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Planck Likelihood Analysis

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On behalf of the Planck Consortium

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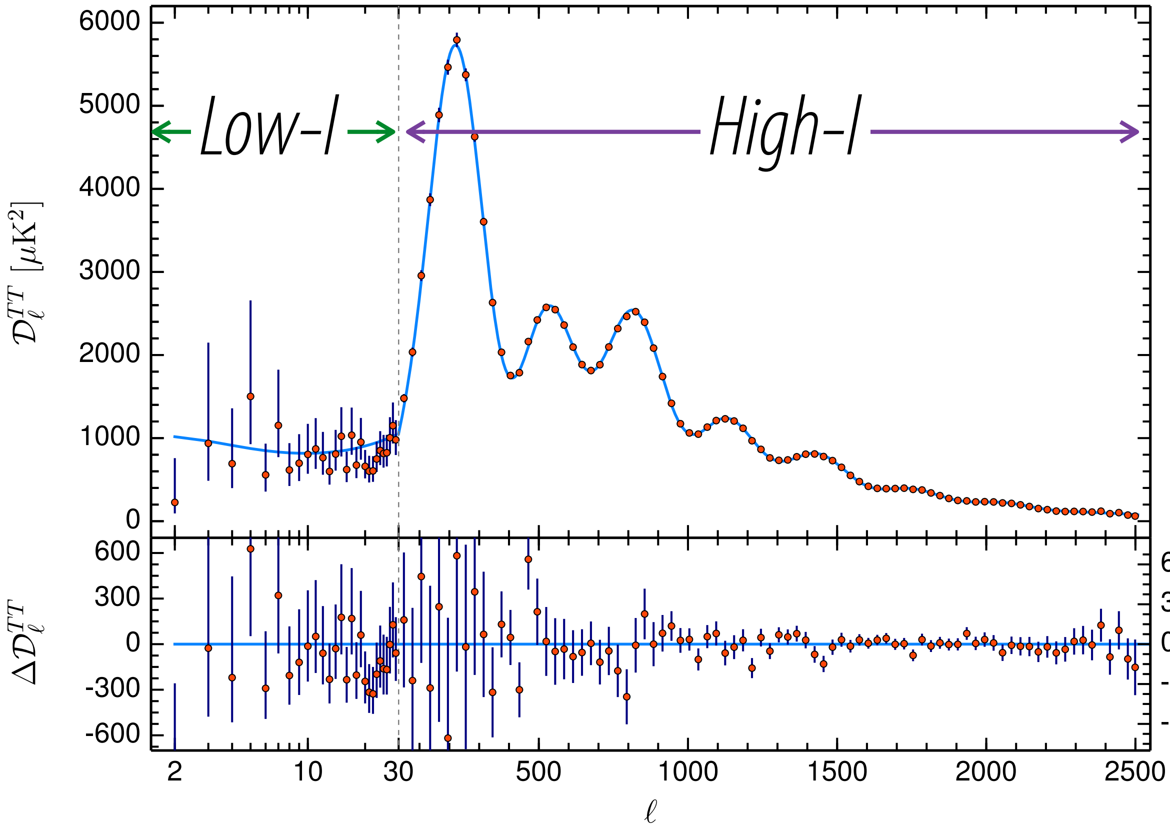
The scientific results that I will present today are a product of the *Planck Collaboration*, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

