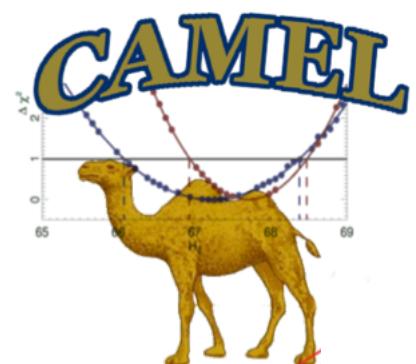


Planck likelihoods and the A_L parameter



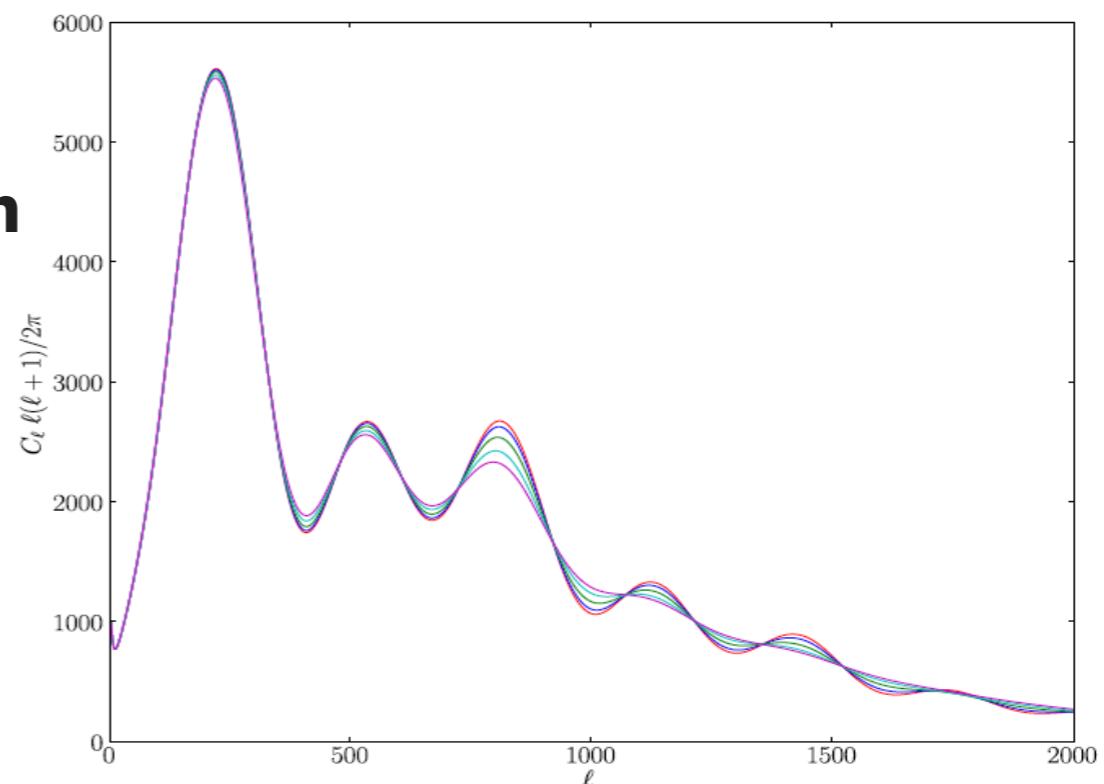
F. Couchot, S. Henrot-Versillé, O. Perdereau, S. Plaszczynski, B. Rouillé d'Orfeuil, M. Spinelli, **M. Tristram**



- “Relieving tensions related to the lensing of the CMB temperature power-spectra”
[Couchot et al., A&A in press, arXiv:1510.07600]
“Cosmology with the CMB temperature-polarization correlation”
[Couchot et al., A&A submitted, arXiv:1609.09730]

The A_L parameter

- In Boltzman codes, the **weak lensing** enters the prediction of the CMB spectrum through a **convolution of the unlensed spectrum with the lensing potential power spectrum** C_ℓ^Ψ
 - smooth out the main peaks



- The A_L parameter is a fudge factor defined as: $C_\ell^\Psi \rightarrow A_L C_\ell^\Psi$.
 - $A_L = 0$: weak lensing ignored
 - $A_L = 1$: standard Λ CDM
- **Measuring $A_L \neq 1$ indicates either a problem in the model or remaining systematics in the data**

$$A_L = 1.22 \pm 0.10$$

[Planck 2015 results. XIII, A&A 594, A13 (2016)]

**Where does this tension come from ?
What can we do to relieve it ?**

Setting the stage

Planck 2015 constraints from CMB anisotropies are derived from

- **two-component likelihoods**
 - **low- ℓ** (lowTEB)
temperature and polarisation map based likelihood
 - **high- ℓ** (Plik but also Hillipop, CamSpec, Mspe)
gaussian likelihood (temperature & TE/EE polarisation)
- **Parameter estimation**
 - **Bayesian inference using Monte Carlo Markov Chains** to explore the likelihood function (usual in cosmology)
 - **Profile likelihoods** (more common in particle physics)

[Planck 2015 results. XI, A&A 594, A11 (2016)]
[Planck 2015 results. XIII, A&A 594, A13 (2016)]

- **Results from Planck:**

[Planck 2015 results. XIII, A&A 594, A13 (2016)]

$$A_L = 1.22 \pm 0.10 \quad (\text{Plik+lowTEB, camb/MCMC})$$

- **Role of the Boltzman solver:**

CLASS [J. Lesgourges, arXiv:1104.2932]

$$A_L = 1.24 \pm 0.10 \quad (\text{Plik+lowTEB, class/MCMC})$$

- **Profile Likelihood Analysis:**

$$A_L = 1.26^{+0.11}_{-0.10} \quad (\text{Plik+lowTEB, class/profile})$$

- ✓ **theoretical uncertainties (but low level)**
- ✓ **small volume effect**
(difference between best-fit and posterior maximum)

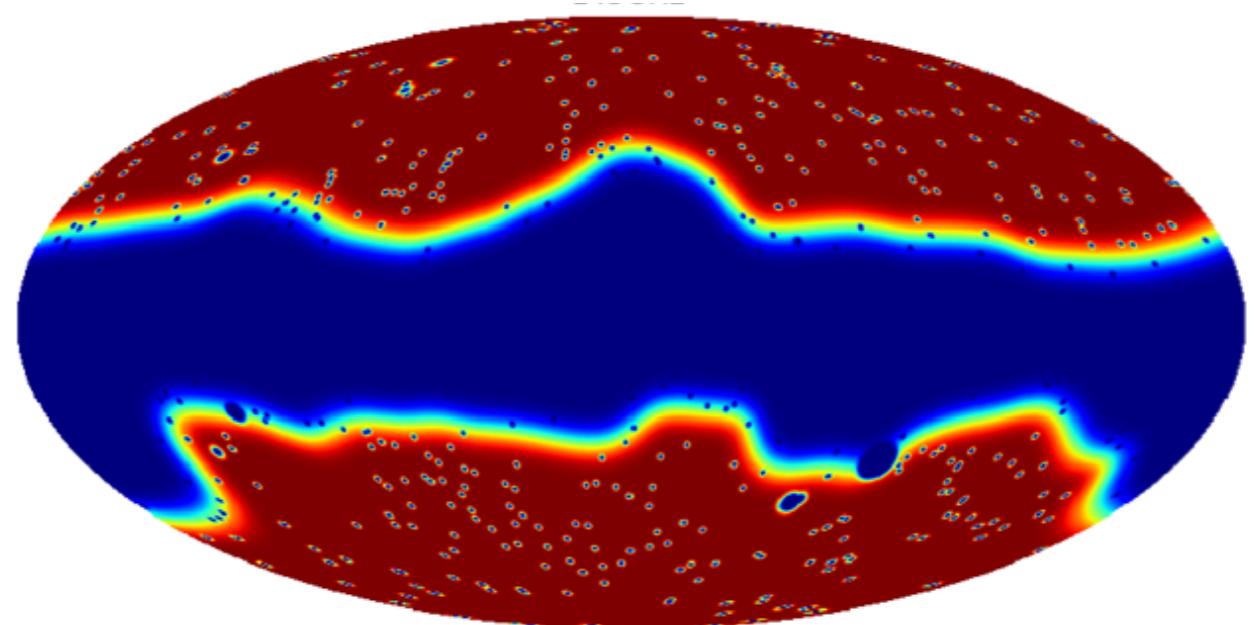
**Where does this tension come from ?
What can we do to relieve it ?**

The Hillipop high- ℓ likelihood

One of the high- ℓ Planck likelihood ($\ell > 50$) in **temperature and polarisation** based on cross-spectra of the 100, 143 and 217GHz maps of the 2015 Planck release

$$C_\ell^{XY} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^X a_{\ell m}^{*Y}$$

