (LCDM) EE power spectrum to TT data using 3rd anf 5th order Crossing functions

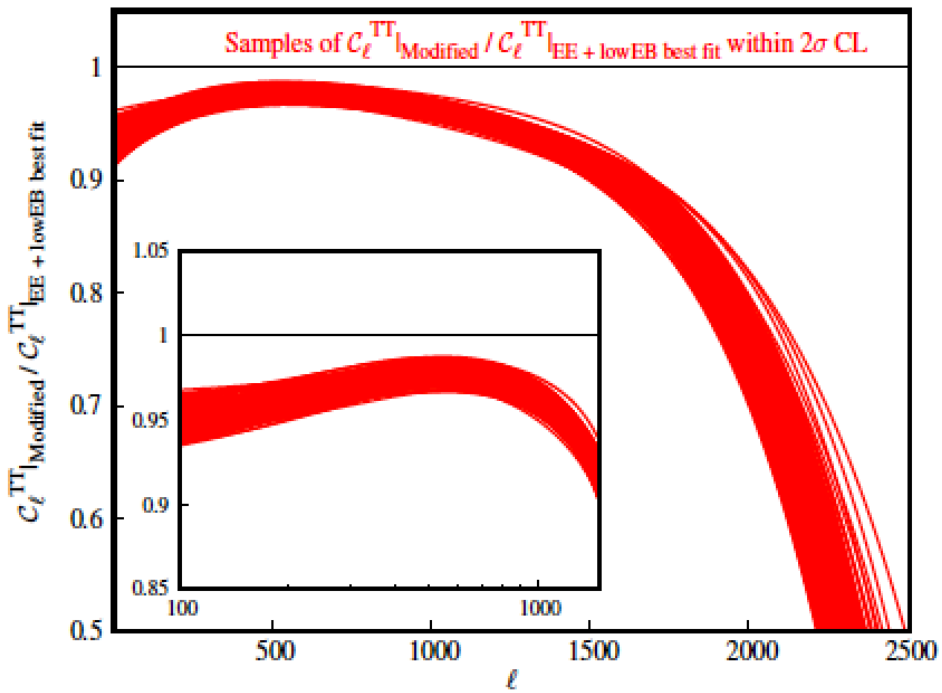


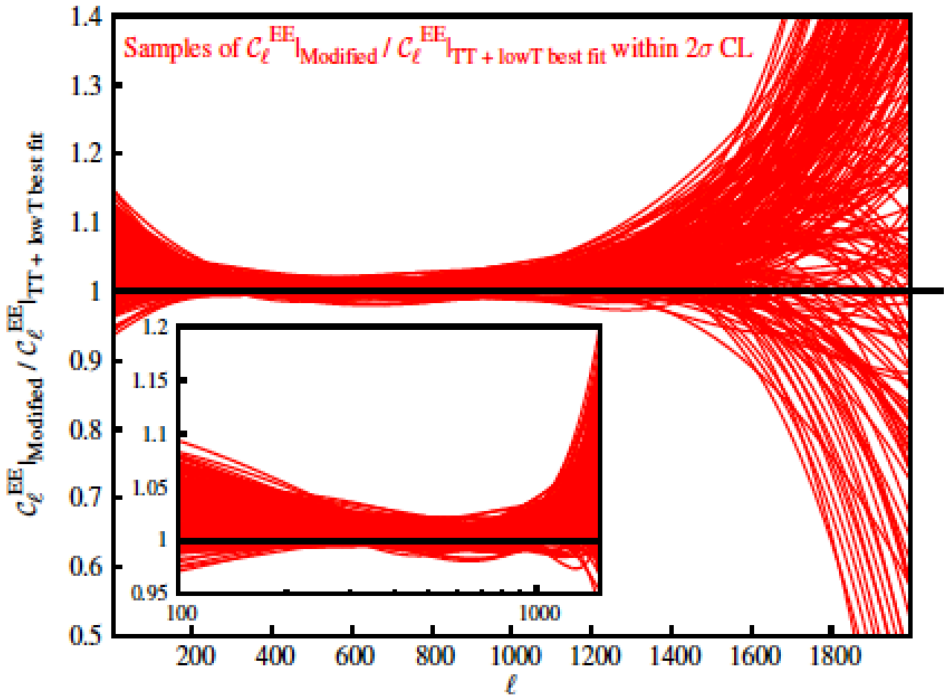


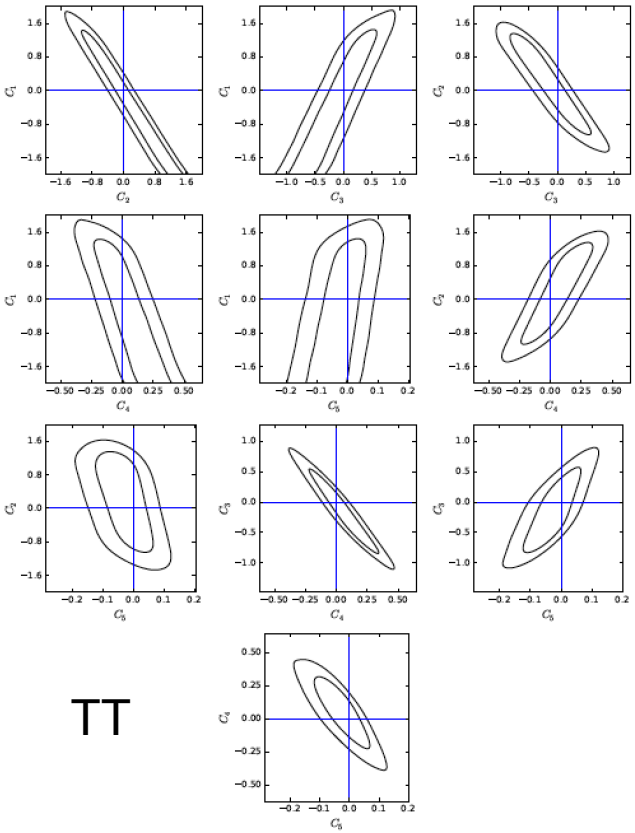
Test of consistency between temperature and polarization data from Planck 2015

Two data are consistent considering large uncertainties of the EE data.

There seems to be an amplitude shift (seen also in GP analysis).