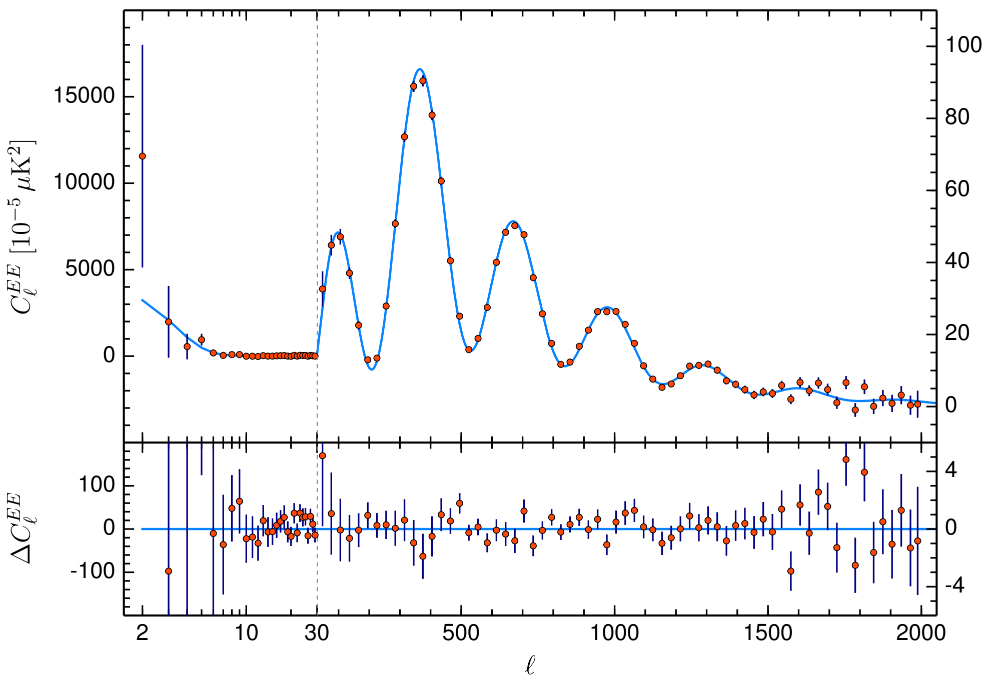


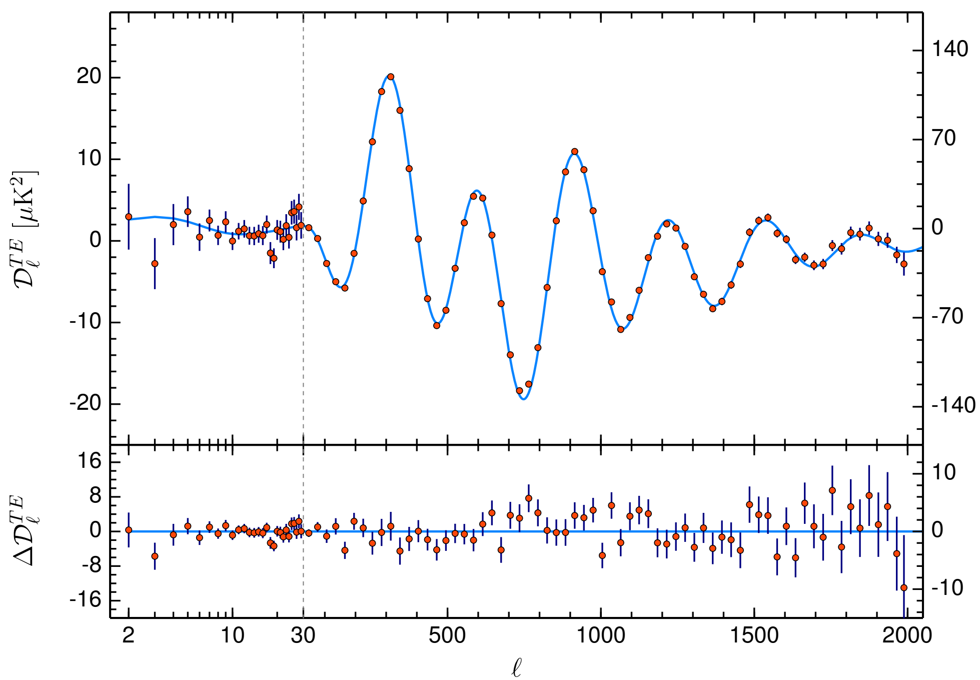
Planck Likelihood is

a strong compression of the data

a statistical description of the data

an approximation



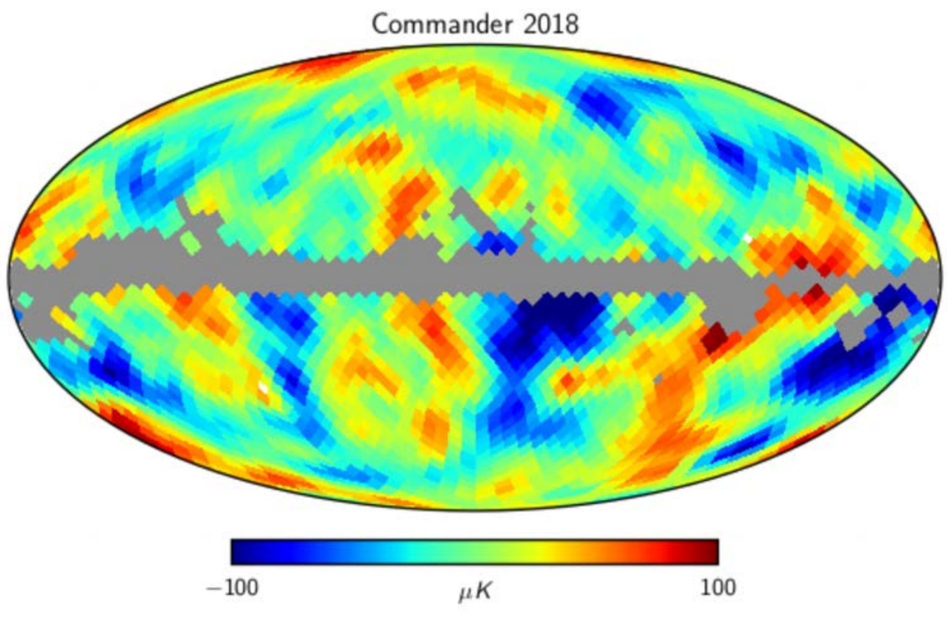


Hybrid Approximation

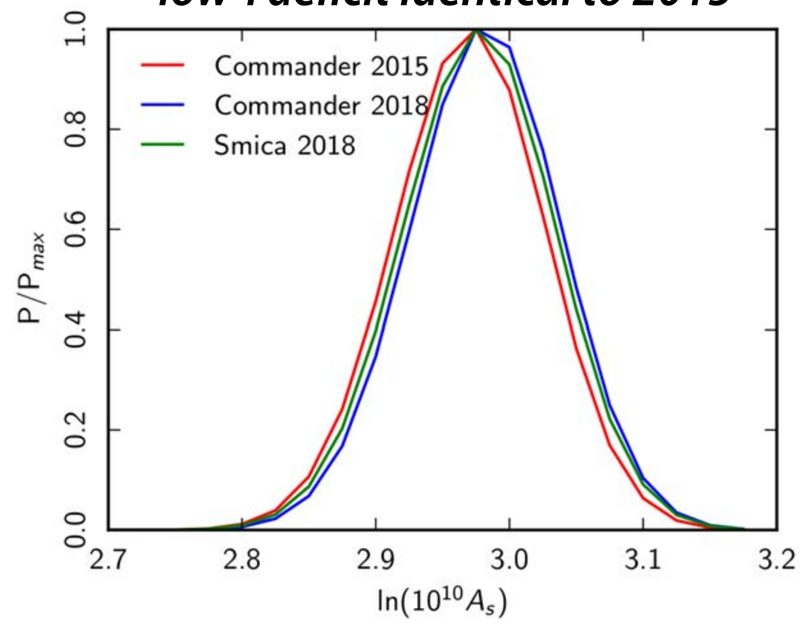
- Low-l (l<30)
  - TT only likelihood (Commander samples). As in 2013
  - EE only, HFI based likelihood. Updated from Intermediate Paper XLVI (2016)
  - Was before TEB LFI based likelihood (also updated)
- High-l (l≥30)
  - Same approach as 2015
  - Important improvements in Polarisation
- *Alternative products for each part (cross validation, or exploration of different approximation and data selections)*
  - *Low-l TEB, based on LFI data + Commander T map*
  - *Alternative high-l likelihood (Camspec)Foreground and nuisance marginalised High-l likelihood (Pliklite)*

Low-l TT

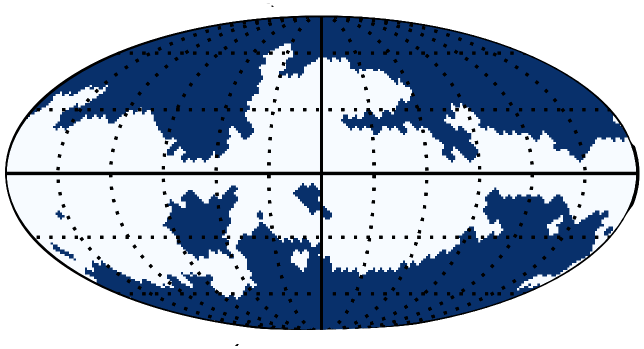
- Low-l joint bayesian exploration of CMB and Foregrounds (Commander)
  - reuse the CMB only posteriors to approximate a FG marginalised likelihood
- Very close to 2013 and 2015 BUT
  - Use less data (no external data set, no single detector maps)
  - Simpler model
  - Slightly larger mask (2018: 86%, 2015: 94%)

