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

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

Laboratoire de l'Accélérateur Linéaire

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Estimating parameters in cosmology

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

1. cosmo $\Omega = (\omega_{\mathrm{b}}, \omega_{\mathrm{c}}, \theta_s, ...)$
2. nuisances ν =(calibs, beams,foregrounds...)

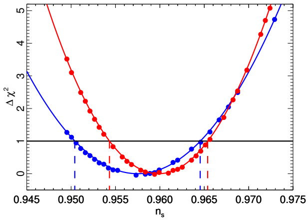
Likelihood $\mathscr{L}(\theta) = \mathscr{L}(C_\ell(\Omega), \nu)$

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

Statistics

1. point estimate: max likelihood solution (or minχ^2(= $-2\ln\mathscr{L}$)='best-fit'
2. individual parameters='intervals'
    1. sample $\mathscr{L}$(MCMC)+ histogram (marginalize)=Bayesian
    2. focus on $\mathscr{L}$ shape (profile likelihood)=Frequentist

Profile-likelihood

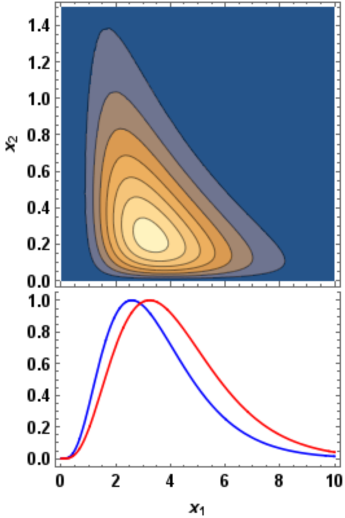


- each point can be computed independently (//) but heavy for all variables
- multi-dim min must be extremely precise (`Minuit` + increase Boltzmann precision)

Planck Collaboration Int. XVI (2014)

1. minimum always coincides with global best-fit
2. interval has coverage properties
3. invariant on change of variables: $f(\theta) \to \hat{f} = f(\hat{\theta})$
4. OK for non-linear cases
5. no priors, no volume effects

Volume effects



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

$\mathscr{L}(x_1) \propto \max_{x_2} \mathscr{L}(x_1, x_2)$

Statistics does not matter...

..when problem is well constrained:

Planck high+low ℓ likelihoods

ΛCDM par	$MCMC$	$profile - \mathscr{L}$
$\Omega_b h^2$	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

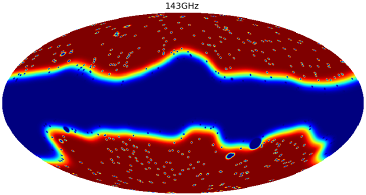
$$\mathscr{L}(C_\ell, \nu)$$

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

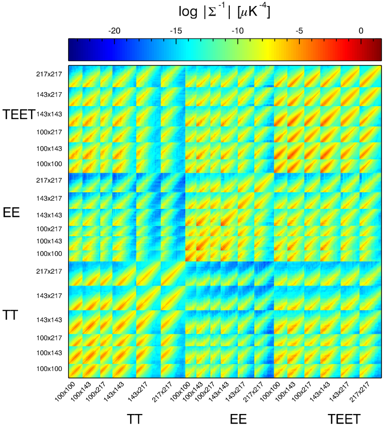
The high-ℓ HiLLiPOP likelihood

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

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

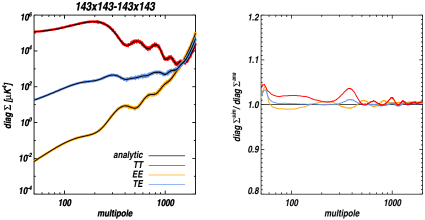
- $modes \in TT, EE, TE$
- Σ: ℓ-by-ℓ, cross-by-cross, mode-by-mode covariance matrix
- $\mathcal{C}_\ell^{model,XY} = c_x c_y \left(\mathcal{C}_\ell^{CMB}(\boldsymbol{\Omega}) + \sum_{\text{fg}} A_{\text{fg}} \mathcal{C}_\ell^{\text{fg}}\right)$
  - $\mathcal{C}_\ell^{\text{fg}}$ from Planck templates Planck Collaboration XXII (2015),Planck Collaboration XXX (2014)
    A_{fg} is a scaling factor
  - +calibrations (c_i)