- regions with high level of **foregrounds contamination** are **masked** before computing spectra
- foregrounds **residuals** are modeled in Hillipop as power spectra templates from Planck measurements
 - Galactic emission (dust)
 - Galaxy clustering (CIB)
 - SZ (thermal, kinetic and SZxCIB)
 - Point sources



[Planck 2015 results. XI, A&A 594, A11 (2016)]

[Couchot et al., A&A in press, arXiv:1510.07600]

[Couchot et al., A&A submitted, arXiv:1609.09730]

The high- ℓ likelihoods

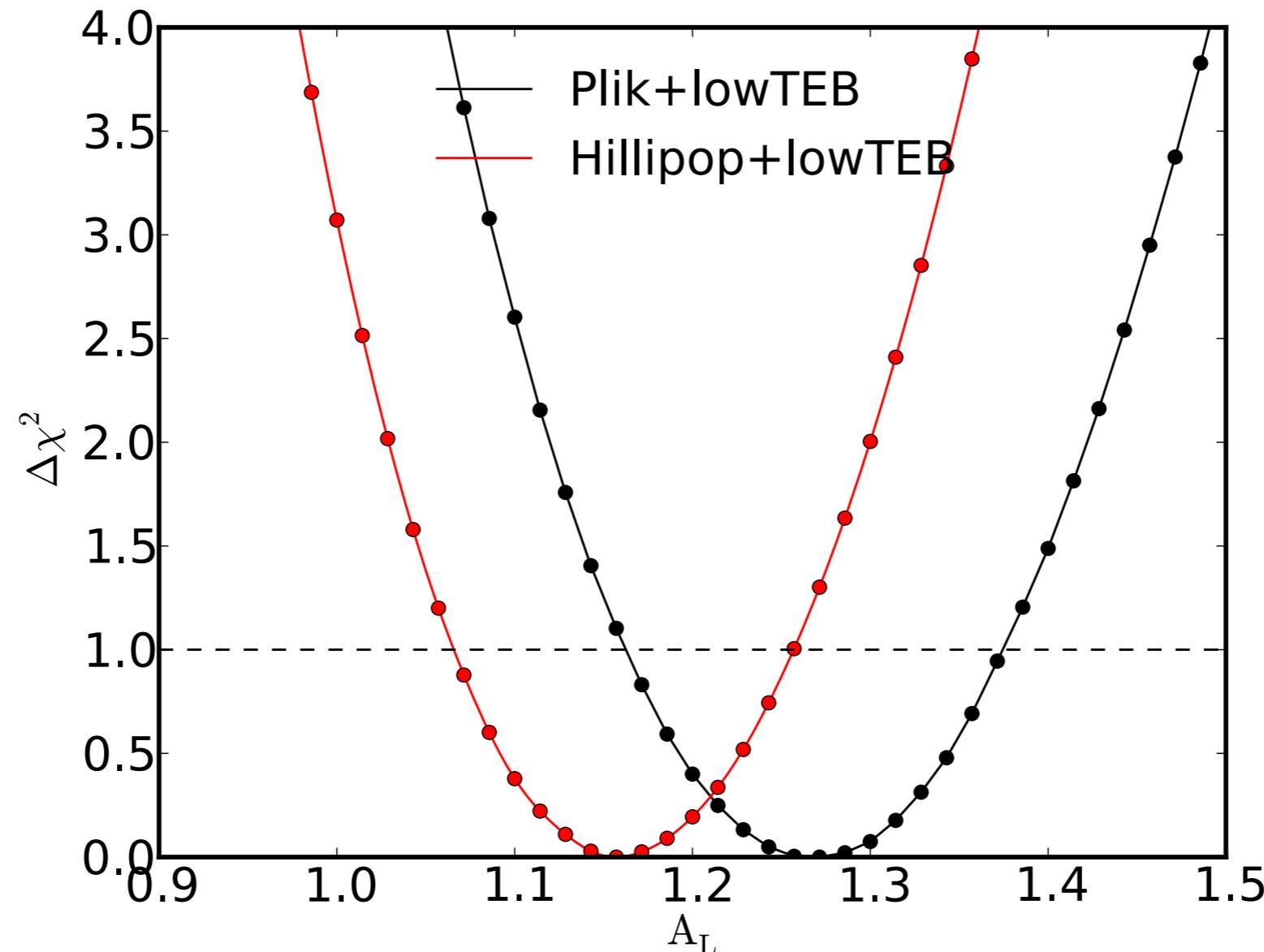
- **The main differences with Plik* ?**

1. we use all 15 cross-spectra** from 6 maps
v.s. only 7 selected cross-spectra in Plik
2. intercalibration coefficients are defined at the map level
v.s. spectra level in Plik
3. PS are identified and separated from high latitude cirrus dust clouds before masking
v.s. mixed in Plik masks
4. residual foregrounds are modeled using Planck measurements for SED and spectral shape
v.s. analytical models for Plik with additional constraint in the SZ sector derived from ACT data: $A^{\text{SZ}} = A^{\text{kSZ}} + 1.6A^{\text{tSZ}} = 9.5\mu\text{K}^2$ and a dispersion $3\mu\text{K}^2$

- Comparison between Hillipop and Plik

Parameters	Plik + lowTEB	Hillipop T + lowTEB
$\Omega_b h^2$	0.02225 ± 0.00023	0.02220 ± 0.00022
$\Omega_c h^2$	0.1197 ± 0.0022	0.1196 ± 0.0022
$100\theta_s$	1.04188 ± 0.00044	1.04178 ± 0.00044
τ	0.078 ± 0.019	0.070 ± 0.018
$\log(10^{10} A_s)$	3.089 ± 0.036	3.071 ± 0.035
n_s	0.9655 ± 0.0062	0.9659 ± 0.0060

A_L profile likelihood



$$A_L = 1.26^{+0.11}_{-0.10} \quad (\text{Plik+lowTEB})$$

$$A_L = 1.16^{+0.10}_{-0.09} \quad (\text{Hillipop + lowTEB})$$

- Comparison between Hillipop and Plik

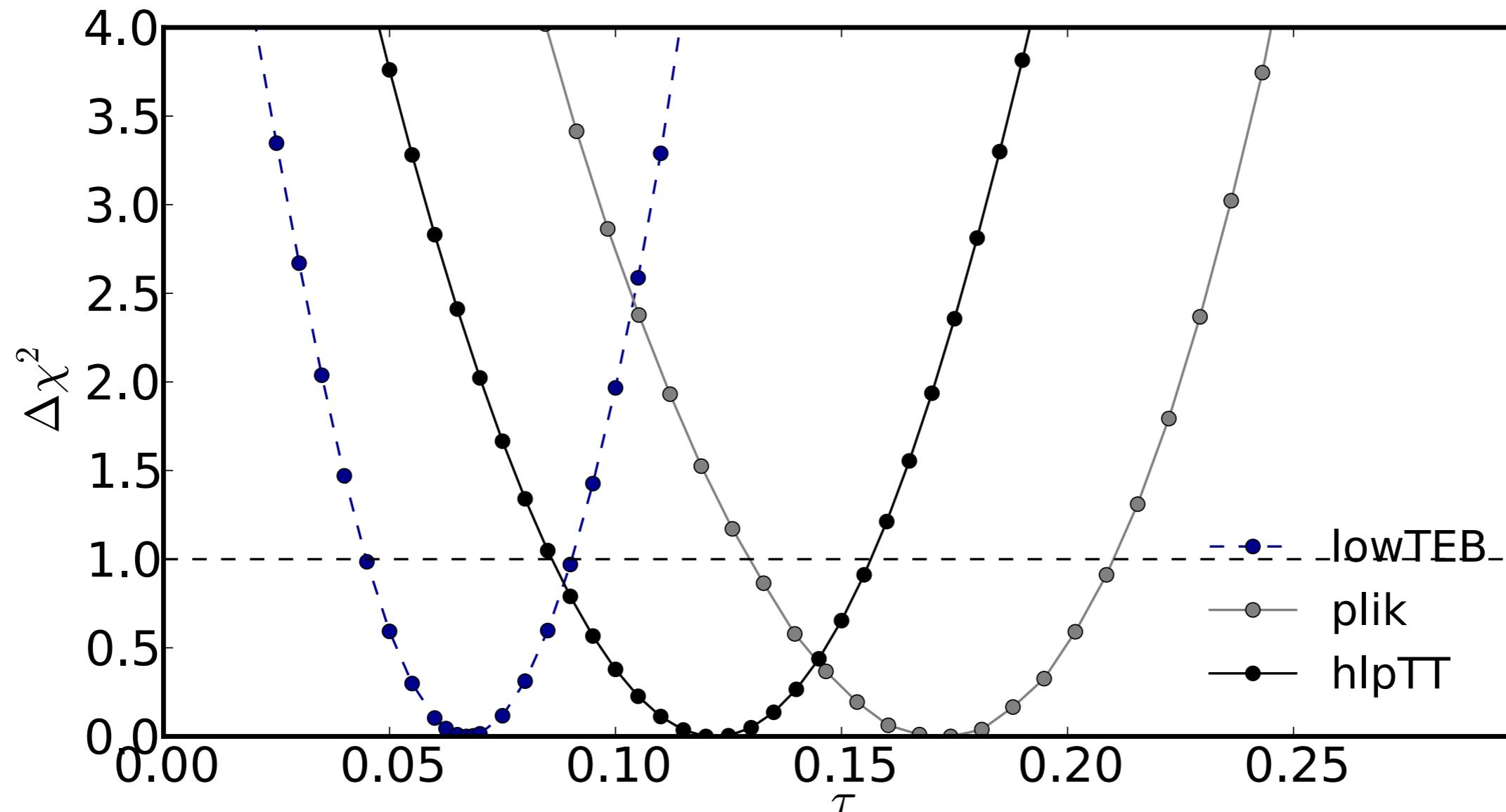
Parameters	Plik + lowTEB	Hillipop T + lowTEB
$\Omega_b h^2$	0.02225 ± 0.00023	0.02220 ± 0.00022
$\Omega_c h^2$	0.1197 ± 0.0022	0.1196 ± 0.0022
100θ	1.04188 ± 0.00044	1.04178 ± 0.00044
τ	0.078 ± 0.019	0.070 ± 0.018
$\log(10^{10} A_s)$	3.089 ± 0.036	3.071 ± 0.035
n_s	0.9055 ± 0.0002	0.9059 ± 0.0000

