

Relieving tensions related to the lensing of CMB temperature power spectra (astro-ph1510.07600)

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February 8, 2016



Estimating parameters in cosmology

Parameters $\theta = (\Omega, \nu)$

- ❶ cosmo $\Omega = (\omega_b, \omega_c, \theta_s, \dots)$
- ❷ nuisances $\nu = (\text{calibs, beams, foregrounds} \dots)$

Likelihood $\mathcal{L}(\theta) = \mathcal{L}(C_\ell(\Omega), \nu)$

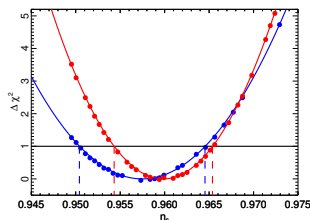
Boltzmann solver : $C_\ell(\Omega)$ `camb` (fortran) or `class` (C)

Statistics

- ❶ point estimate: max likelihood solution (or $\min \chi^2 (= -2 \ln \mathcal{L}) = \text{'best-fit'}$)
- ❷ individual parameters = 'intervals'
 - ❶ sample $\mathcal{L}$ (MCMC) + histogram (marginalize) = Bayesian
 - ❷ focus on $\mathcal{L}$ shape (profile likelihood) = Frequentist



Profile-likelihood



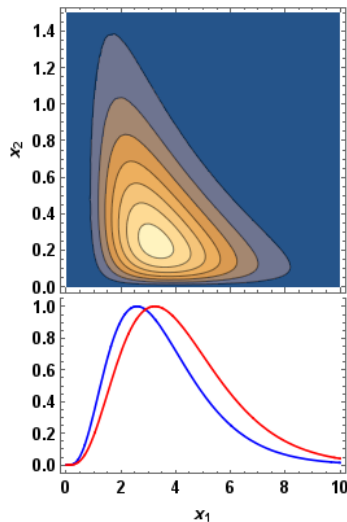
- each point: fix n_s and perform $N - 1$ minimization $\rightarrow$ report $\chi^2_{min}(n_s)$
- multi-dim min must be extremely precise (Minuit + increase Boltzmann precision)

- 1 cut: 1 $\rightarrow$ 68%CL, 3.8 $\rightarrow$ 95%CL (coverage)
- 2 OK if non-parabolic
- 3 invariant under re-parametrization
- 4 minimum coincides with global best-fit (no volume effects)

Planck Collaboration Int. XVI (2014)



Volume effects



$$p(x_1) \propto \int \mathcal{L}(x_1, x_2) dx_2$$
$$\mathcal{L}(x_1) \propto \max_{x_2} \mathcal{L}(x_1, x_2)$$



Statistics does not matter...

..when problem is **well constrained**:

Planck high+low ℓ likelihoods

Λ CDM par	<i>MCMC</i>	<i>profile</i> - $\mathcal{L}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02207 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0022
H_0	67.31 ± 0.96	67.38 ± 0.98
τ	0.078 ± 0.019	0.082 ± 0.020
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.098 ± 0.037
n_s	0.9655 ± 0.0062	0.9663 ± 0.0063

Planck Collaboration XIII (2015)

NB: different Boltzman solvers



Planck likelihoods

$$\mathcal{L}(C_\ell, \nu)$$

- 1 high- ℓ ($\ell \gtrsim 30 \rightarrow$ Gaussian) cross-spectra HFI, masks + param foregrounds : $\underbrace{\text{Plik}}_{\text{Planck papers}}$, Hillipop, CamSpec, Mspec:

Planck papers

TT, ~~pol~~, ~~TT+pol~~

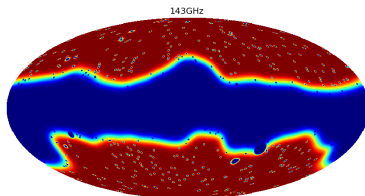
- 2 low- ℓ : auto-spectrum LFI, low resolution pixel based :
lowTEB: TT+pol (constrains τ)



The high- ℓ HiLLiPOP likelihood

- 6 maps: 2x HFI 100 GHz, 143 GHz, 217 GHz
- 15 cross-spectra: 100Ax100B, 100Ax143A etc..