Full covariance matrix

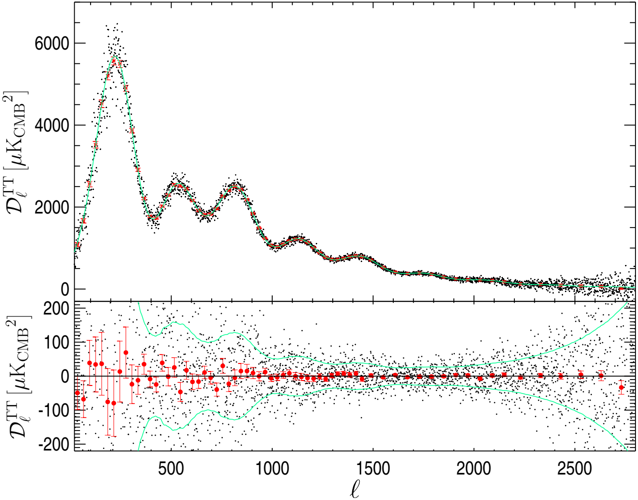


Semi-analytical calculation
(+data: no need for noise model)

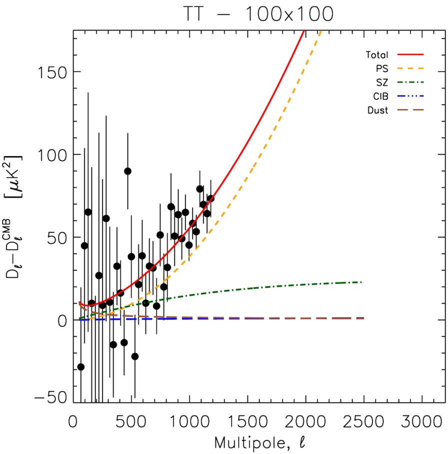
- Monte Carlo validation of approximations (15k sims)
- $\sim$ % precision
- residual effects from point source masks do not bias the results



Hillipop 2015

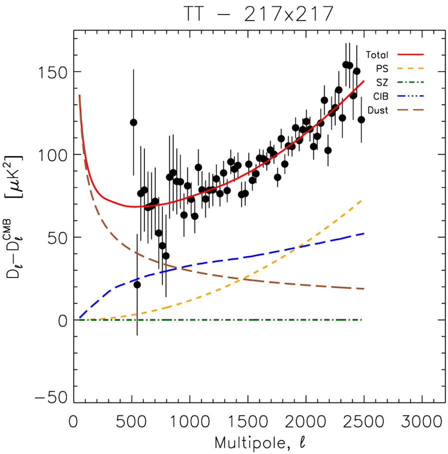


Residual foreground modeling



- 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
- background from galaxies (CIB)
- clusters (SZ)

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	
$A_{\mathrm{PS}}^{100\times100}$	PS amplitude in TT (100x100 GHz)	
$A_{\mathrm{PS}}^{100\times143}$	PS amplitude in TT (100x143 GHz)	
$A_{\mathrm{PS}}^{100\times217}$	PS amplitude in TT (100x217 GHz)	
$A_{\mathrm{PS}}^{143\times143}$	PS amplitude in TT (143x143 GHz)	
$A_{\mathrm{PS}}^{143\times217}$	PS amplitude in TT (143x217 GHz)	
$A_{\mathrm{PS}}^{217\times217}$	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	
$A_{\mathrm{dust}}^{\mathrm{TT}}$	scaling parameter for the dust in TT	1.00 ± 0.20
$A_{\mathrm{dust}}^{\mathrm{EE}}$	scaling parameter for the dust in EE	1.00 ± 0.20
$A_{\mathrm{dust}}^{\mathrm{TE}}$	scaling parameter for the dust in TE	1.00 ± 0.20

Differences with `Plik`

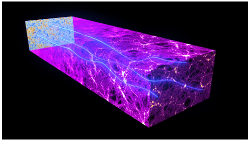
- all cross-spectra used
- more calibration coefficients (map level)
- cleaned point-sources mask →galactic dust parametrized as in Planck Collaboration Int. XXX (2014)
- Planck foreground templates (SZ, CIB...)
- all ℓ values (no binning)
- ...