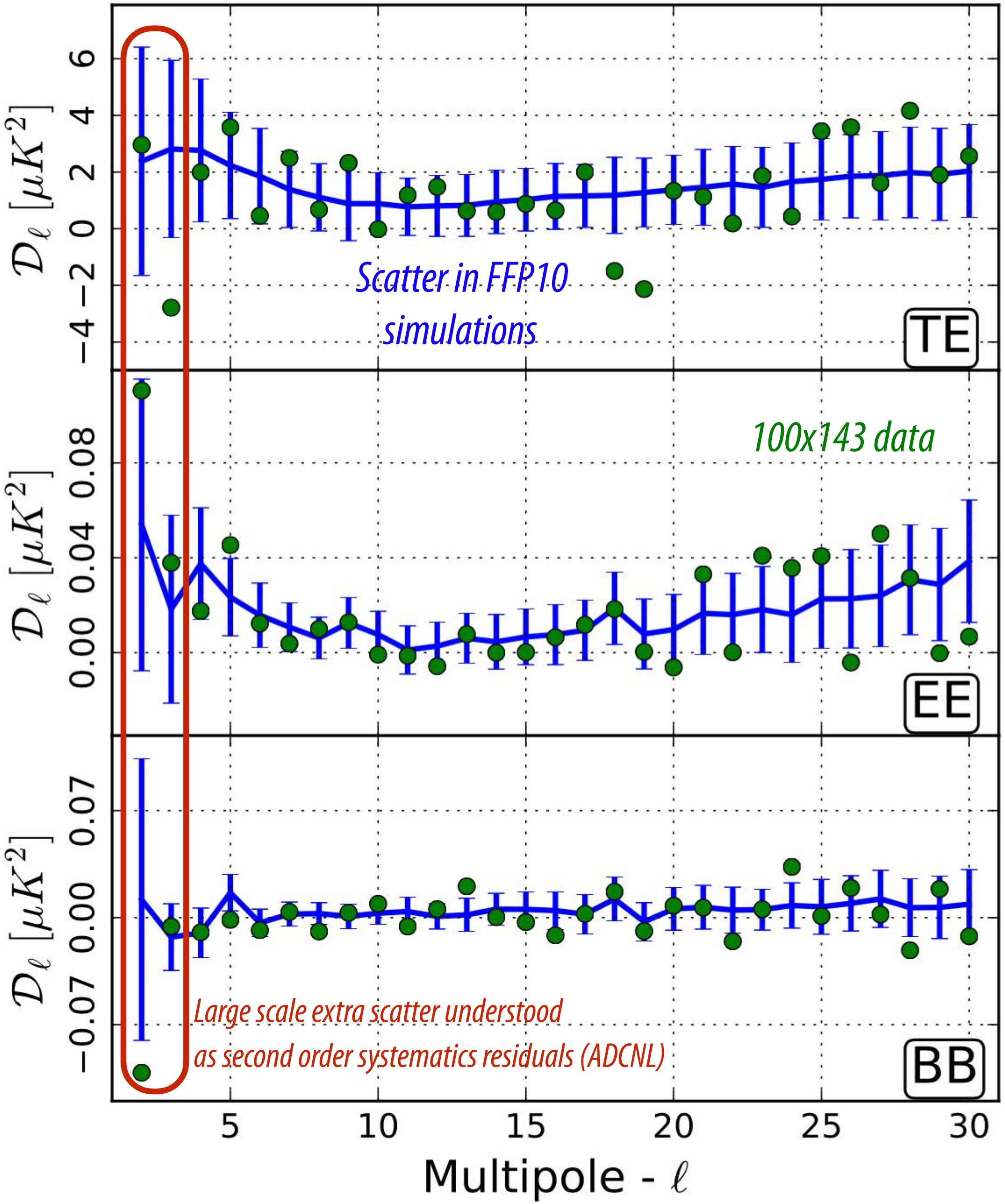


low-l deficit identical to 2015



Low-l HFI Polarization

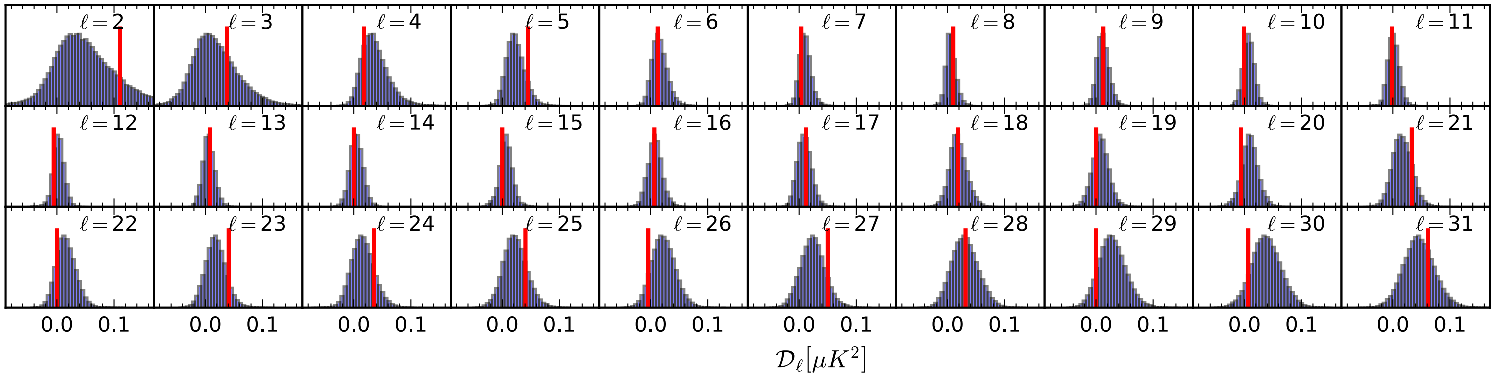




- Residual systematics at low-l prevents us from implementing a pixel based likelihood
- Cross QML spectra 100x143 on 50% of the sky
  - Use latest SRoll maps
  - Galaxy cleaned using 30 GHz and 353 GHz maps
- Likelihood computes the Data QML spectra using the FFP10 End2End simulations
  - 300 noise & systematics simulations on the same sky realization
  - Swap sky realization after the fact (ok at large scale)

Likelihood details

- Sample Cosmology $10^9 A_s \sim U(0.6, 3.8)$ $\tau \sim U(0, 0.14)$ $r \sim U(0, 1)$
  $0\,\mu K^2 \leq \mathcal{D}_\ell^{EE} \leq 0.30\,\mu K^2, \quad 0\,\mu K^2 \leq \mathcal{D}_\ell^{BB} \leq 0.20\,\mu K^2$
- For each model, explore instrument and cosmic variance *1000 CMB 300 noise*
- Measure data probability at each multipole



- Interpolate probability for each multipole and model as a function of the C_l of the model
- Likelihood is the product of those interpolations