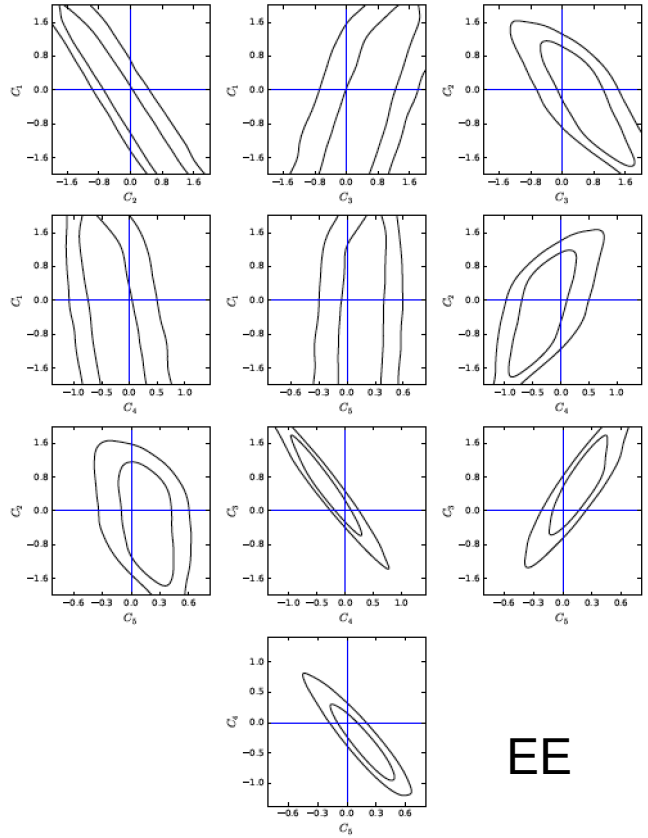






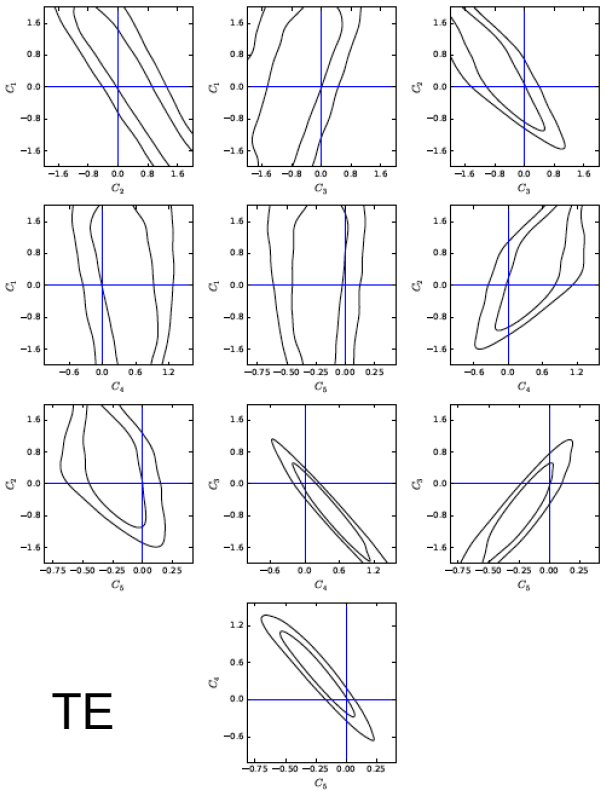
TT

Test of consistency between LCDM model and Planck 2015 data



EE

Crossing parameters marginalized over cosmological parameters fitting TT data



TE

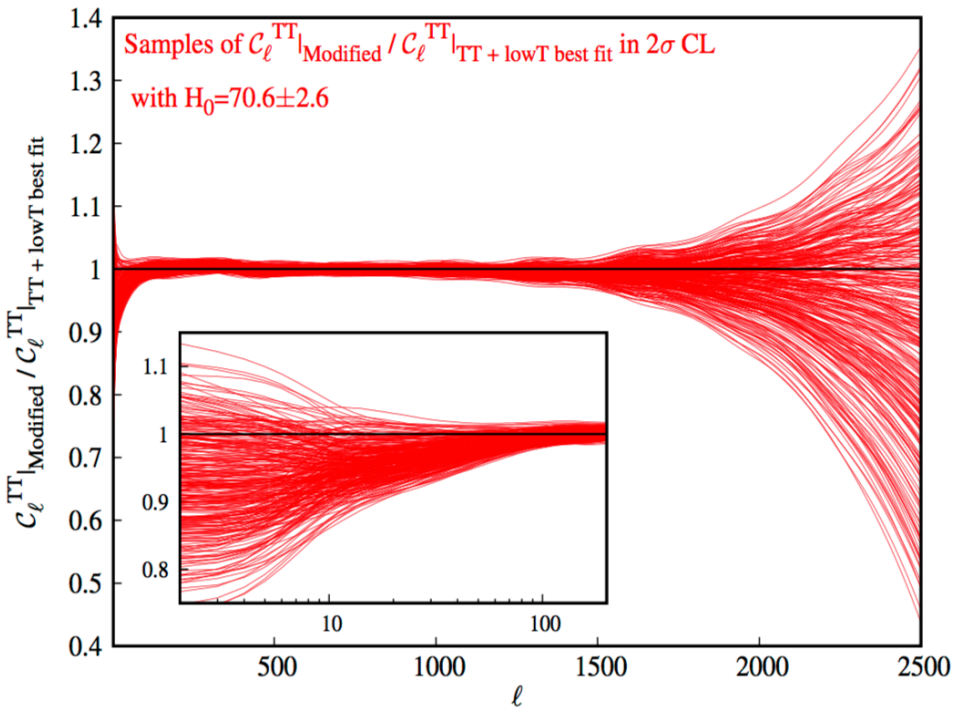
Crossing Statistic (Bayesian Interpretation)