Any difference on ΛCDM parameters?

ΛCDM par	`Plik` + lowTEB	*Hillipop* + 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):

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

$P_{\mathcal{R}}(k) = A_\mathrm{s}(k/k_0)^{n_\mathrm{s}} \rightarrow \boxed{C_\ell^\Phi \propto A_\mathrm{s}}$

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

A_L

Boltzmann code:

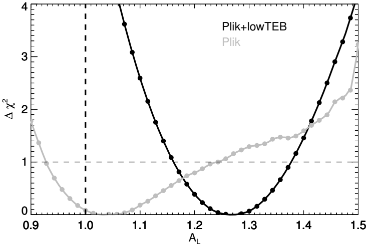
1. $\Omega \to (C_\ell, C_\ell^\Phi) \to \tilde{C}_\ell \to \mathscr{L}$
2. $(\Omega, A_\mathrm{L}) \to (C_\ell, A_\mathrm{L} C_\ell^\Phi) \to \tilde{C}_\ell \to \mathscr{L}$

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

$$\boxed{C_\ell^\Phi \propto A_\mathrm{s} A_\mathrm{L}}$$

Plik results : A_L (TEST1)



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

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

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

Planck Collaboration XIII (2015)

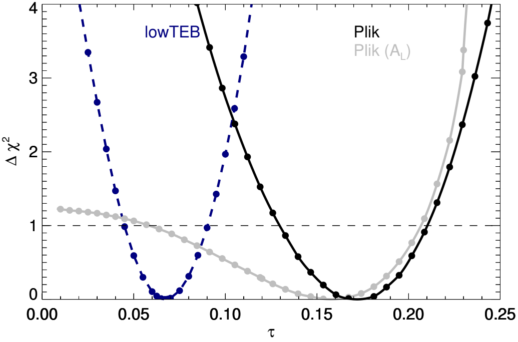
Can we measure τ only with high-ℓ?

high-ℓ only:

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

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

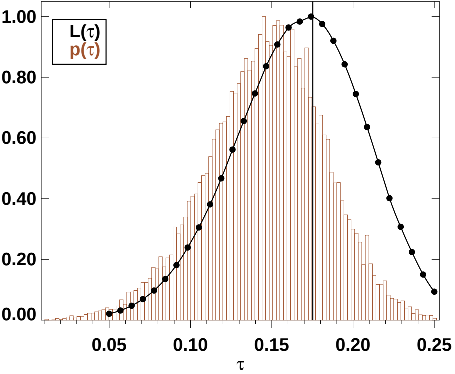
Plik results : τ (TEST2)



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

2.2σ mismatch

A methodology issue?



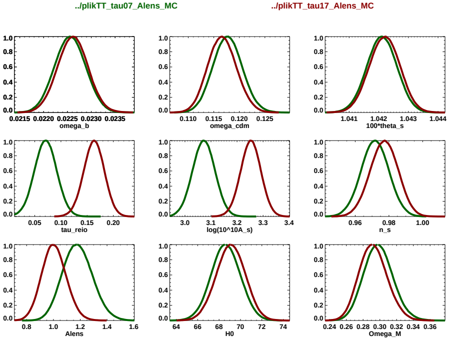
$$\tau = 0.067^{+0.023}_{-0.021} \quad \text{(lowTEB)} \qquad \text{v.s} \qquad \tau = 0.149^{+0.034}_{-0.036} \quad (\texttt{Plik})$$

$$\simeq 1.9\sigma$$

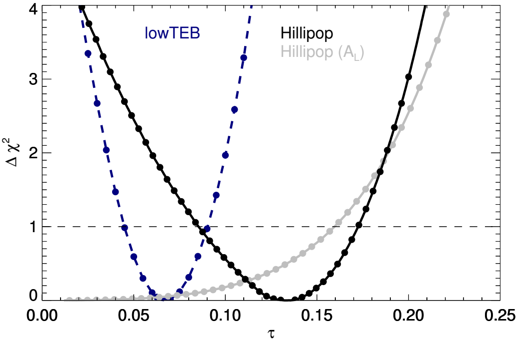
The $[\tau, A_\mathrm{s}, A_\mathrm{L}]$ correlation