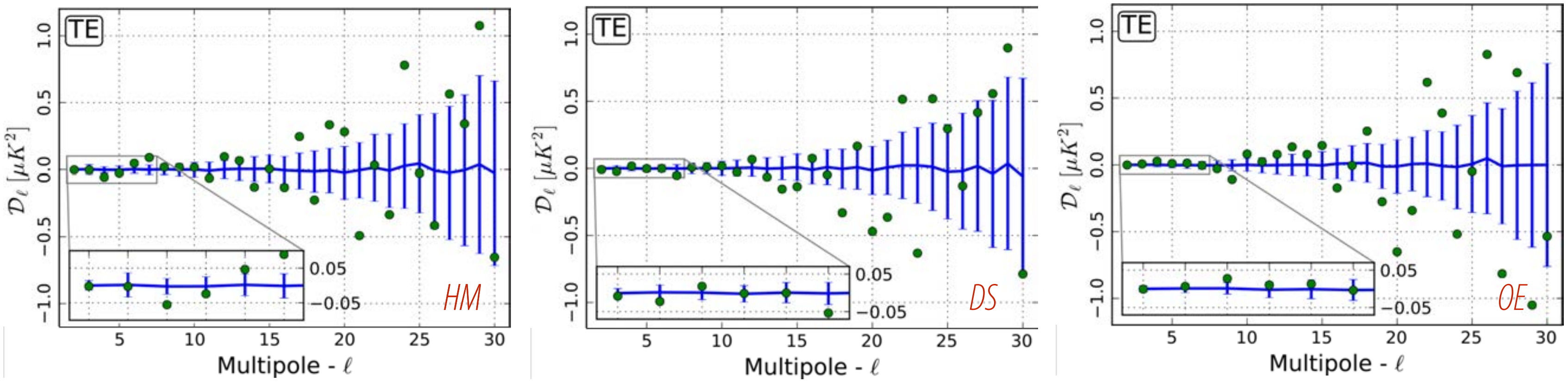
$$\log \mathcal{L}\left(C^{\text{theory}} \middle| C^{\text{data}}\right) \approx \sum_{\ell=2}^{29} g_\ell\left(C_\ell^{\text{data}}, C_\ell\right)$$

- Ignore l to l correlations and TT-EE, TT-TE, TE-EE correlations
- Covariance entirely determined by sims

no TE

- TE null test (using 3 different data selection cuts) are consistently low
  - *Driven by the higher ells*

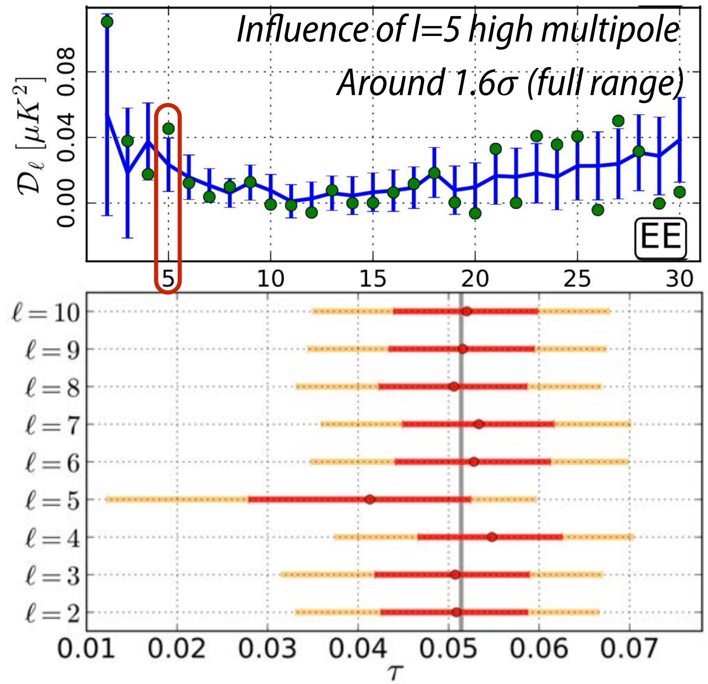
	$\ell_{\max} = 10(29)$	$\ell_{\max} = 10(29)$	$\ell_{\max} = 10(29)$
	HM	DS	OE
TE	8.0 (0.3)	73.0 (1.6)	12.9 (0.1)
EE	7.0 (17.7)	83.1 (69.5)	96.7 (73.9)
BB	71.6 (60.0)	85.1 (96.0)	91.1 (83.2)

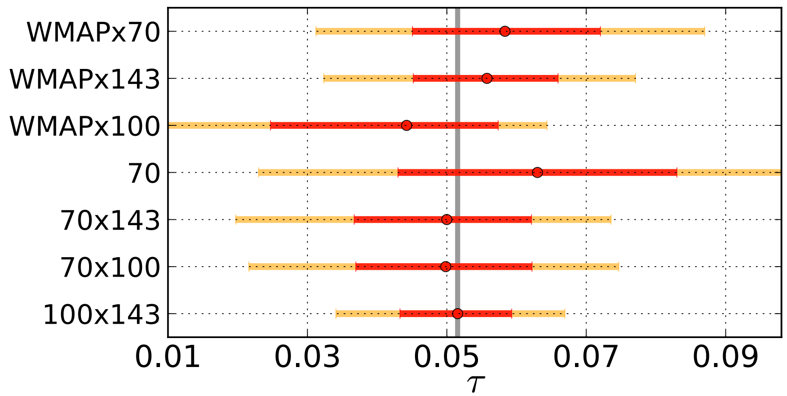


- *Nota: In the TE simulation, no propagation of component separation residual. Taken into account with 2muK extra white noise.*

- TE-TT and TE-EE correlation would need to be taken into account to include TE.

Consistency and Constraints





Good compatibility with LFI and WMAP data

Also tested : masks, data selection nulls, synchrotron cleaning…

Parameter	ΛCDM	ΛCDM + r
$\ln[10^{10}A_s]$	2.924 ± 0.052	$2.863^{+0.089}_{-0.062}$
τ	0.0506 ± 0.0086	0.0503 ± 0.0087
$r_{0.002}$	–	≤ 0.41
$A_s e^{-2\tau}$	$1.685^{+0.083}_{-0.091}$	$1.59^{+0.11}_{-0.13}$

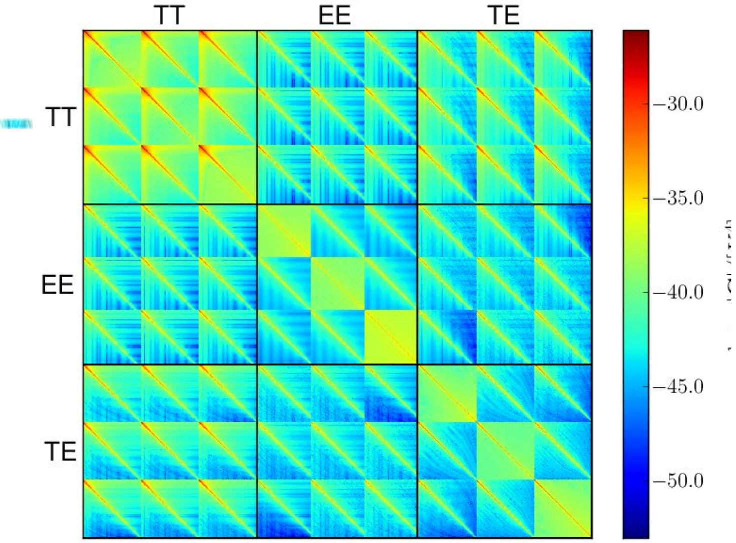
- 0.5σ downward shift compared to XLVI
  - Effect of the 1000 discarded rings
  - Improvement in synchrotron correction
  - FFP10 has larger scatter than XLVI sims and pushes tau down