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



- masking strategy to limit contamination from foregrounds
- parametric models for residuals foregrounds

The high- ℓ HiLLiPOP likelihood

C_ℓ^{XY} for $\ell > 50 \rightarrow$ Gaussian approx (central limit theorem)

$$-2\ln\mathcal{L}(\mathcal{C}_\ell^{CMB}, \nu) = \sum_{modes} \sum_{cross} (\mathcal{C}_\ell^{data} - \mathcal{C}_\ell^{model})^\dagger \Sigma^{-1} (\mathcal{C}_\ell^{data} - \mathcal{C}_\ell^{model})$$

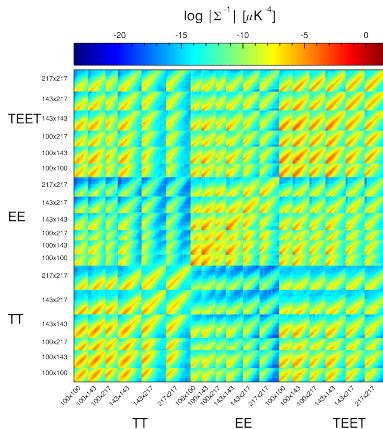
- $modes \in TT, EE, TE$
- Σ : ℓ -by- ℓ , cross-by-cross, mode-by-mode covariance matrix

- $\mathcal{C}_\ell^{model, XY} = c_x c_y \left(\mathcal{C}_\ell^{CMB}(\Omega) + \sum_{fg} A_{fg} \mathcal{C}_\ell^{fg} \right)$

- $\mathcal{C}_\ell^{fg}$ from Planck templates Planck Collaboration XXII (2015), Planck Collaboration XXX (2014)
- A_{fg} is a scaling factor
- +calibrations (c_i)

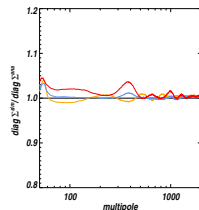
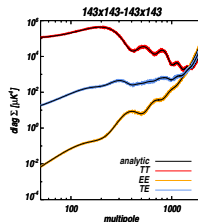


Full covariance matrix

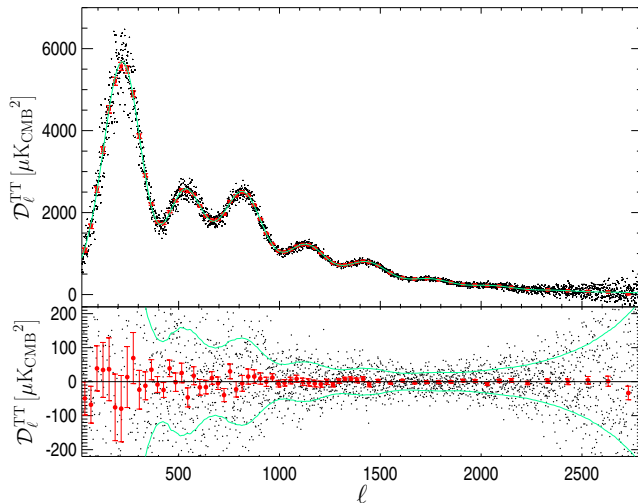


Semi-analytical calculation
(+data: no need for noise model)

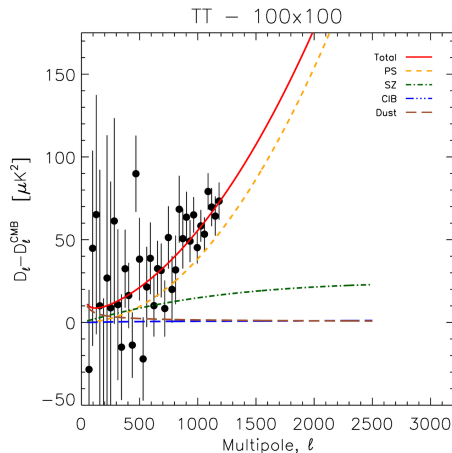
- Monte Carlo validation of approximations (15k sims)
- $\sim$ % precision
- residual effects from point source masks do not bias the results



Hillipop 2015



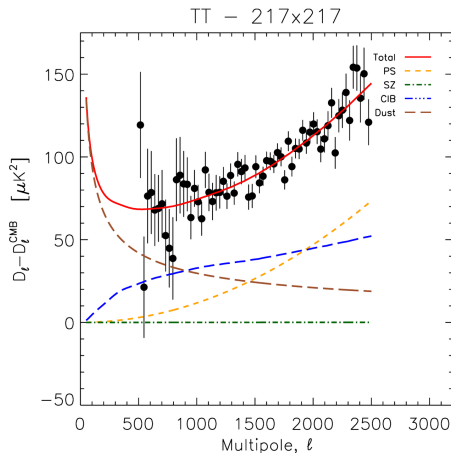
Residual foreground modeling



- galactic dust (TT, EE, TE)
- unresolved Point Sources
- background from galaxies (CIB)
- clusters (SZ)