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

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



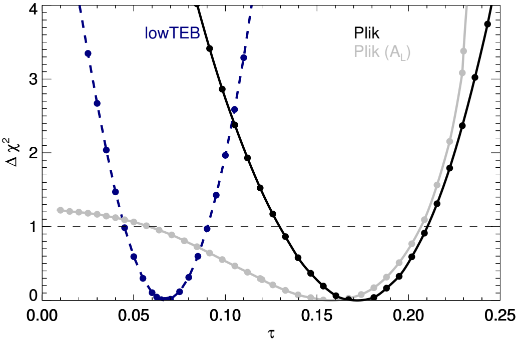
Hillipop results : τ (TEST2)



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

$$1.3\sigma$$

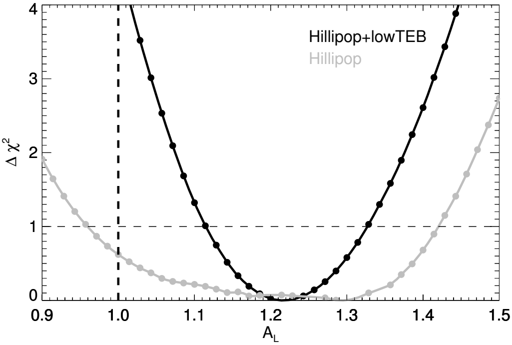
Plik results : τ (TEST2)



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

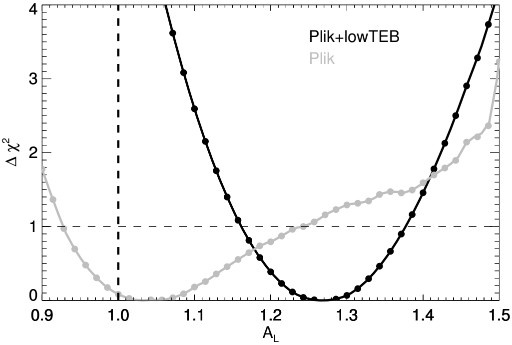
$$2.2\sigma$$

Hillipop results : A_L (TEST1)



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

Plik results : A_L (TEST1)



$$A_\mathrm{L} = 1.26^{+0.11}_{-0.10} \quad (\texttt{Plik}+\mathrm{lowTEB})$$

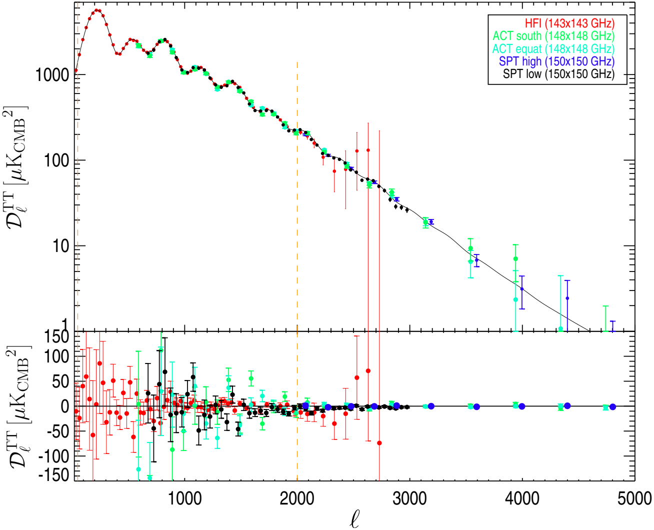
More CMB data: very-high-ℓ (VHL)