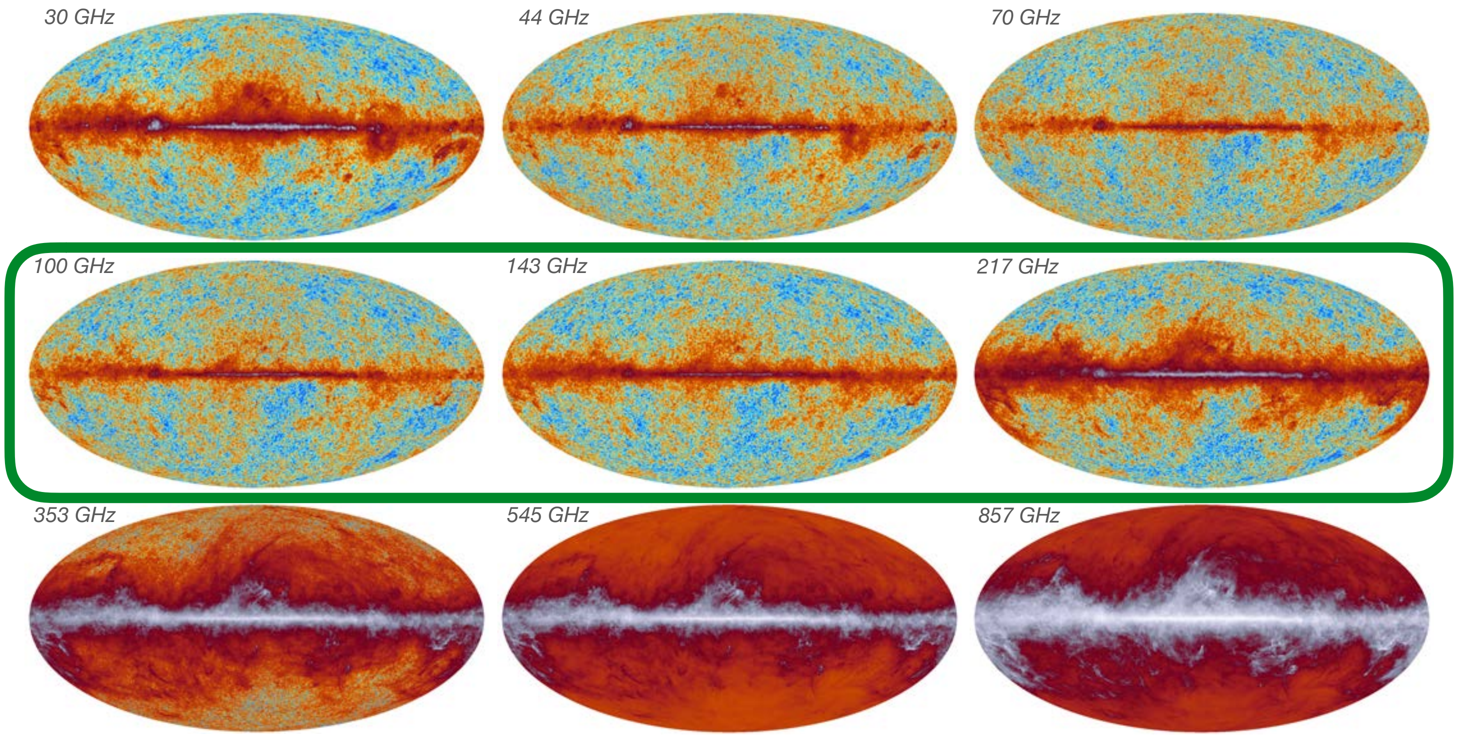
- Overall limitations of 2018 low-l
  - Dependency on simulations
    - fidelity
    - correlations
  - ADCNL residual (coupling with FG)
    - large scatter for the first 2 modes
    - constraint relies heavily on l=4 and l=5

High-l

- Similar approach than 2013 and 2015
  - Gaussian approximation with semi analytic covariance estimate
  - 100 to 217 GHz Data used
    - *LFI and HFI high frequencies for galactic contamination templates*

$$-\ln \mathcal{L}(\hat{\boldsymbol{C}}|\boldsymbol{C}(\theta)) = \frac{1}{2}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right]^{\mathsf{T}} \mathsf{C}^{-1}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right] + \text{const}$$





High-l

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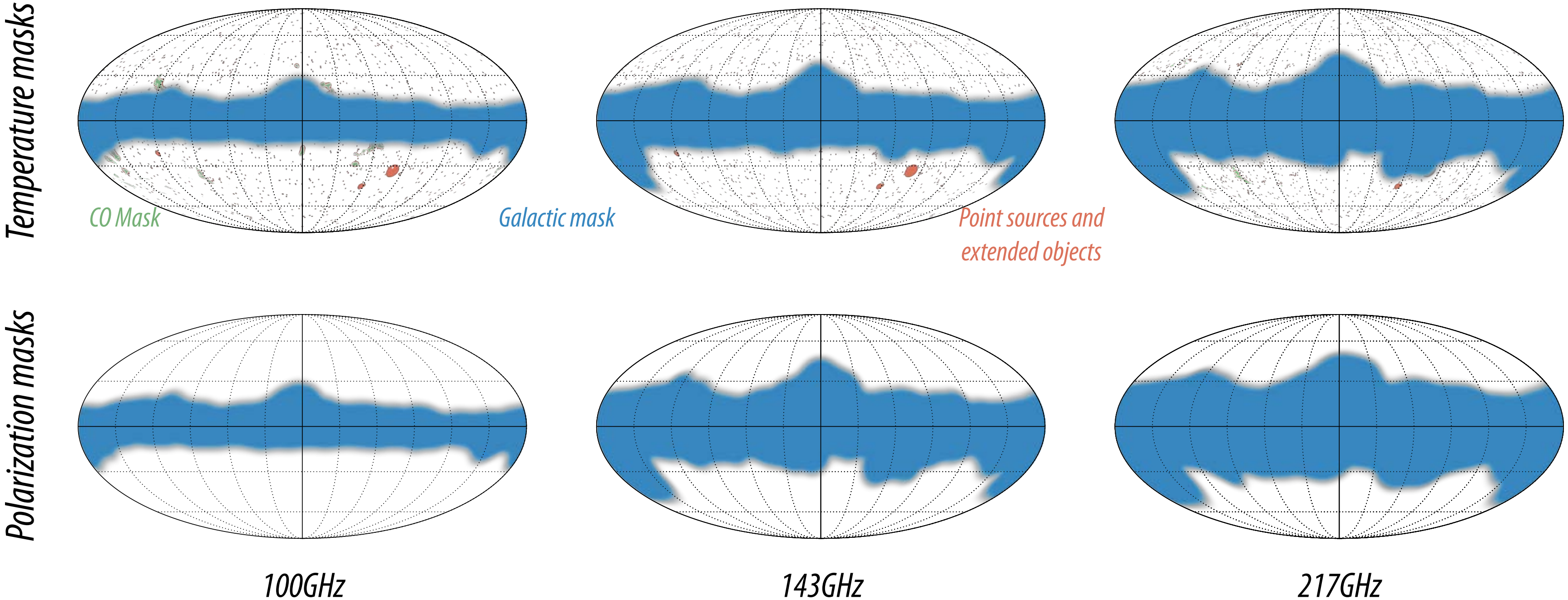
  - Sky Masks and selection cuts to avoid large FG contamination and low S/N
    - *Same as 2015*