Residual foreground modeling



- galactic dust (TT, EE, TE)
- unresolved Point Sources
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Hillipop nuisances

name	definition	prior (if any)
instrumental		
c_0	map calibration (100-hm1)	1.000 ± 0.002
c_1	map calibration (100-hm2)	1.000 ± 0.002
c_2	map calibration (143-hm1)	fixed to 1.
c_3	map calibration (143-hm2)	1.0000 ± 0.002
c_4	map calibration (217-hm1)	1.0025 ± 0.002
c_5	map calibration (217-hm2)	1.0025 ± 0.002
A	absolute calibration	1.0000 ± 0.0025
foreground modelling		
$A_{\text{PS}}^{100 \times 100}$	PS amplitude in TT (100x100 GHz)	
$A_{\text{PS}}^{100 \times 143}$	PS amplitude in TT (100x143 GHz)	
$A_{\text{PS}}^{100 \times 217}$	PS amplitude in TT (100x217 GHz)	
$A_{\text{PS}}^{143 \times 143}$	PS amplitude in TT (143x143 GHz)	
$A_{\text{PS}}^{143 \times 217}$	PS amplitude in TT (143x217 GHz)	
$A_{\text{PS}}^{217 \times 217}$	PS amplitude in TT (217x217 GHz)	
A_{SZ}	scaling for the tSZ template (TT)	
A_{CIB}	scaling for the CIB template (TT)	1.00 ± 0.20
A_{kSZ}	scaling for the kSZ template (TT)	
A_{SZxCIB}	scaling parameter for the cross correlation between kSZ and CIB	
$A_{\text{dust}}^{\text{TT}}$	scaling parameter for the dust in TT	1.00 ± 0.20
$A_{\text{dust}}^{\text{EE}}$	scaling parameter for the dust in EE	1.00 ± 0.20
$A_{\text{dust}}^{\text{TE}}$	scaling parameter for the dust in TE	1.00 ± 0.20



Differences with Plik

- all cross-spectra used
- more calibration coefficients (map level)
- cleaned point-sources mask $\rightarrow$ galactic dust parametrized as in Planck Collaboration Int. XXX (2014)
- Planck foreground templates (SZ, CIB...)
- all ℓ values (no binning)
- ...



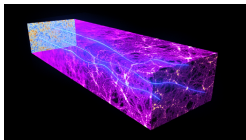
Any difference on Λ CDM parameters?

Λ CDM par	Planck + lowTEB	<i>Hillipop</i> + lowTEB
$\Omega_b h^2$	0.02222 ± 0.00023	0.02221 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022	0.1192 ± 0.0022
H_0	67.31 ± 0.96	67.51 ± 0.97
τ	0.078 ± 0.019	0.072 ± 0.020
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.068 ± 0.038
n_s	0.9655 ± 0.0062	0.9645 ± 0.0071
σ_8	0.829 ± 0.014	0.816 ± 0.015

(MCMC)

- lowTEB in common
- $\tau, \ln(10^{10} A_s)$ correlated through $C_\ell \propto A_s e^{-2\tau}$





CMB lensing

We do not measure C_ℓ but $\tilde{C}_\ell$

CMB light deflected by matter structures : tiny ($\sigma \simeq 3'$)-
parametrized by lensing potential with spectrum Lewis and
Challinor (2006):

$$C_\ell^\Phi = 16\pi \int \frac{dk}{k} P_{\mathcal{R}}(k) \left[\int_0^{\chi_*} d\chi T(k, \eta_0 - \chi) \left(\frac{\chi - \chi_*}{\chi \chi_*} \right) \right]^2$$

$$P_{\mathcal{R}}(k) = A_s (k/k_0)^{n_s} \rightarrow C_\ell^\Phi \propto A_s$$

mostly in linear regime : $C_\ell^\Phi \propto \sigma_8^2$ Planck Collaboration XV (2015)



A_L

Boltzmann code:

- ① $\Omega \rightarrow (C_\ell, C_\ell^\Phi) \rightarrow \tilde{C}_\ell \rightarrow \mathcal{L}$
- ② $(\Omega, A_L) \rightarrow (C_\ell, A_L C_\ell^\Phi) \rightarrow \tilde{C}_\ell \rightarrow \mathcal{L}$

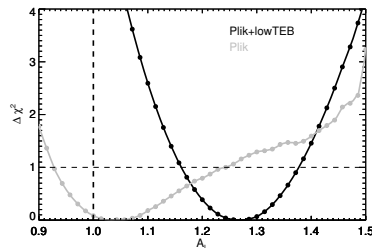
Interest:

- ① **TEST1**: A_L should be compatible with 1 (otherwise: data problem or modify GR)
- ② marginalize (or left free in fits): neglect lensing effect (to 1st order) in estimations

$$C_\ell^\Phi \propto A_s A_L$$



Plik results : A_L (TEST1)



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

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

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

Planck Collaboration XIII (2015)



Can we measure τ only with high- ℓ ?