- τ mainly driven by the low- ℓ data
- τ and A_s are correlated through the amplitude of spectra $C_\ell \propto A_s e^{-2\tau}$

why different ?

tension between low- ℓ and high- ℓ data ?

optical depth profile likelihoods

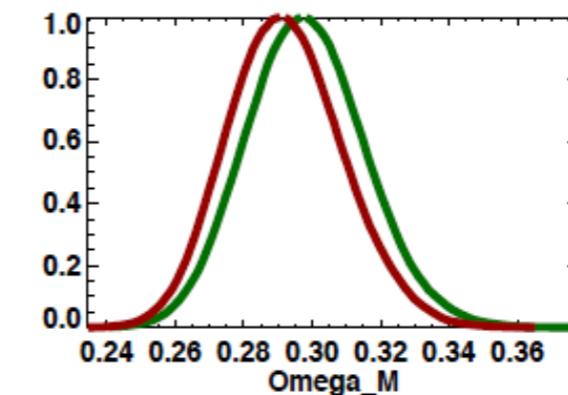
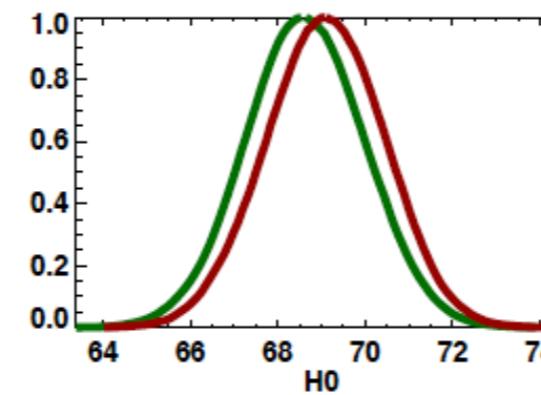
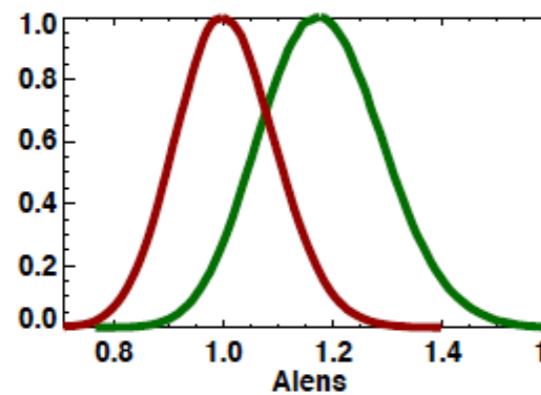
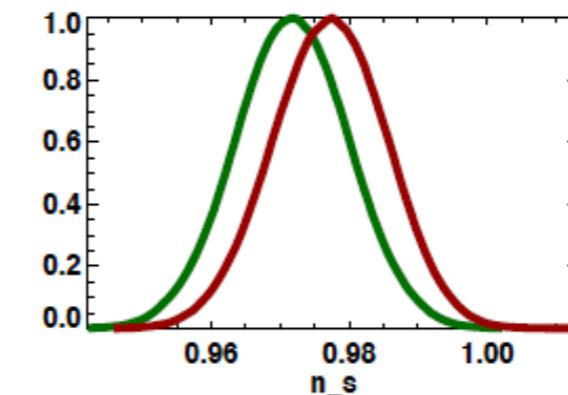
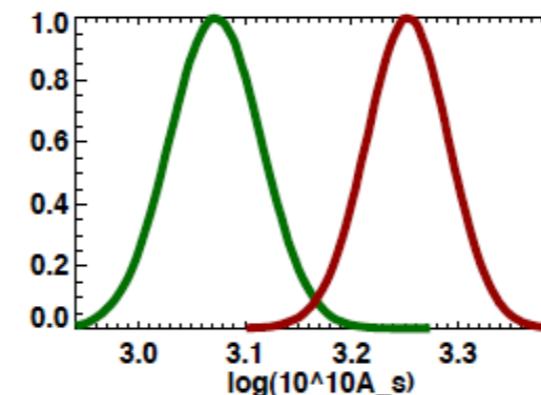
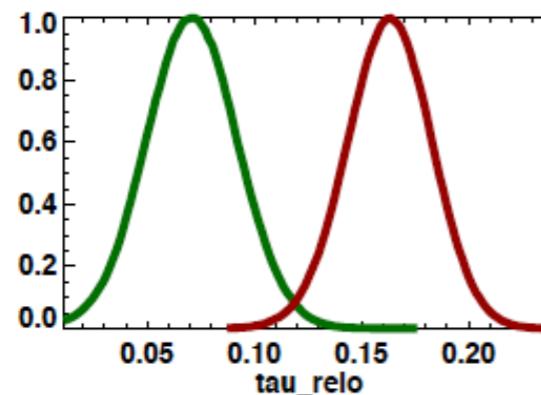
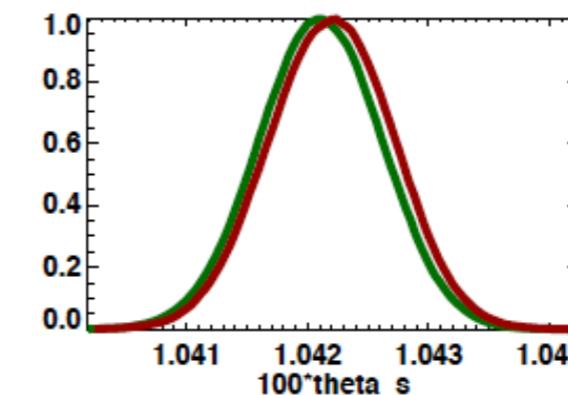
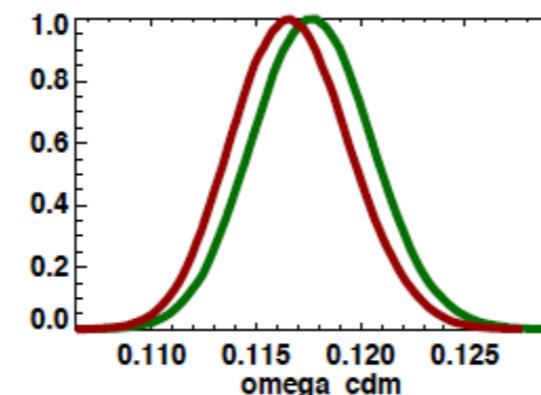
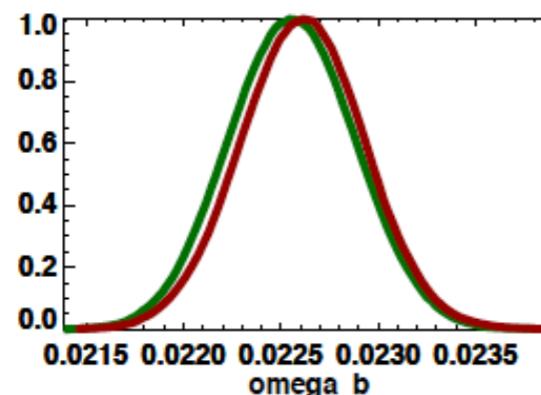


$$\tau = 0.067_{-0.021}^{+0.023} \text{ (lowTEB)} \xleftarrow[2.2\sigma]{} \tau = 0.172_{-0.042}^{+0.038} \text{ (Plak)}$$

$$\tau = 0.067_{-0.021}^{+0.023} \text{ (lowTEB)} \xleftarrow[1.3\sigma]{} \tau = 0.122_{-0.036}^{+0.034} \text{ (Hillipop)}$$

optical depth and A_L

low- ℓ : pulls $\tau \searrow$
 high- ℓ : amplitude $C_\ell \propto A_s e^{-2\tau} \rightarrow A_s \searrow$
 high- ℓ : to preserve lensing information ($C_\ell^\Phi \propto A_s A_L$) :
 $A_L \nearrow$