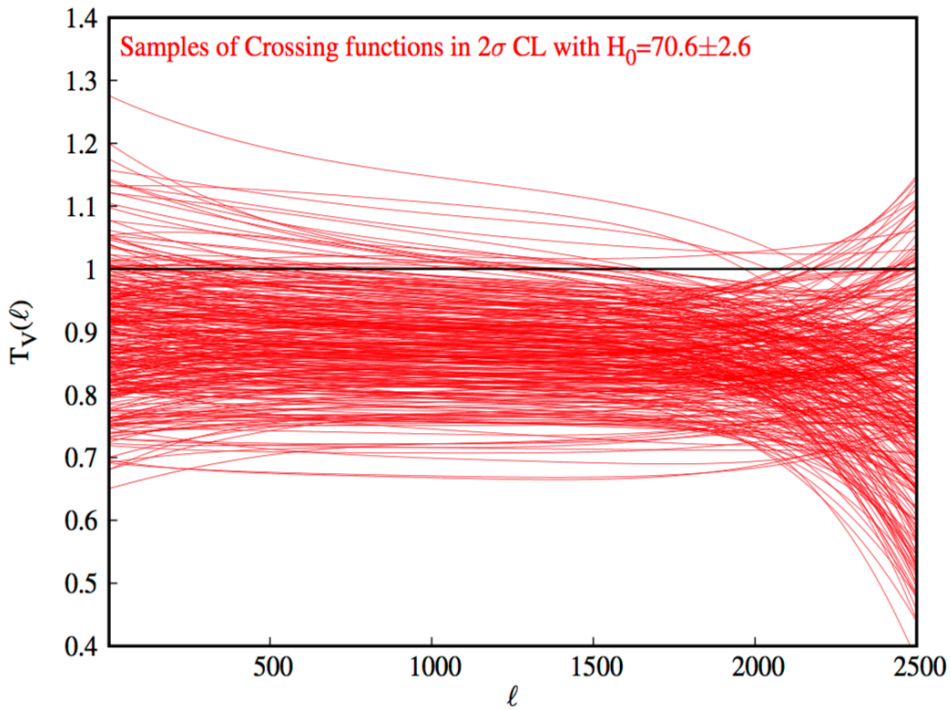
Theoretical model Crossing function

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

Confronting the concordance model of cosmology with ***Planck 2015*** data