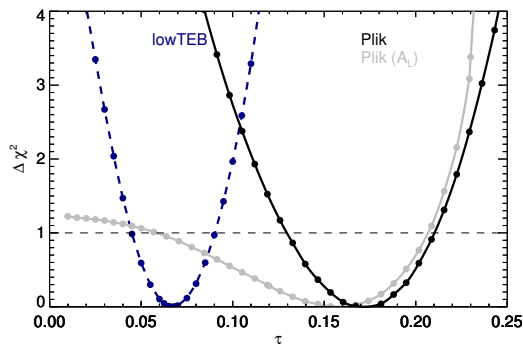
high- ℓ only:

- $C_\ell = A_s e^{-2\tau} \rightarrow (\tau, \ln(10^{10} A_s))$ degenerate
- but $\tilde{C}_\ell(C_\ell^\Phi \propto A_s)$ breaks it!
- $\implies$ one can get a measurement of τ with only a high- ℓ likelihood.

TEST2: compare high- ℓ only likelihood results to low- ℓ .



Plik results : τ (TEST2)

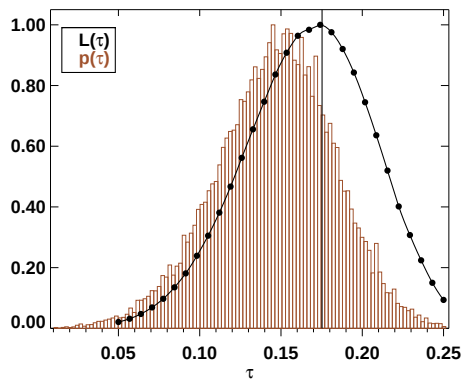


$$\tau = 0.067^{+0.023}_{-0.021} \quad (\text{lowTEB}) \quad \text{v.s.} \quad \tau = 0.172^{+0.038}_{-0.042} \quad (\text{Plik})$$

2.2 σ mismatch



A statistics issue?



$$\tau = 0.067^{+0.023}_{-0.021} \quad (\text{lowTEB}) \quad \text{v.s.} \quad \tau = 0.149^{+0.034}_{-0.036} \quad (\text{Plik})$$

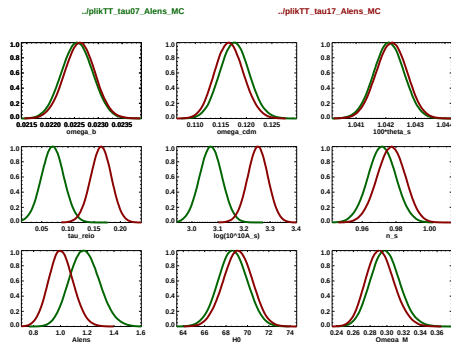
$$\simeq 1.9\sigma$$



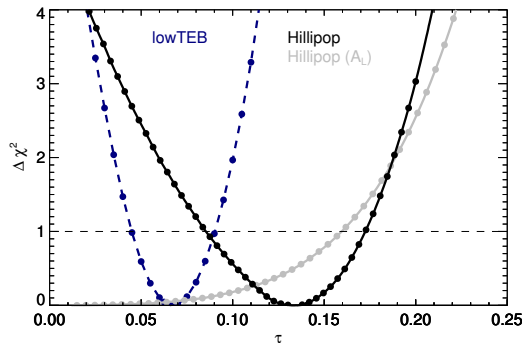
The $[\tau, A_s, A_L]$ correlation

TEST1 (A_L) performed on high- ℓ +low- ℓ . For fixed data:

- 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 ($C_\ell^\Phi \propto A_s A_L$) :
 $A_L \nearrow$



Hillipop results : τ (TEST2)

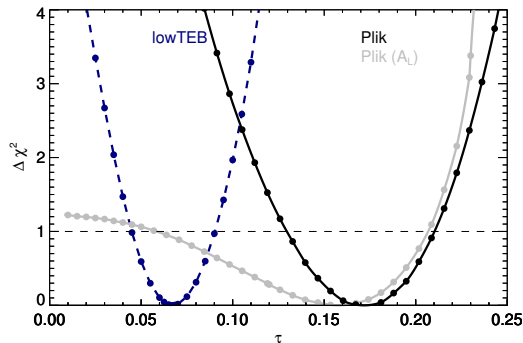


$$\tau = 0.067^{+0.023}_{-0.021} \quad (\text{lowTEB}) \quad \tau = 0.134^{+0.038}_{-0.048} \quad (\text{Hillipop})$$

1.3σ



Plik results : τ (TEST2)