Plik
+

τ prior = 0.07
 τ prior = 0.17

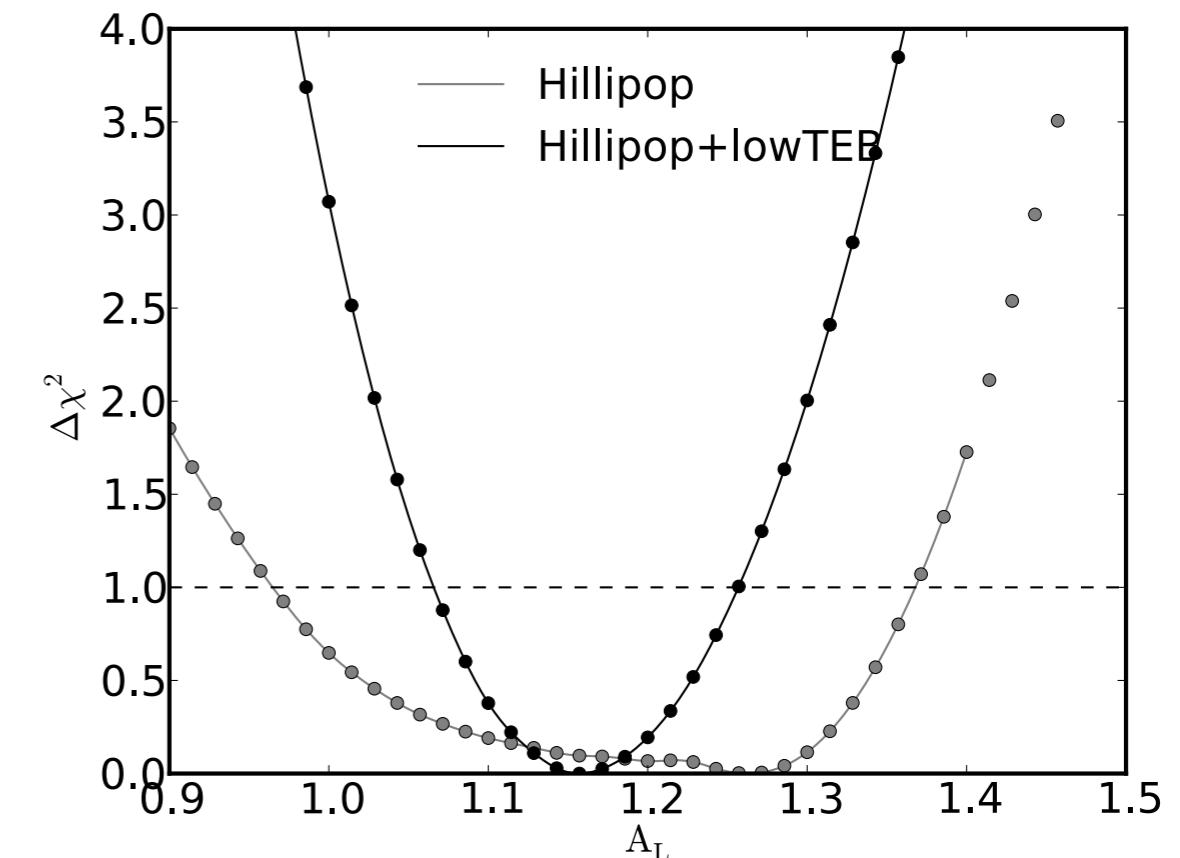
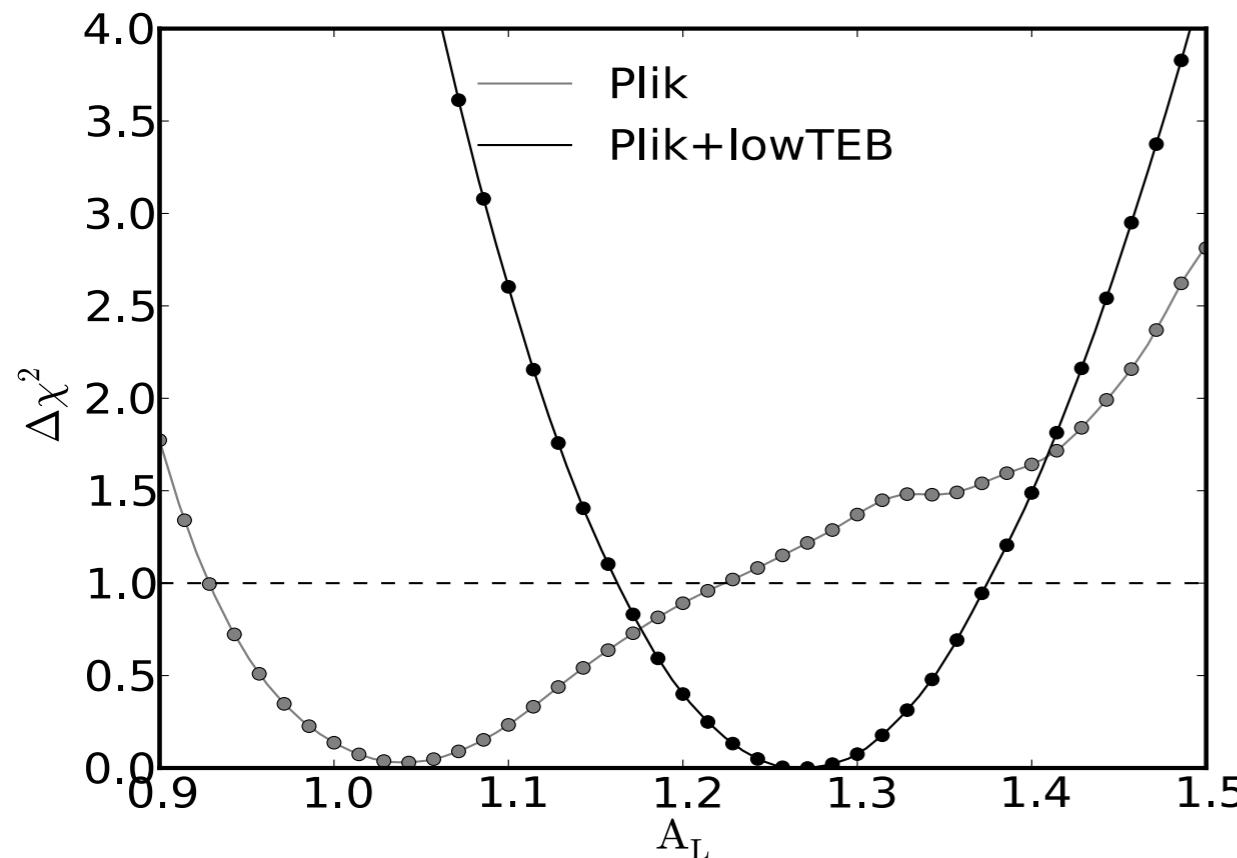
A_L profile likelihood