Frequency [GHz]	Multipole range
TT	
100 × 100 . .	30–1197
143 × 143 . .	30–1996
143 × 217 . .	30–2508
217 × 217 . .	30–2508
TE & ***EE***	
100 × 100 . .	30–999
100 × 143 . .	30–999
100 × 217 . .	505–999
143 × 143 . .	30–1996
143 × 217 . .	505–1996
217 × 217 . .	505–1996



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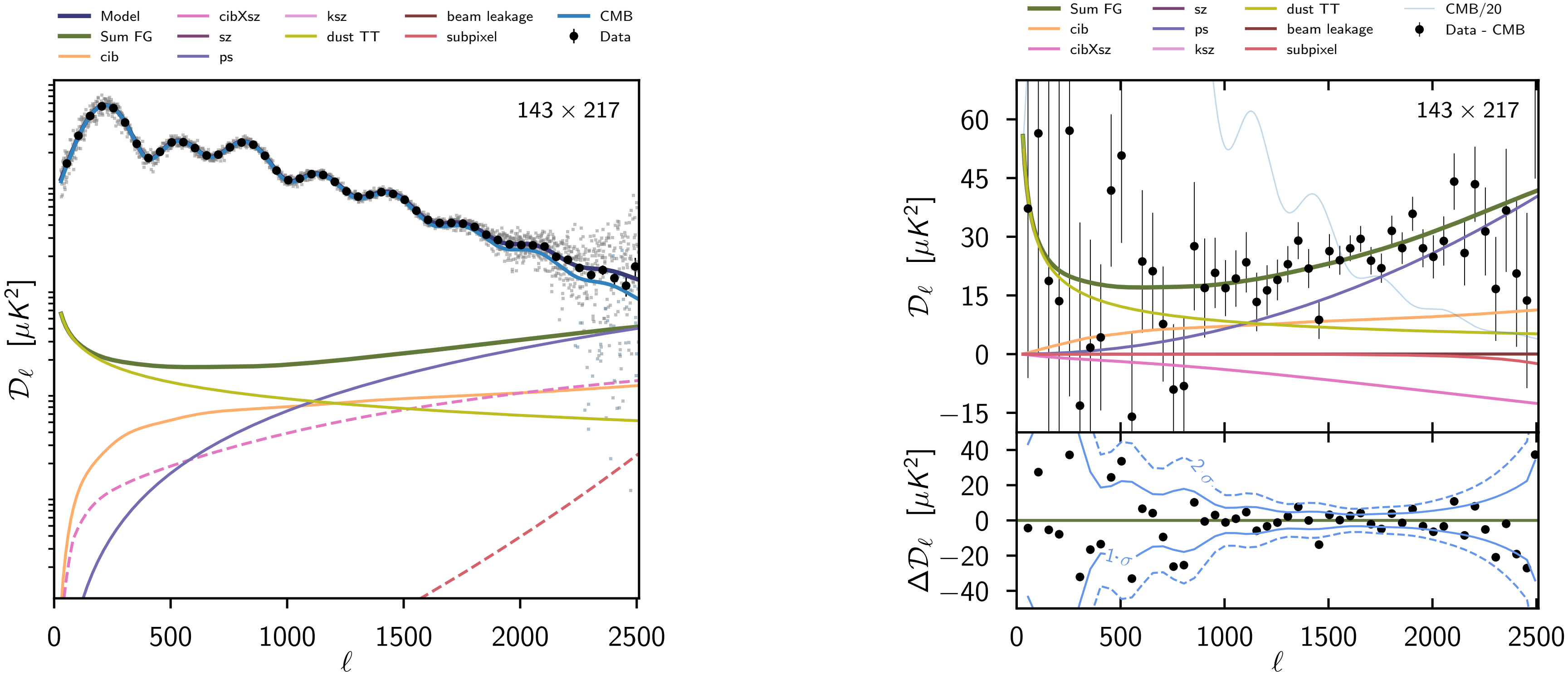
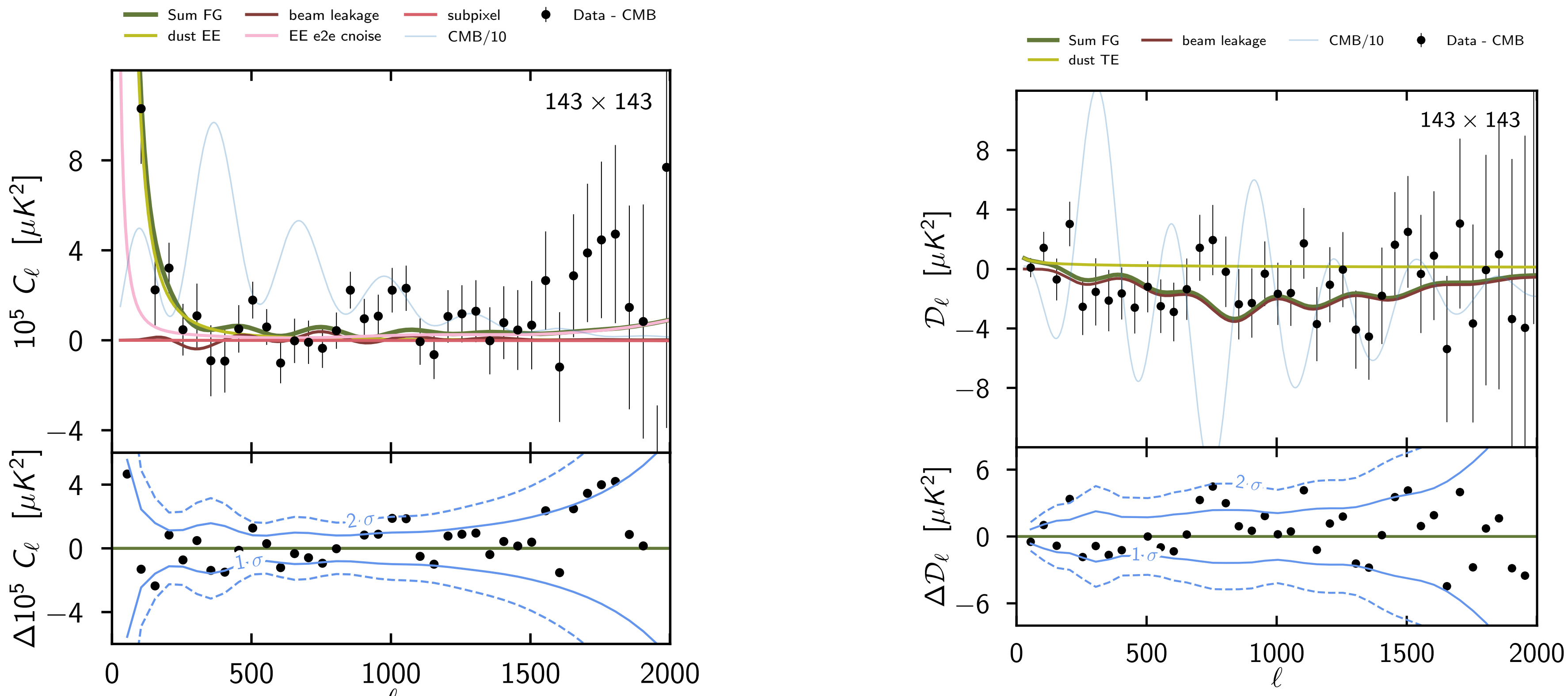
  - Half-mission cross spectra to avoid noise biases
  - Spectrum based templates for FG & nuisance corrections
    - *Extra nuisance parameter for most of them*
    - *Keep cross frequency spectra in the data vector*