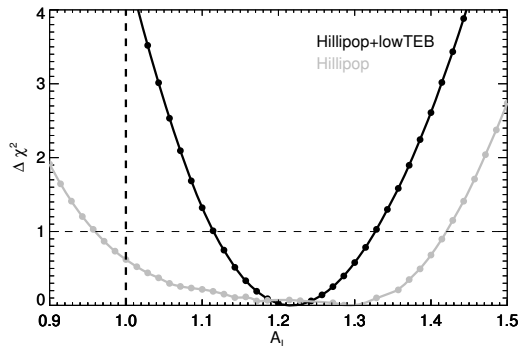


$$\tau = 0.067^{+0.023}_{-0.021} \quad (\text{lowTEB}) \quad \tau = 0.172^{+0.038}_{-0.042} \quad (\text{Plik})$$

2.2σ

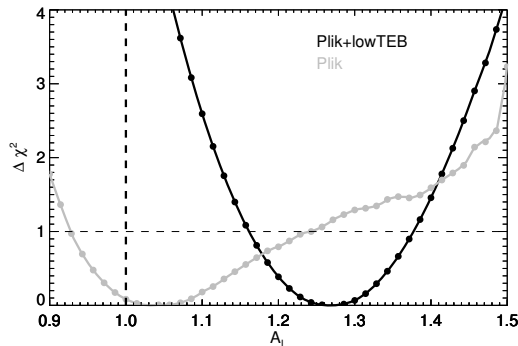


Hillipop results : A_L (TEST1)



$$A_L = 1.22^{+0.11}_{-0.10} \quad (\text{Hillipop+lowTEB})$$

Plik results : A_L (TEST1)



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

More CMB data: very-high- ℓ (VHL)

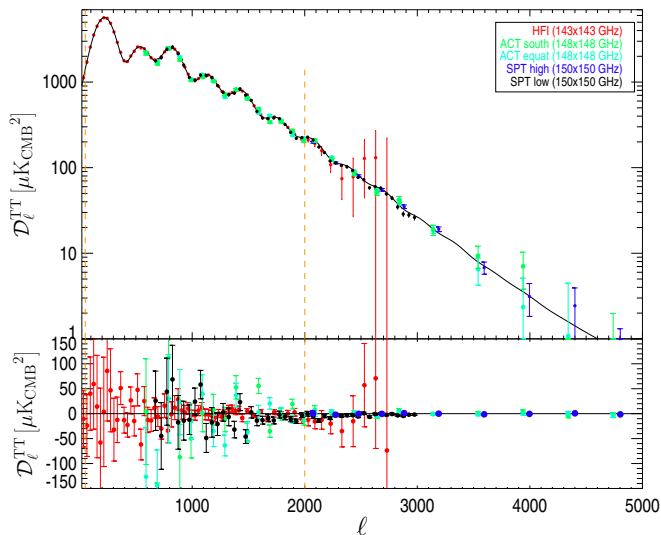
ACT+SPT/ essentially constrain foregrounds

Dataset		ℓ range	freq (GHz)	#spectra	#nuisances	ref
ACT	south/equat	[1500,10000]	148, 218	6	12	Das et al. (2014)
	SPT_high	[2000,13000]	95, 150, 220	6	9	Reichardt et al. (2012)
	SPT_low	[650,3000]	150	1	2	Story et al. (2012)

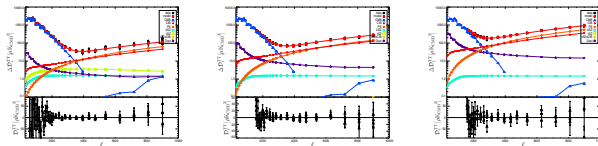
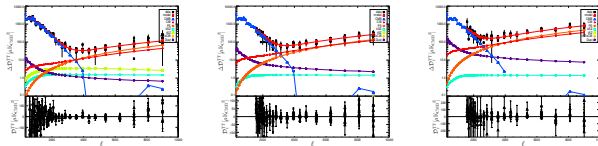
- each provides window functions + cov matrix
- for SPT_high: prefer Reichardt et al. (2012) over George et al. (2014) since the latter include calibrations based on *Planck* 2013 results: both give similar results.