- lowTEB+Plik

$$A_L = 1.26^{+0.11}_{-0.10} \text{ (Plik+lowTEB)}$$

- lowTEB+Hillipop

$$A_L = 1.16^{+0.10}_{-0.09} \text{ (Hillipop + lowTEB)}$$

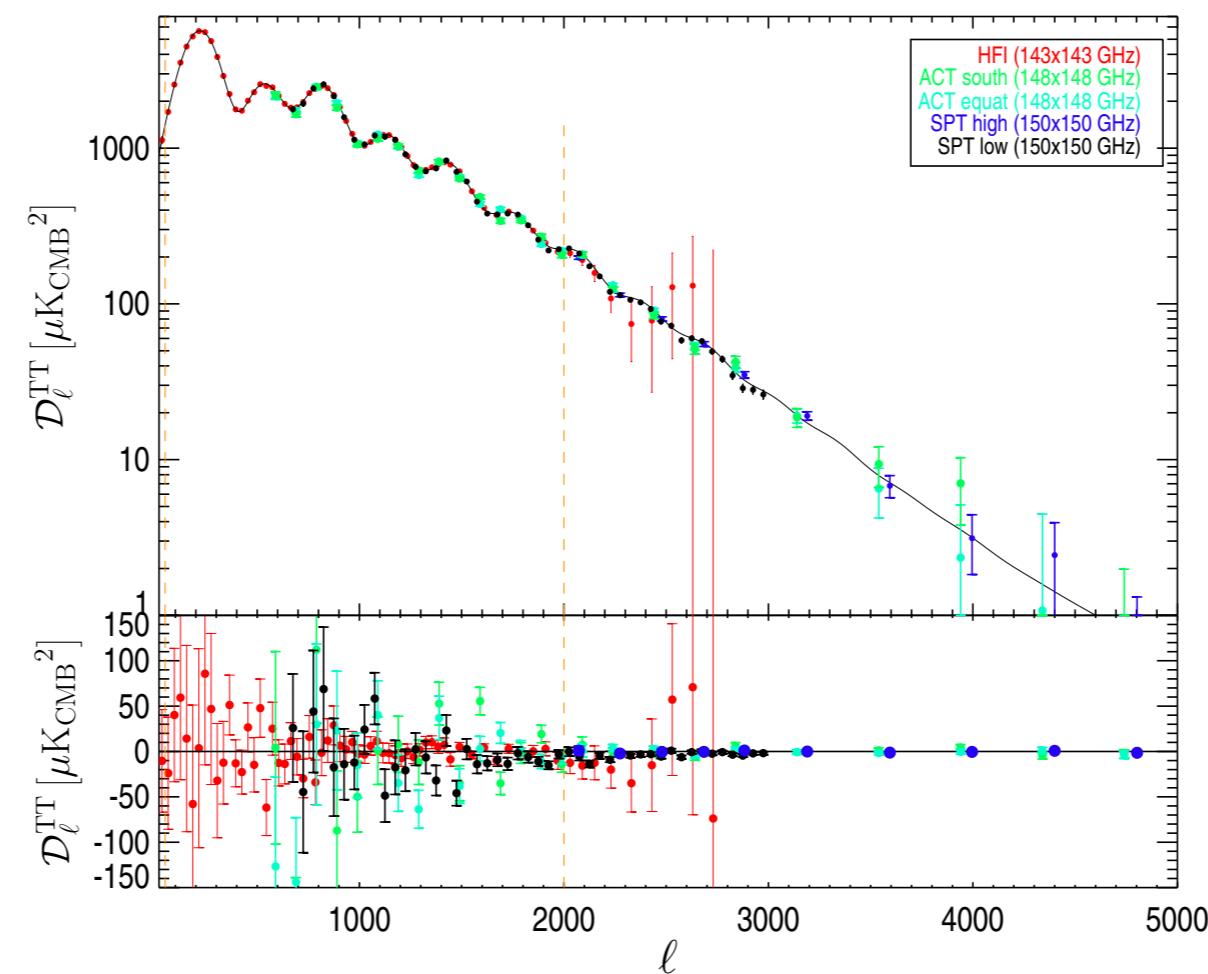


- still 1.6σ
- still correlated with foregrounds (mainly with A_{ksz})
- use VHL data to further constrain the SZ sector

The VHL likelihood

- Very-High-L data used
 - ACT [Das et al. 2014]
 - SPTHigh [Reichardt et al. 2012]
 - SPTLow [Story et al. 2012]
- We construct a VHL likelihood using the same foreground models than the ones used in Hillipop (for tSZ, CIB, kSZ and CIBxSZ)

Dataset	freq (GHz)	#spectra	#nuisances
SPT_low	150	1	2
SPT_high	95, 150, 220	6	9
ACT south/equat ...	148, 218	6	12

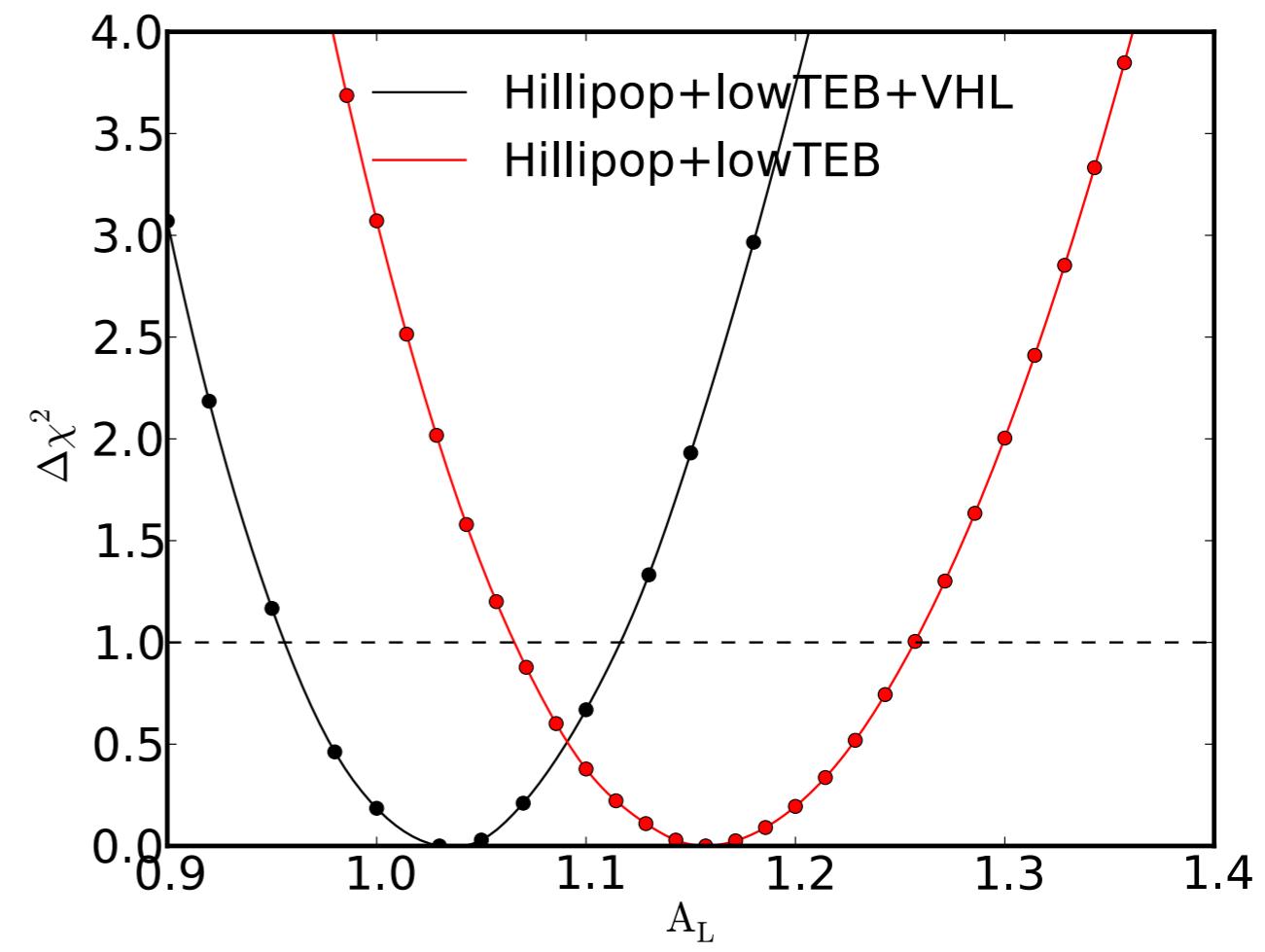


A_L from Hillipop+lowTEB+VHL

$$A_L = 1.03 \pm 0.08 \quad (\text{Hillipop+lowTEB+VHL})$$

- compatible with 1, passing successfully the A_L test
- combined-likelihood more consistent, cosmology very compatible to Planck results (but optical depth closer to low- ℓ likelihoods)

Parameter	Hillipop+lowTEB +VHL
$\Omega_b h^2$	0.02200 ± 0.00019
$\Omega_c h^2$	0.1200 ± 0.0020
$100\theta_s$	1.04200 ± 0.00040
τ	0.059 ± 0.017
n_s	0.9630 ± 0.0054
$\ln(10^{10} A_s)$. . .	3.045 ± 0.032
<hr/>	
Ω_m	0.315 ± 0.012
H_0	67.19 ± 0.88
σ_8	0.811 ± 0.013