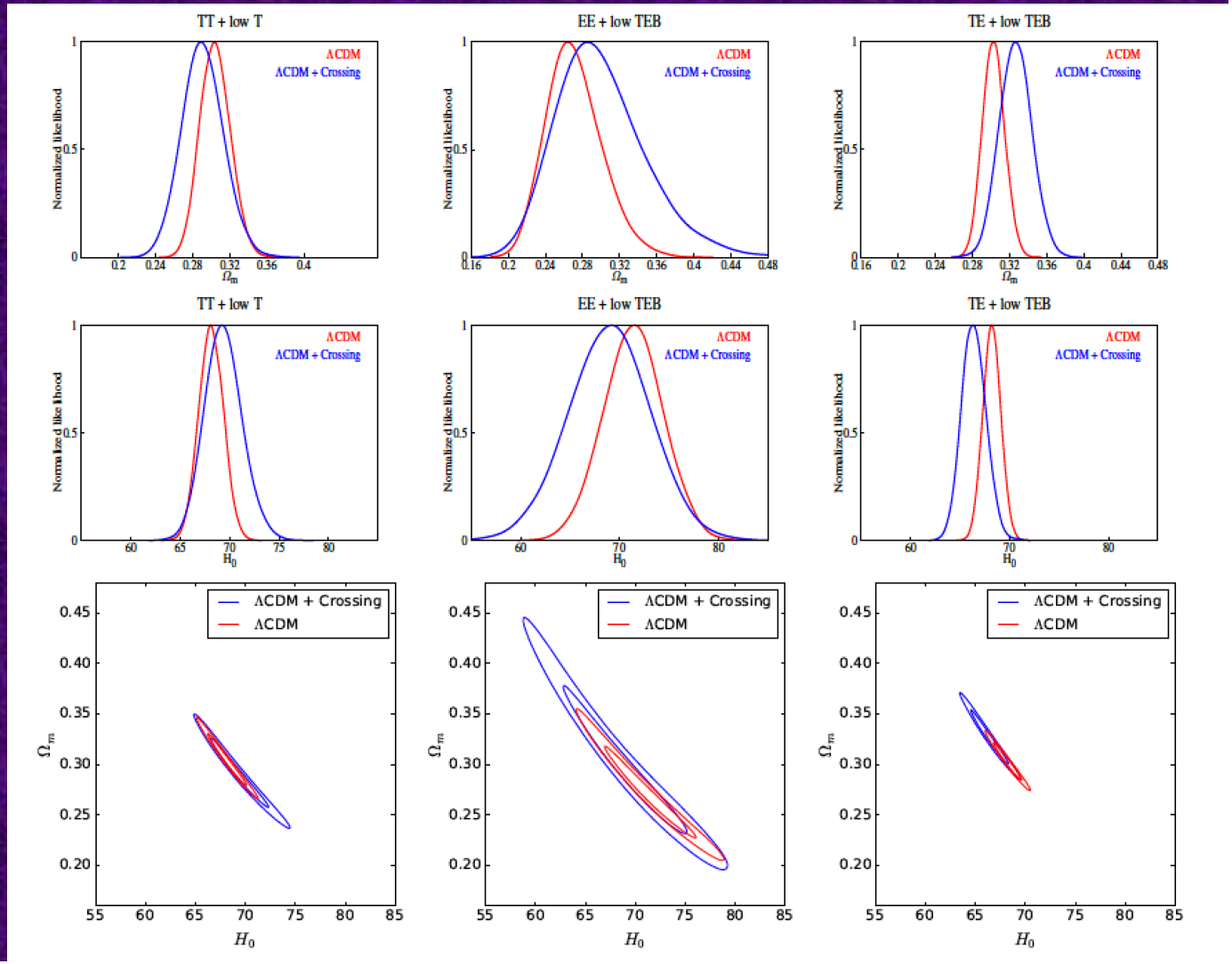
Shafieloo and Hazra, JCAP 2017 ***Completely Consistent***





Planck 2015:
No feature but interesting effect on background parameters.