Consistency with *Planck* @150GHz

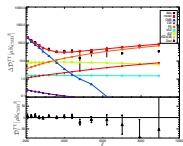
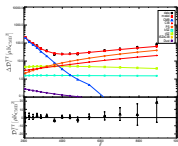
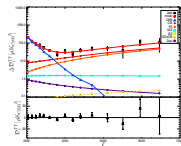
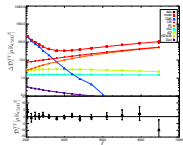
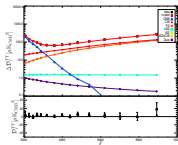
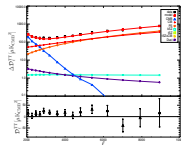


ACT

(a) ACT_equat 148×148 (b) ACT_equat 148×218 (c) ACT_equat 218×218 (d) ACT_south 148×148 (e) ACT_south 148×218 (f) ACT_south 218×218

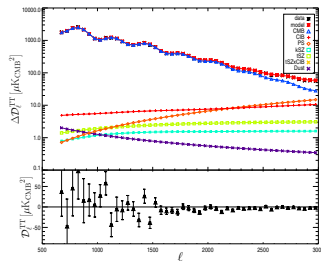
$$\chi^2/ndof = 651/710$$

SPT_high

(g) SPT_high 95×95 (h) SPT_high 95×150 (i) SPT_high 95×220 (j) SPT_high 150×150 (k) SPT_high 150×220 (l) SPT_high 220×220

$$\chi^2/ndof = 77/90$$

SPT_low



(m) SPT_low 150 × 150 GHz

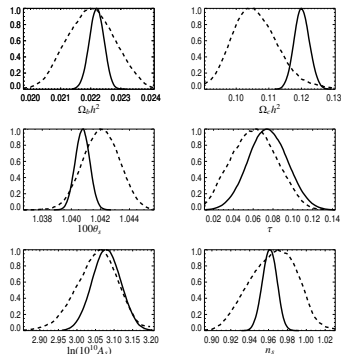
$$\chi^2/ndof = 58/47$$

More consistency tests

build a $\mathcal{L}^{VHL}$ (Gaussian with cov matrix+window functions from expts)

Is VHL cosmology consistent with *Planck*?

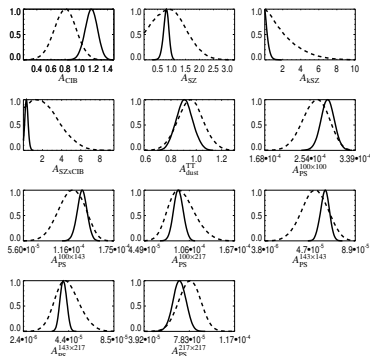
sample *independently* $\mathcal{L}^{Hillipop}$ (full) and $\mathcal{L}^{VHL}$ (dashed)



Combined likelihood

put A_{SZ} , A_{CIB} , A_{kSZ} , $A_{SZ \times CIB}$ in common in $\mathcal{L}^{Hillipop}$ and $\mathcal{L}^{VHL}$

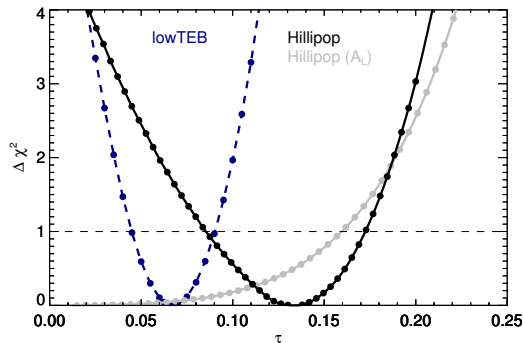
Hillipop w/o VHL (full/dashed):



A_{CIB} , A_{kSZ} , $A_{SZ \times CIB}$, A_{dust}^{TT} are scalings $\rightarrow 1$



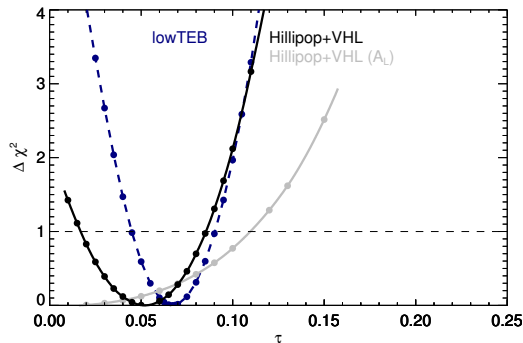
τ Hillipop



$$\tau = 0.067^{+0.023}_{-0.021} \quad (\text{lowTEB}) \quad \tau = 0.134^{+0.038}_{-0.048} \quad (\text{Hillipop})$$