ACT+SPT/ essentially constrain foregrounds

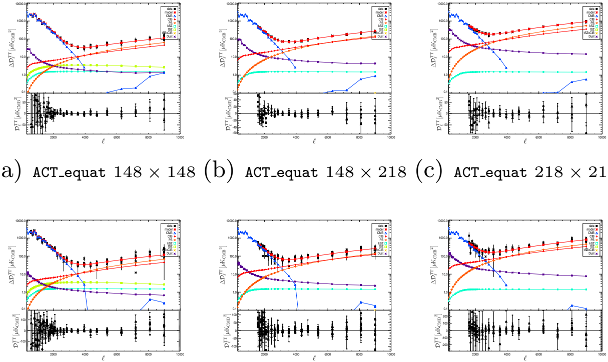
Dataset	ℓ range	freq (GHz)	#spectra	#nuisances	ref
`ACT south/equat`	[1500,10000]	148, 218	6	12	Das et al. (2014)
`SPT_high`	[2000,13000]	95, 150, 220	6	9	Reichardt et al. (2012)
`SPT_low`	[650,3000]	150	1	2	Story et al. (2012)

- 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

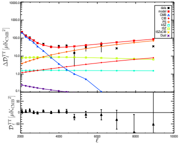


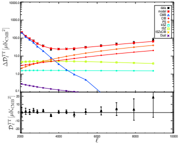
(a) `ACT_equat` 148 × 148 (b) `ACT_equat` 148 × 218 (c) `ACT_equat` 218 × 218

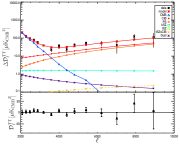
(d) `ACT_south` 148 × 148 (e) `ACT_south` 148 × 218 (f) `ACT_south` 218 × 218

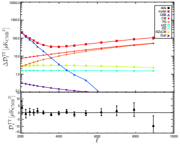
$$\chi^2/ndof = 651/710$$

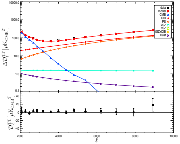
SPT_high

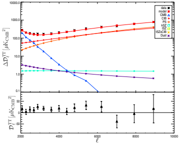

(g) SPT_high 95 × 95


(h) SPT_high 95 × 150


(i) SPT_high 95 × 220

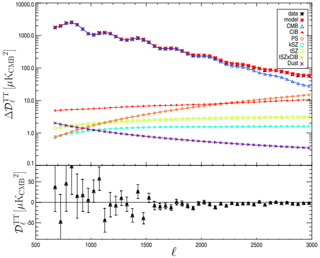

(j) SPT_high 150 × 150


(k) SPT_high 150 × 220


(l) SPT_high 220 × 220

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

SPT_low



(m) `SPT_low` 150 × 150 GHz

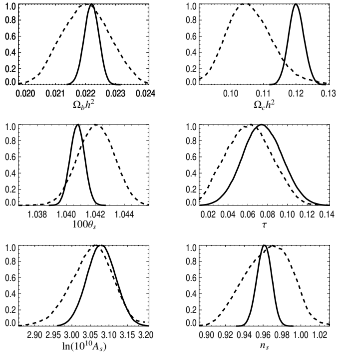
$$\chi^2/ndof = 58/47$$

More consistency tests

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

Is VHL cosmology consistent with *Planck*?

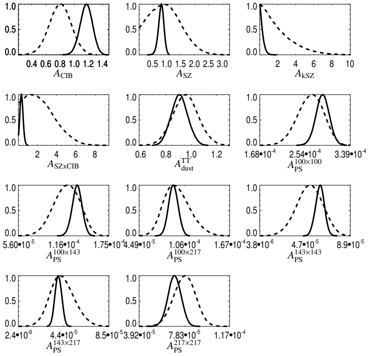
sample *independently* $\mathscr{L}^{Hillipop}$ (full) and $\mathscr{L}^{VHL}$ (dashed)



Combined likelihood

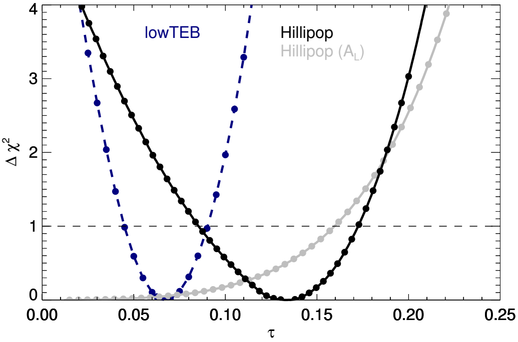
put $A_{SZ}, A_{CIB}, A_{kSZ}, A_{SZ\times CIB}$ in common in $\mathscr{L}^{Hillipop}$ and $\mathscr{L}^{VHL}$