Crossing Statistics

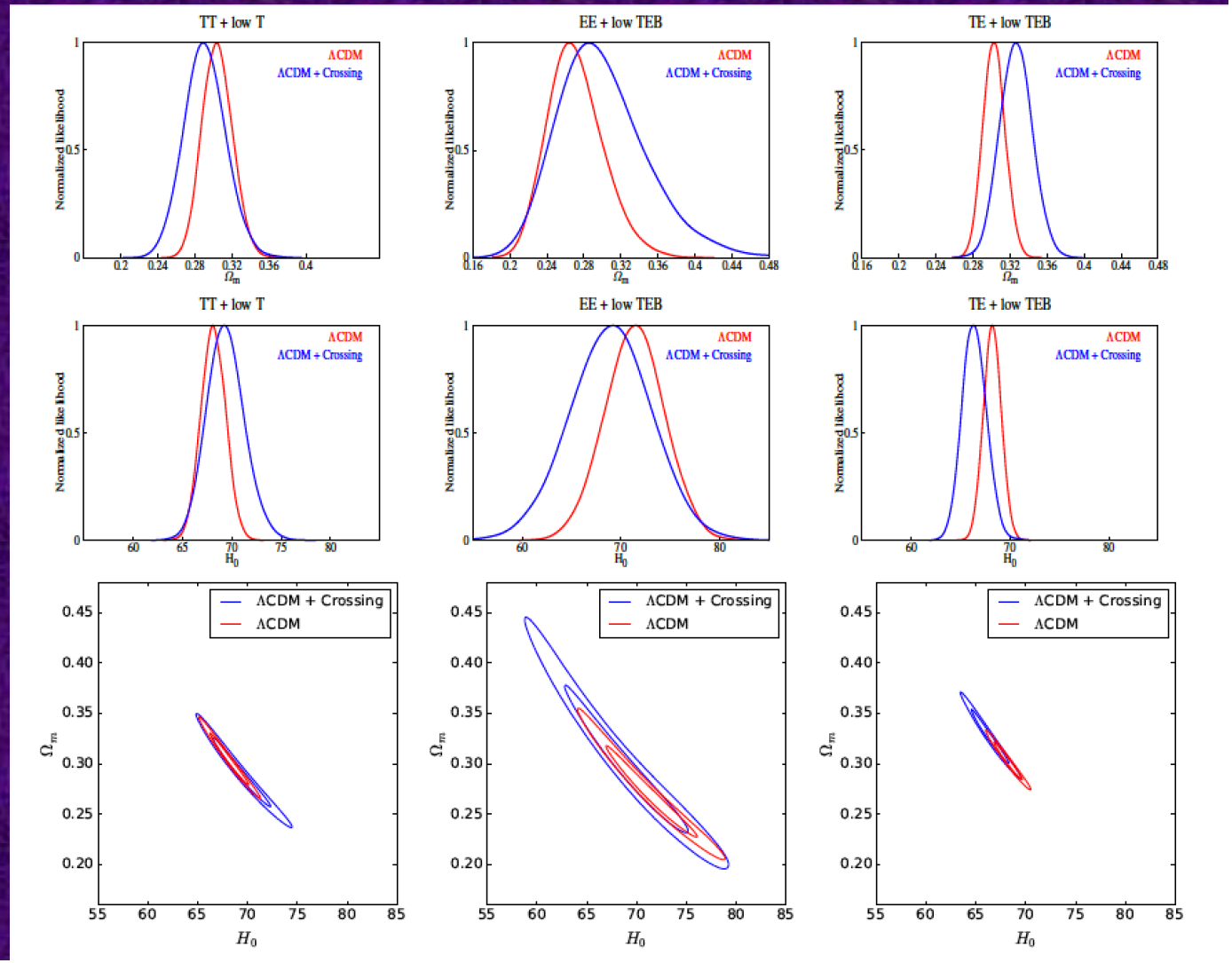


Shafieloo & Hazra, JCAP 2017

Planck 2015:
No feature but interesting effect on background parameters.

Crossing Statistics

Planck polarization data and local H0 measurements seems having irresolvable tension. Maybe either or both have systematics? If not, new physics might be the answer.



Shafieloo & Hazra, JCAP 2017

Summary

No clear tension between Planck temperature and polarization data. There is a small amplitude shift.

No tension between Planck data and concordance LCDM model.

Even by allowing additional flexibility, Planck polarization data restrain to allow larger values of H0.