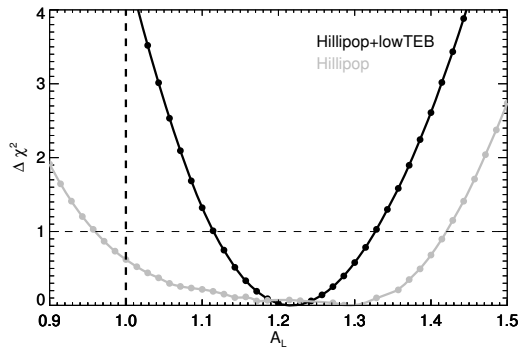


τ Hillipop+VHL

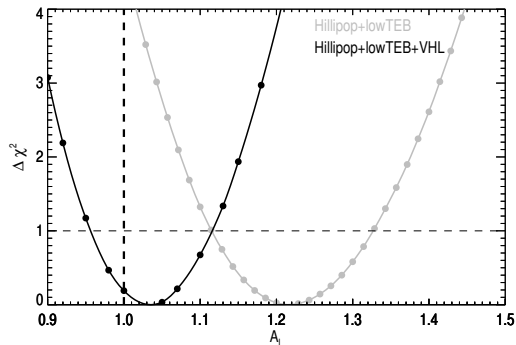


$$\tau = 0.067^{+0.023}_{-0.021} \quad (\text{lowTEB}) \quad 0.052 \pm 0.035 \quad (\text{Hillipop+VHL})$$



A_L Hillipop

$$A_L = 1.22^{+0.11}_{-0.10} \quad (\text{Hillipop+lowTEB})$$

A_L Hillipop+VHL

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

Various VHLs

Hillipop+lowTEB+...	A_L
-	1.22 ± 0.11
SPT_low	1.16 ± 0.10
SPT_high	1.12 ± 0.10
ACT	1.19 ± 0.10
SPT_low+SPT_high	1.02 ± 0.08
SPT_low+ACT	1.09 ± 0.09
SPT_high+ACT	1.12 ± 0.09
SPT_low+SPT_high+ACT	1.03 ± 0.08
SPT_low+SPT_high2014 +ACT	1.04 ± 0.08

many combinations OK



More checks on SPT_high

to improve on SPT_high 220×220 increase dust level

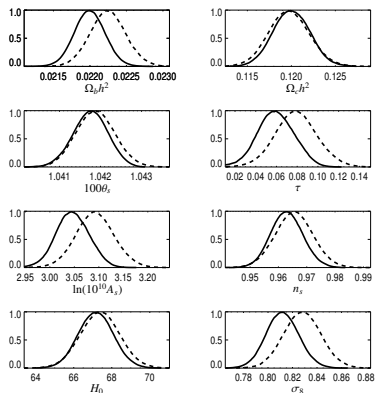
$$\begin{aligned} A_L &= 1.12 \pm 0.10 \text{ (Hillipop+lowTEB+SPT_high)} \\ &= 1.13 \pm 0.10 \text{ (Hillipop+lowTEB+SPT_high, } A_{\text{dust}}^{\text{SPT}} \times 3) \end{aligned}$$

$$\begin{aligned} A_L &= 1.03 \pm 0.08 \text{ (Hillipop+lowTEB+VHL)} \\ &= 1.04 \pm 0.08 \text{ (Hillipop+lowTEB+VHL, } A_{\text{dust}}^{\text{SPT}} \times 3) \end{aligned}$$



Λ CDM revisited

all now OK $\rightarrow$ fix $A_L = 1$



Hillipop+lowTEB+VHL : full Planck+lowTEB+cor(SZ): dashed



Λ CDM parameters revisited (Hillipop)

Parameter	<i>Hillipop</i> + lowTEB	<i>Hillipop</i> + lowTEB +VHL	<i>Hillipop</i> + lowTEB +VHL + BAO + SN
$\Omega_b h^2$	0.02221 ± 0.00023	0.02200 ± 0.00019	0.02207 ± 0.00018
$\Omega_c h^2$	0.1192 ± 0.0022	0.1200 ± 0.0020	0.1187 ± 0.0012
$100\theta_s$	1.04175 ± 0.00044	1.04200 ± 0.00040	1.04188 ± 0.00036
τ	0.072 ± 0.020	0.059 ± 0.017	0.063 ± 0.017
n_s	0.9645 ± 0.0071	0.9630 ± 0.0054	0.9663 ± 0.0040
$\ln(10^{10} A_s)$	3.068 ± 0.038	3.045 ± 0.032	3.050 ± 0.032
Ω_m	0.311 ± 0.013	0.315 ± 0.012	0.308 ± 0.007
H_0	67.51 ± 0.97	67.19 ± 0.88	67.72 ± 0.53
σ_8	0.816 ± 0.015	0.811 ± 0.013	0.810 ± 0.013

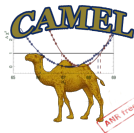
- stable
- reionization depth is low
- $\sigma_8 \simeq 0.81$ less in tension with local measurements (WL, SZ cluster counts..)