Hillipop w/o VHL (full/dashed):



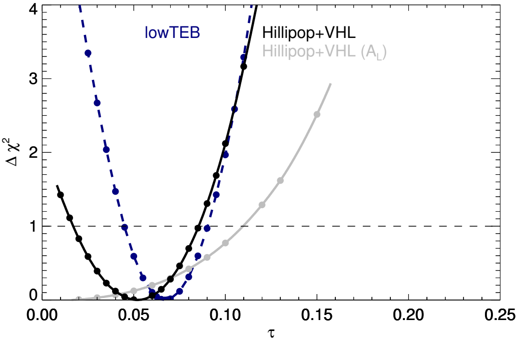
$A_{CIB}, A_{kSZ}, A_{SZ\times CIB}, A^{TT}_{dust}$ are scalings $\rightarrow 1$

τ Hillipop



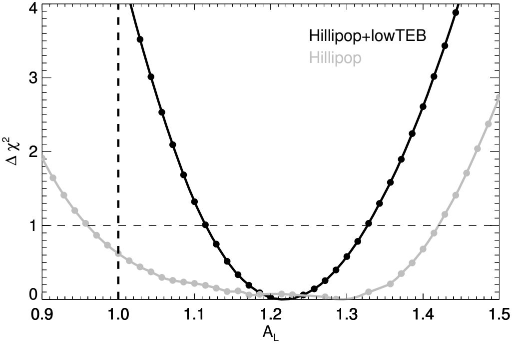
$$\tau = 0.067^{+0.023}_{-0.021} \quad \text{(lowTEB)} \qquad \tau = 0.134^{+0.038}_{-0.048} \quad \text{(Hillipop)}$$

τ Hillipop+VHL



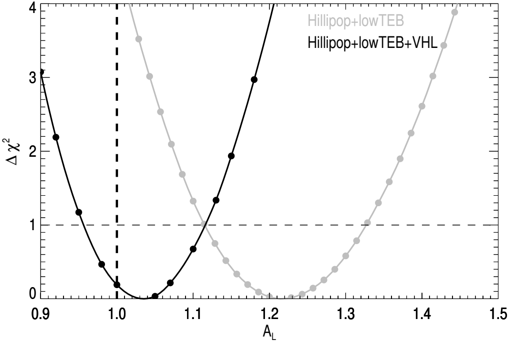
$$\tau = 0.067^{+0.023}_{-0.021} \quad \text{(lowTEB)} \qquad 0.052 \pm 0.035 \quad \text{(Hillipop+VHL)}$$

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`

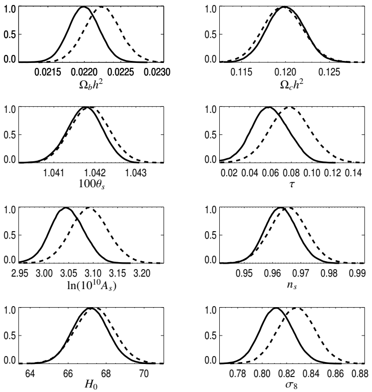
to improve on `SPT_high` 220×220 increase dust level

$$
\begin{aligned}
A_{\rm L} &= 1.12 \pm 0.10 \text{ (Hillipop+lowTEB+SPT\_high)} \\
&= 1.13 \pm 0.10 \text{ (Hillipop+lowTEB+SPT\_high, } A^{\rm SPT}_{\rm dust} \times 3\text{)}
\end{aligned}
$$

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

ΛCDM revisited

all now OK $\rightarrow$fix $A_{\rm L} = 1$



Hillipop+lowTEB+VHL : full `Plik`+lowTEB+cor(SZ): dashed

ΛCDM parameters revisited (Hillipop)

Parameter	$Hillipop$ + lowTEB	$Hillipop$ + lowTEB $+VHL$	$Hillipop$ + 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
- $\sigma_8 \simeq 0.81$ not so in tension with local measurements (WL, SZ cluster counts..)