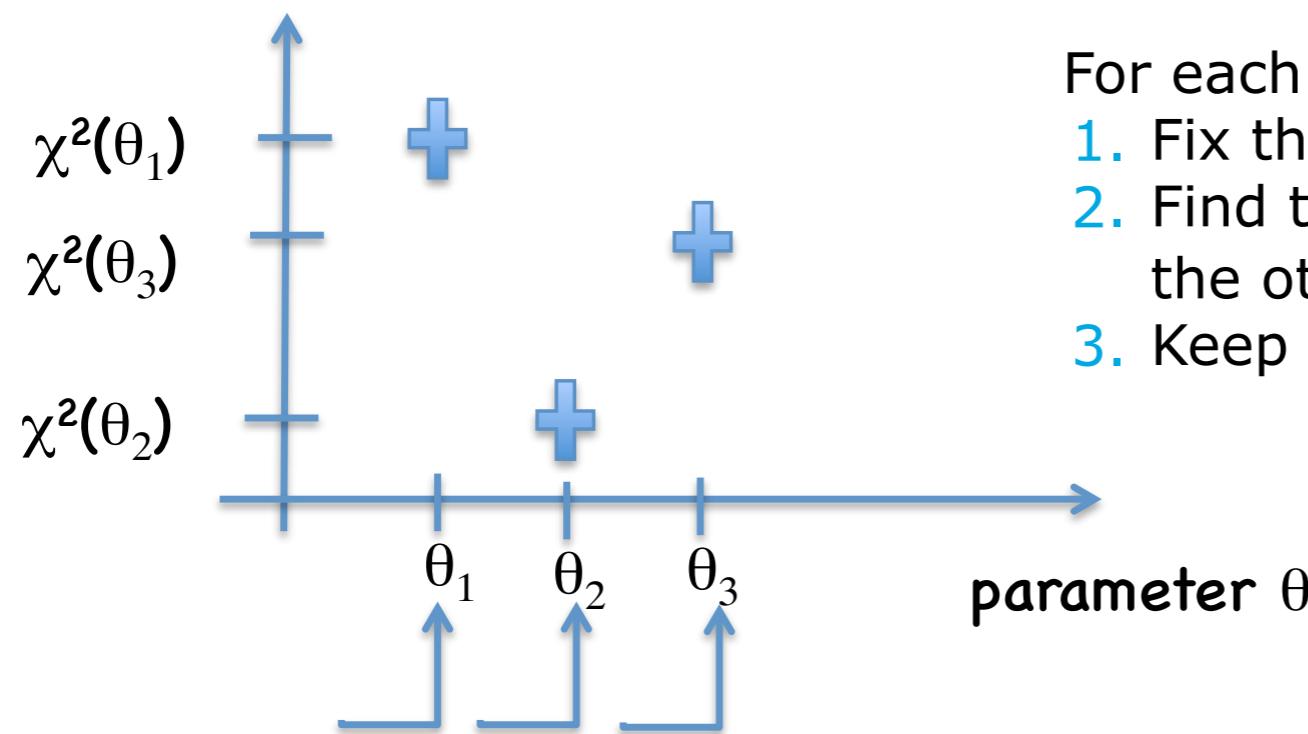
Conclusions

- We investigated the **tension** on A_L using Planck likelihoods
- This can be explained neither by **theoretical uncertainties** nor by **volume effects** in the likelihood sampling (difference between bestfit and posterior maximum)
- Comparing with the alternative Planck high- ℓ likelihood **Hillipop**, and using profile likelihoods we found on A_L :
 - 2.6σ with **(Plik+lowTEB)**
 - 1.6σ with **(Hillipop+lowTEB)**
- We showed that this tension is directly related to a tension on τ between low- ℓ and high- ℓ likelihoods (2.2σ with Plik, 1.3σ with Hillipop)
- Combining with **high resolution CMB data** helps constraining the foreground parameters and allow for a more coherent combined-likelihood ($A_L = 1.03 \pm 0.08$), with **no significant changes** on Λ CDM parameters except on optical depth.



Profile Likelihoods

$$\chi^2 = -2 \ln(\mathcal{L})$$



For each value of parameter θ :

1. Fix the value of θ : θ_i
2. Find the minimum of the χ^2 , fitting over all the other dimensions
3. Keep the corresponding value of the $\chi^2(\theta_i)$

applied in cosmology:

[Planck intermediate results. XVI, A&A 566, A54 (2014)]

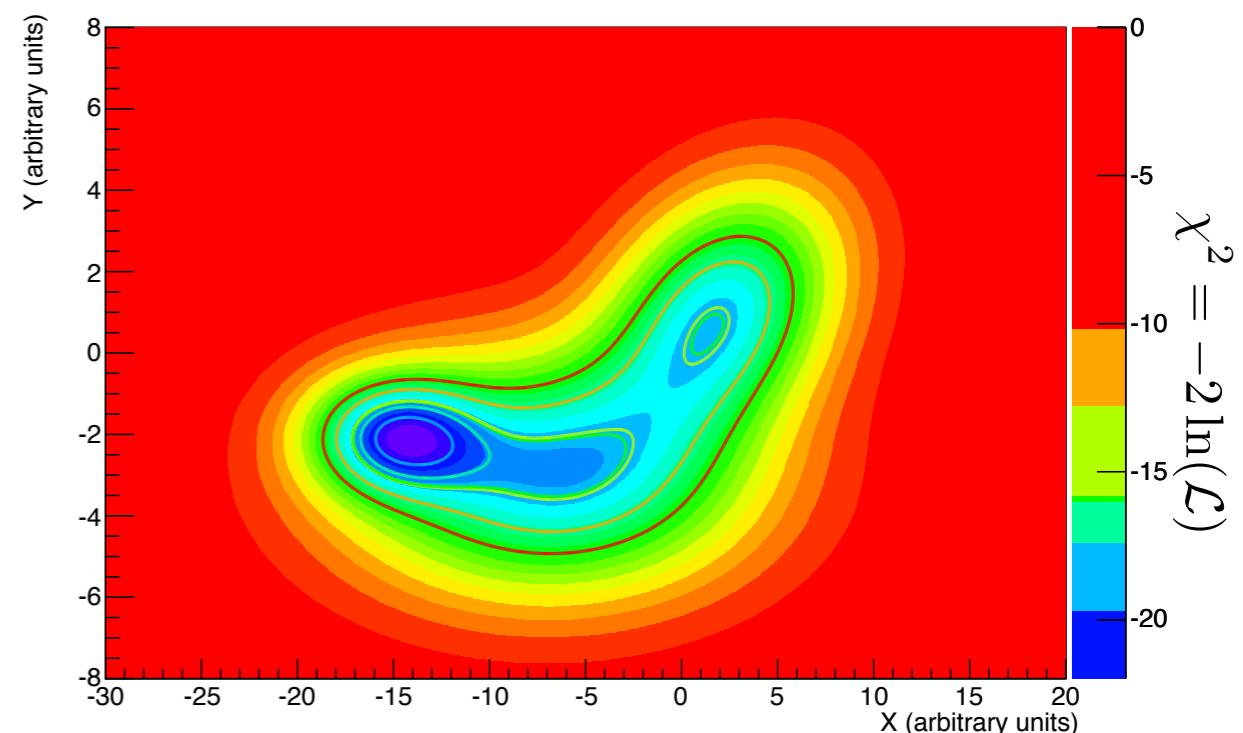
[Henrot-Versillé et al., Classical & Quantum Grav. 32 045003]

- A potential difference between both methods (beyond philosophical matters) → The so-called Volume Effects

1/ The Bayesian posterior distribution

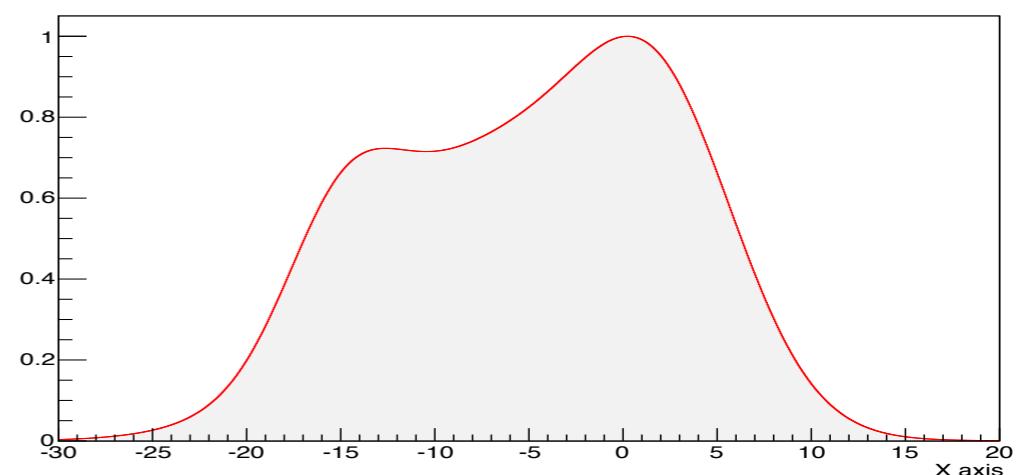
Marginal posterior:

$$P(\theta_1|D) = \int L(\theta_1, \theta_2)p(\theta_1, \theta_2)d\theta_2$$



→ The mean value of the estimated parameter does not match the one of the best fit

Hopefully not the case in Λ CDM,
beware with the extensions !