Conclusions

- to **first order** *Planck* data are **OK** (for Λ CDM)
- but measuring τ , A_s is **subtle** (even **worse** for $\sum m_\nu, N_{\text{eff}}$!)
- precise measurements requires careful knowledge of **astrophysical foregrounds**
- constructing a (CMB) likelihood is **complicated**
- and CMB is a **clean probe**!
- cosmology is now dominated by **systematics**





Cosmological Analysis with Minuit

Exploration of the Likelihood

- clean C++ project
- Boltzmann = `class` (J.Lesgourgues et al), pure C.
- Likelihoods: all recent measurements implemented (CMB, JLA, BAO2D)
- stat:
 - minimization (bestfit): Minuit
 - adaptive MCMC
 - profile likelihoods

debugged and heavily used (at ccin2p3) for papers.

1st version released: [http:](http://planck.lal.in2p3.fr/wiki/pmwiki.php/Softs/Camel)

[//planck.lal.in2p3.fr/wiki/pmwiki.php/Softs/Camel](http://planck.lal.in2p3.fr/wiki/pmwiki.php/Softs/Camel)



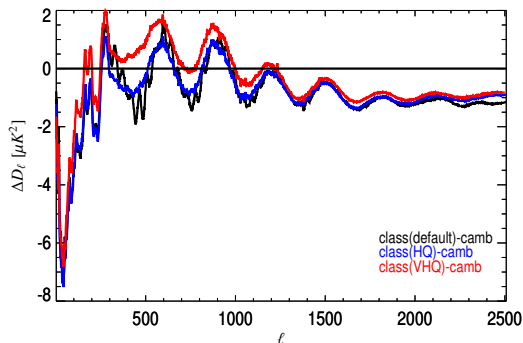
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class v.s camb

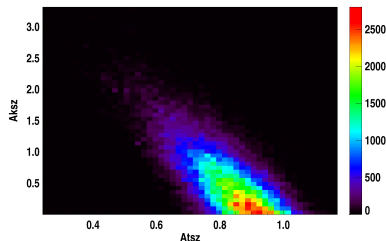
Planck uses `camb` we use `class`. compare both on same cosmo:



- below %
- not that satisfactory but sufficient for our studies (see next)



t/k SZ correlation



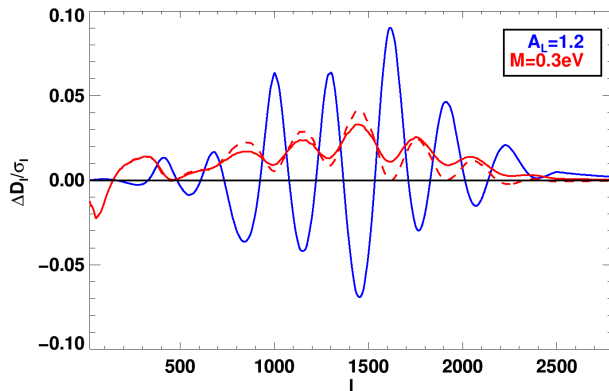
Planck states $VHL \simeq \text{cor}(A_{\text{SZ}})$.

Not for Hillipop:

$$\rightarrow A_L = 1.26^{+0.12}_{-0.10} \quad (\text{Hillipop} + \text{lowTEB} + \text{SZ-cor})$$

Improvement comes from the whole cov. matrix



A_L vs. $\sum m_\nu$ effect on TT spectra

Plik+VHL?

Plik:

$$\tau = 0.17 \pm 0.03 \quad (\text{Plik})$$

$$A_L = 1.26 \pm 0.10 \quad (\text{Plik+lowTEB})$$

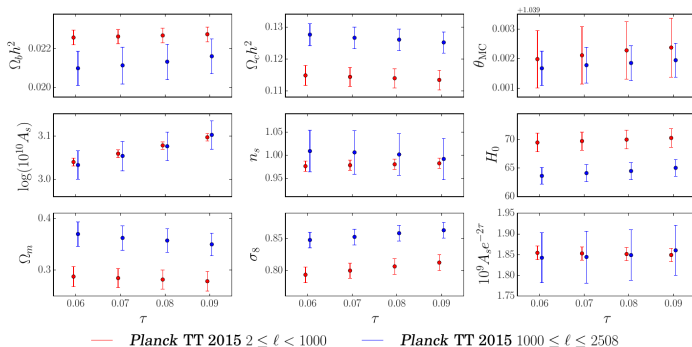
Adding VHL (but keep Plik templates since hard-coded)

$$\tau = 0.08 \pm 0.02 \quad (\text{Plik+VHL})$$

$$A_L = 1.14 \pm 0.08 \quad (\text{Plik+lowTEB+VHL})$$



Addison et al. (2015)



- use Plik+lowTEB and cut at 1000: above 1000 only Plik.
- use same $\tau = 0.07 \pm 0.02$ prior, but we saw Plik only consistent with $\simeq 0.17...$