$$-\ln \mathcal{L}(\hat{\boldsymbol{C}}|\boldsymbol{C}(\theta)) = \frac{1}{2}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right]^{\mathsf{T}} \mathsf{C}^{-1}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right] + \mathrm{const}$$

TT Model and Residuals



EE and TE residuals



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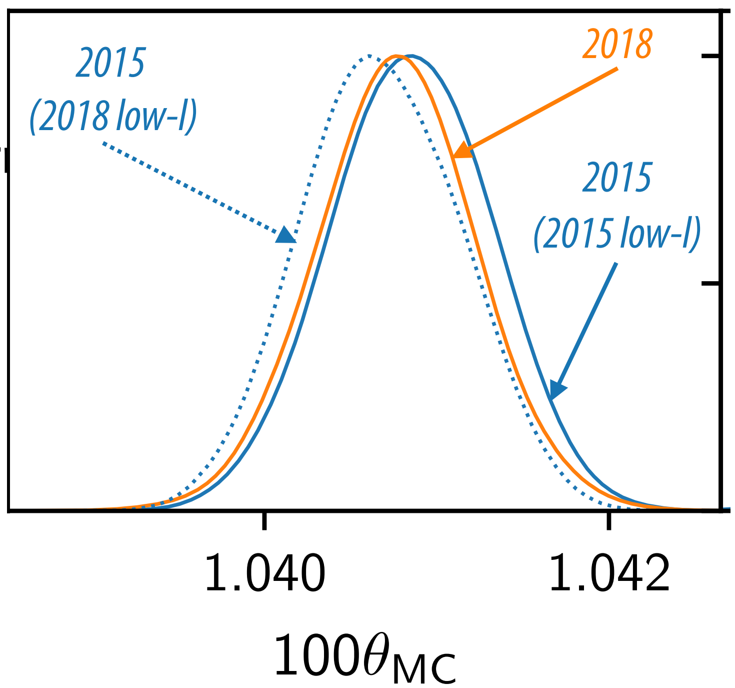
- Numerous improvements over 2015
  - *New maps, Fg and systematics model improvements*
- TT almost identical to 2015

Largest difference between 2015 and 2018 TT



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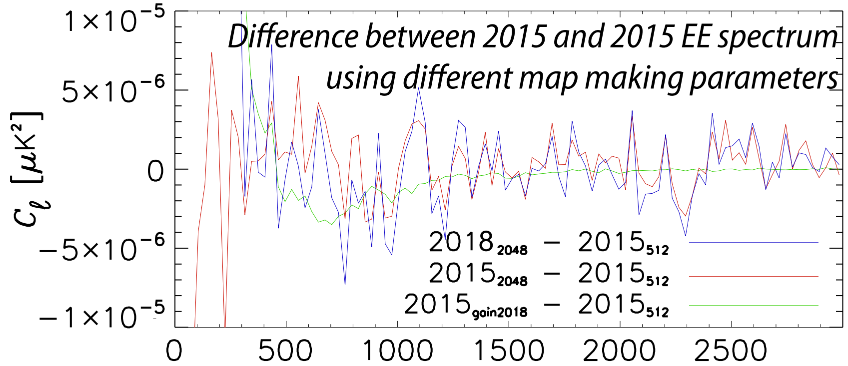
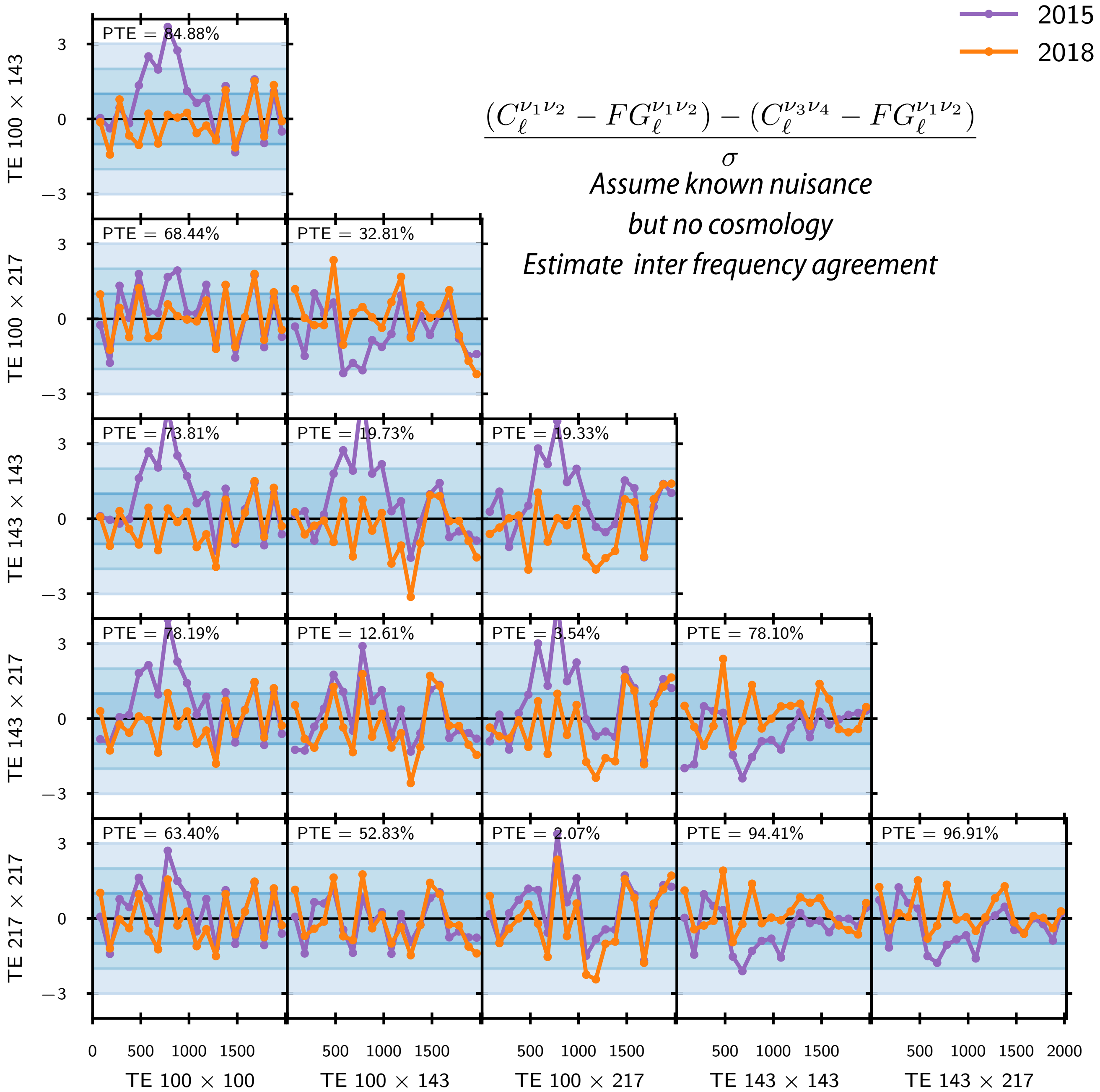
    - *Keep cross frequency spectra in the data vector*
- Numerous improvements over 2015
  - *New maps, Fg and systematics model improvements*
- TT almost identical to 2015
- TT, TE and EE are now retained for cosmology
    - ***Better temperature-to-polarisation leakage correction***
    - ***Better determination of polarisation efficiencies***