Conclusions

- to first order *Planck* data are OK (for ΛCDM)
- but some 2σ tensions: low vs hi-ell τ , $A_{\rm L}$(hi+low)
- another *Planck* high-ℓ likelihood (Hillipop) is less in tension $[\tau, A_{\rm s}, A_{\rm L}, \sigma_8]$ lower
- using more CMB data seems to cure all those tensions (no need to modify GR!)

- cosmology is now dominated by systematics: CMB is a *clean* probe!
- should be the main focuss in the next decade (in particular for $\sum m_\nu, N_{\rm eff}$...)

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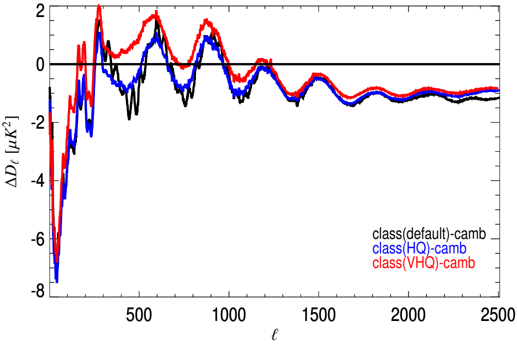
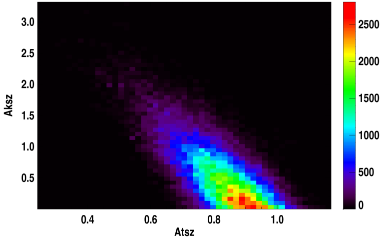
class v.s camb

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

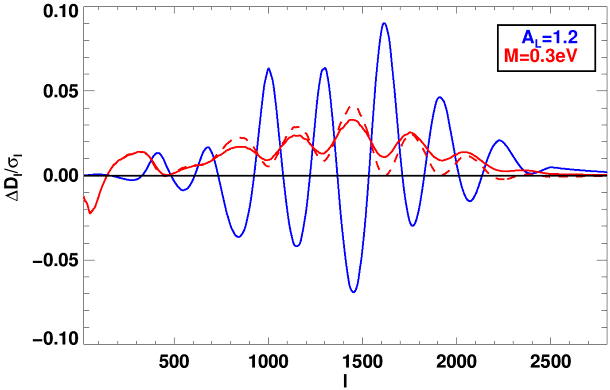


Planck states VHL $\simeq$ cor(Asz).
Not for Hillipop:

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

Improvement comes from the whole cov. matrix

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



Plik+VHL?

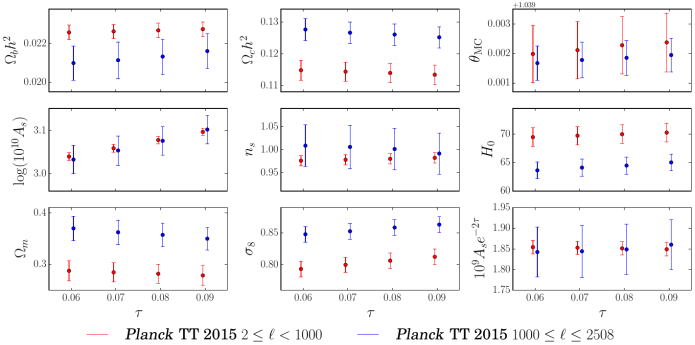
Plik:

$$\tau = 0.17 \pm 0.03 \quad (\texttt{Plik})$$
$$A_{\rm L} = 1.26 \pm 0.10 \quad (\texttt{Plik}+\text{lowTEB})$$

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

$$\tau = 0.08 \pm 0.02 \quad (\texttt{Plik}+\text{VHL})$$
$$A_{\rm L} = 1.14 \pm 0.08 \quad (\texttt{Plik}+\text{lowTEB}+\text{VHL})$$

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 $\simeq 0.17$...

Cosmological Analysis with Minuit Exploration of the Likelihood

- pure C/C++ OO project
- Boltzmann = `class` (J.Lesgourgues etal), 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.