- A potential difference between both methods (beyond philosophical matters) → The so-called Volume Effects

2/ The profile likelihood

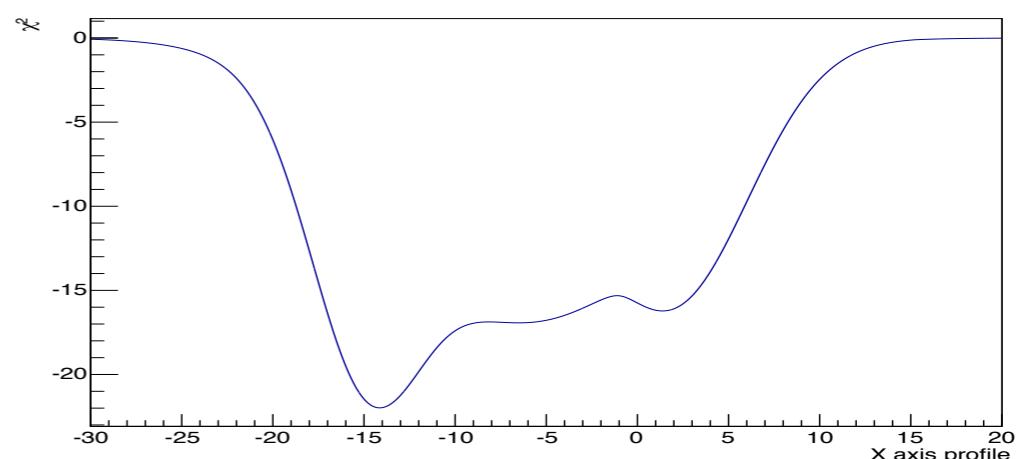
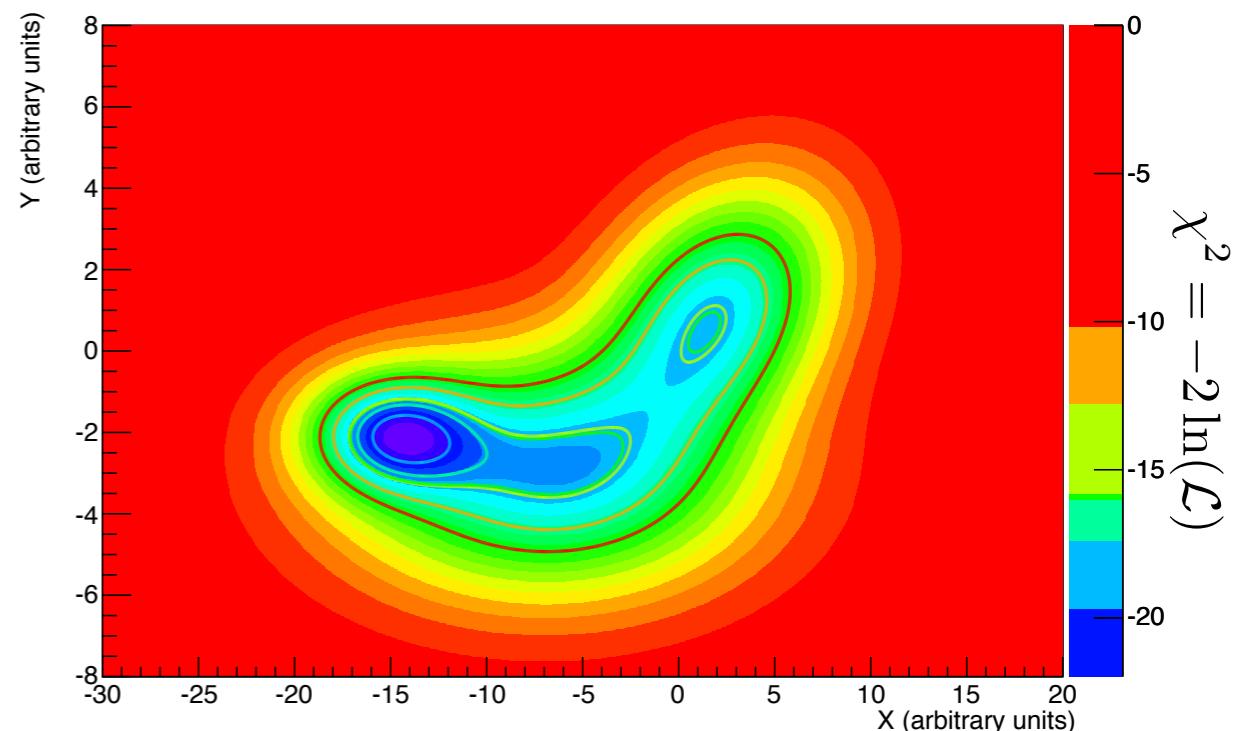
Marginal posterior:

$$P(\theta_1|D) = \int L(\theta_1, \theta_2)p(\theta_1, \theta_2)d\theta_2$$

Profile likelihood:

$$L(\theta_1) = \max_{\theta_2} L(\theta_1, \theta_2)$$

- the best fit determines the mean value of the parameter
- $(\chi^2 - \chi^2_{\min}) = 1$ gives the 1σ error



Parameter estimation

1/ The Bayesian posterior

Marginal posterior:

$$P(\theta_1|D) = \int L(\theta_1, \theta_2)p(\theta_1, \theta_2)d\theta_2$$

&

2/ The profile likelihood

Profile likelihood:

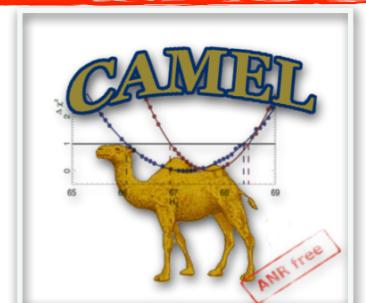
$$L(\theta_1) = \max_{\theta_2} L(\theta_1, \theta_2)$$

- Use a **common software** to compare both approaches in the same framework
- Make sure the results do depend on the physics and **not on the statistical approach** and make sure we understand the discrepancies if any



CAMEL: camel.in2p3.fr

Cosmological analysis with MCMC + Profile Likelihood
based on CLASS for the Boltzman code



CLASS [J. Lesgourges, arXiv:1104.2932]

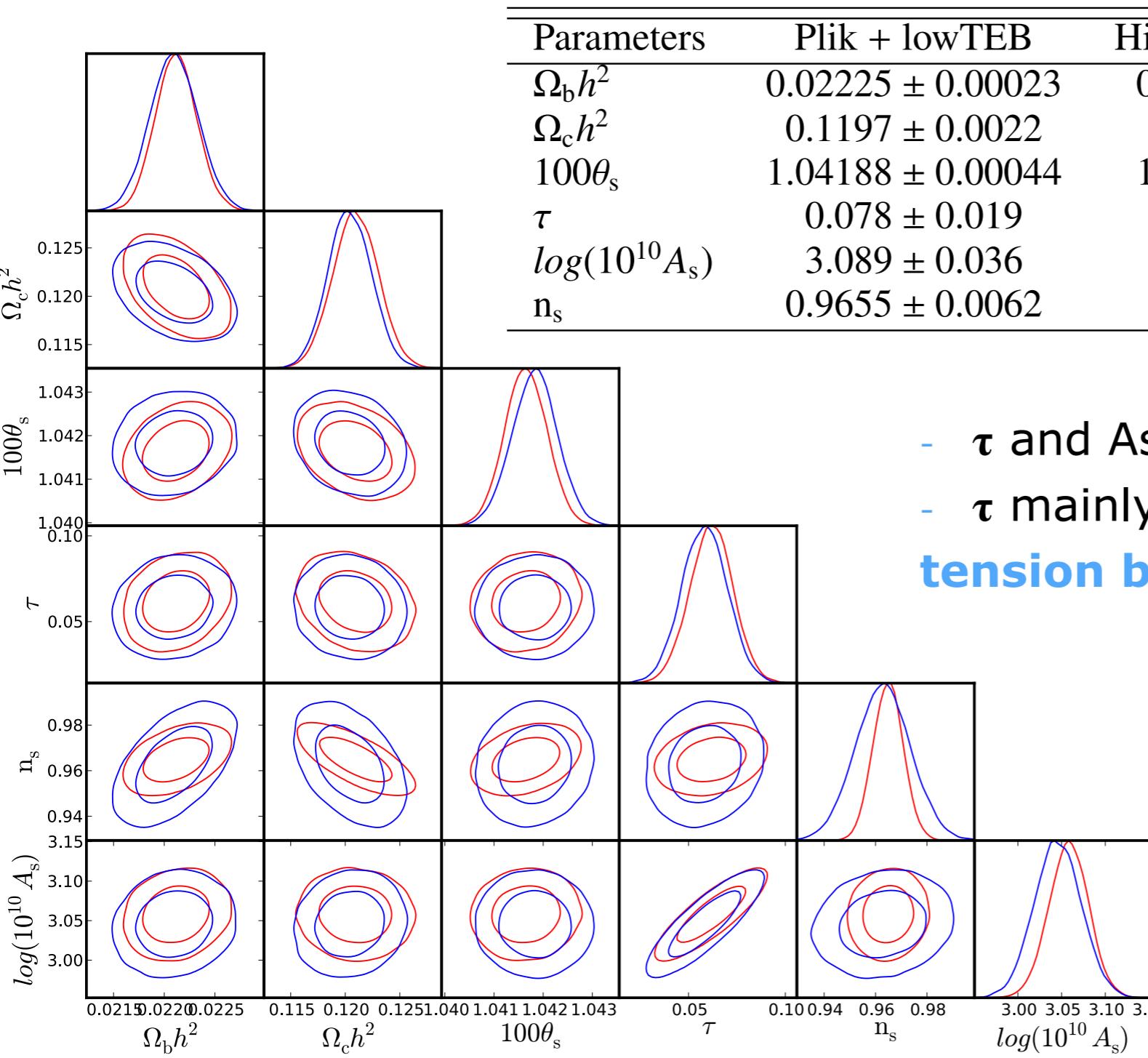
impact of foregrounds

- impact of foregrounds

Parameter	Estimate	Error		
		Full	“statistical”	“foreground”
<i>hlpT</i> parameters				
$\Omega_b h^2$	0.02212	0.00020	0.00018	0.00010 (31%)
$\Omega_c h^2$	0.12093	0.00210	0.00209	0.00020 (1%)
$100\theta_s$	1.04165	0.00043	0.00044	0.00000 (0%)
τ	0.06183	0.01131	0.01091	0.00296 (7%)
n_s	0.96486	0.00580	0.00520	0.00256 (24%)
$\log(10^{10} A_s)$	3.05798	0.02244	0.02181	0.00529 (6%)
<i>hlpX</i> parameters				
$\Omega_b h^2$	0.02210	0.00024	0.00023	0.00004 (2%)
$\Omega_c h^2$	0.12039	0.00203	0.00198	0.00044 (5%)
$100\theta_s$	1.04183	0.00046	0.00047	0.00000 (0%)
τ	0.05841	0.01182	0.01184	0.00000 (0%)
n_s	0.96312	0.01095	0.01084	0.00151 (2%)
$\log(10^{10} A_s)$	3.04603	0.02634	0.02661	0.00000 (0%)

comparison with TE

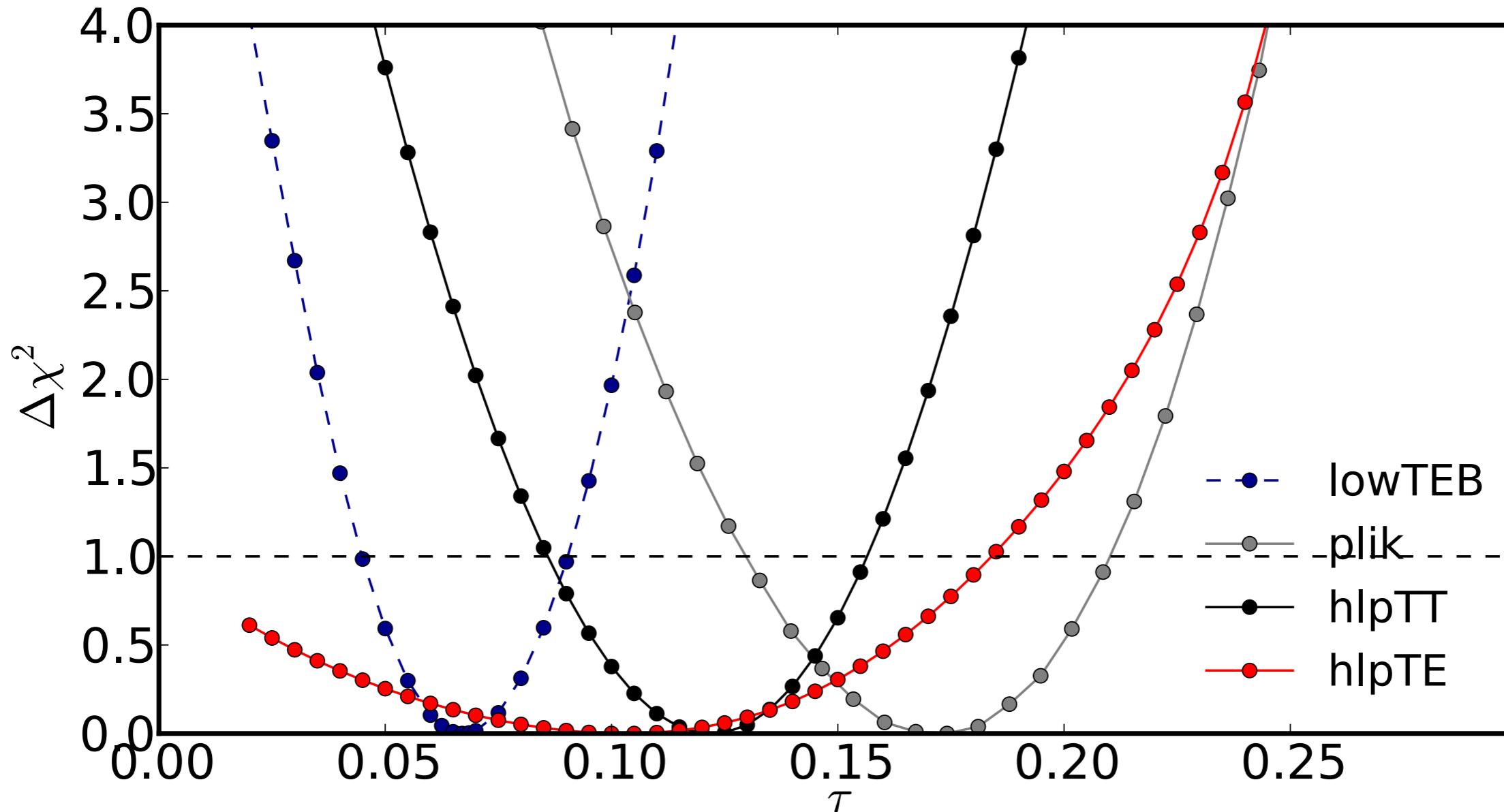
- TE spectra are much **less affected** by foregrounds (only dust matters)
- Hillipop TE results **compatible** in mean and accuracy with TT



Parameters	Plik + lowTEB	Hillipop T + lowTEB	Hillipop X + lowTEB
$\Omega_b h^2$	0.02225 ± 0.00023	0.02220 ± 0.00022	0.02223 ± 0.00024
$\Omega_c h^2$	0.1197 ± 0.0022	0.1196 ± 0.0022	0.1193 ± 0.0020
$100\theta_s$	1.04188 ± 0.00044	1.04178 ± 0.00044	1.04178 ± 0.00049
τ	0.078 ± 0.019	0.070 ± 0.018	0.066 ± 0.020
$\log(10^{10} A_s)$	3.089 ± 0.036	3.071 ± 0.035	3.057 ± 0.042
n_s	0.9655 ± 0.0062	0.9659 ± 0.0060	0.9632 ± 0.0101

- τ and A_s even lower with TE
 - τ mainly driven by the low- ℓ data
tension between low- ℓ and high- ℓ data ?

optical depth profile likelihoods



$$\tau = 0.067_{-0.021}^{+0.023} \text{ (lowTEB)} \quad \leftarrow 2.2\sigma \rightarrow \tau = 0.172_{-0.042}^{+0.038} \text{ (Plik)}$$

$$\tau = 0.067_{-0.021}^{+0.023} \text{ (lowTEB)} \quad \leftarrow 1.3\sigma \rightarrow \tau = 0.122_{-0.036}^{+0.034} \text{ (Hillipop)}$$