High-l Polarization

- Important improvement over 2015
  - Beam leakage correction
  - Polarization efficiency corrections
- Other changes
  - Dust model
  - Subpixel and EE correlated noise



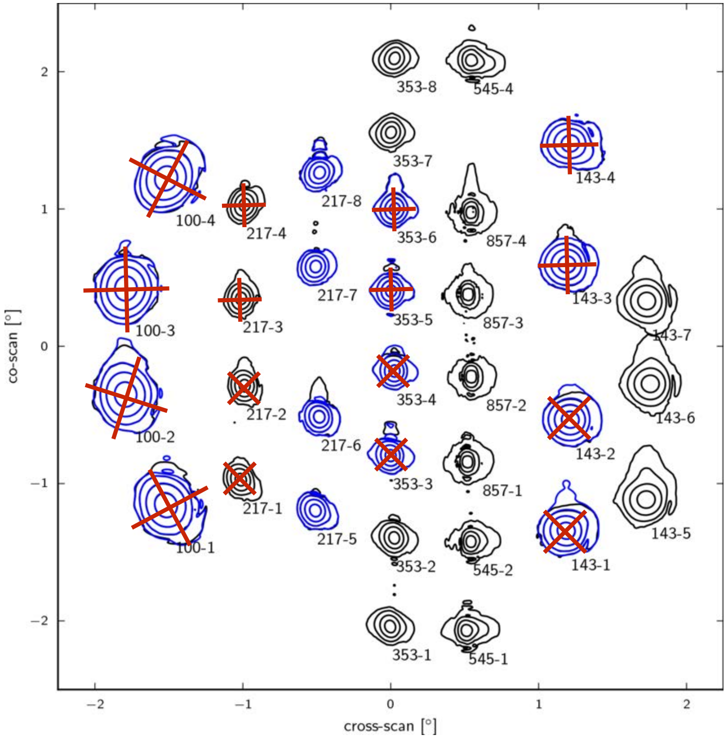
- Map making improvement translate to lower effective noise level in 143GHz and tighter error bars
  - worsen a bit χ^2 compared to 2015, even though inter-frequency agreement have increased significantly
- Interfrequency disagreement was reason for not using 2015 Polarization
  - ***Now good enough for cosmology at μK^2 precision, with up to 1σ shifts compared to 2015***
  - ***Some caveats at <0.5σ(on TTTEEE)***



$$\frac{(C_\ell^{\nu_1\nu_2} - FG_\ell^{\nu_1\nu_2}) - (C_\ell^{\nu_3\nu_4} - FG_\ell^{\nu_1\nu_2})}{\sigma}$$

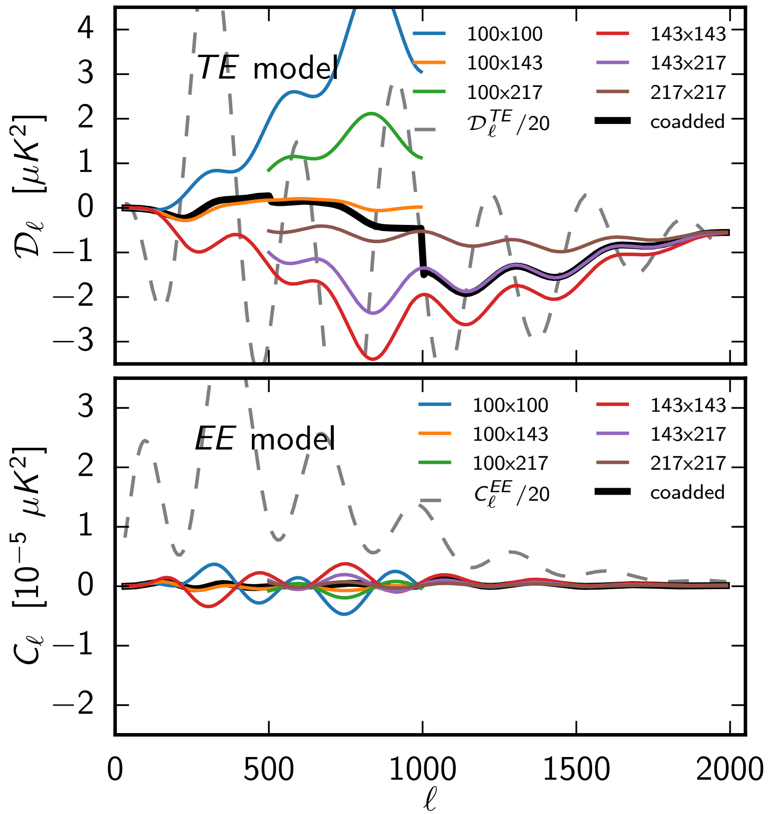
Assume known nuisance
but no cosmology
Estimate inter frequency agreement

Improved inter frequency agreement
2015 outliers greatly reduced
Overall Chi2 (unbinned coadded) is 1.053 (5% PTE) (compared to TTTEEE+lowE+lensing best fit)



$$d(\mathbf{r},\alpha) = B(\mathbf{r}) \otimes [T(\mathbf{r}) + \rho(Q(\mathbf{r})\cos 2\alpha + U(\mathbf{r})\sin 2\alpha)]$$

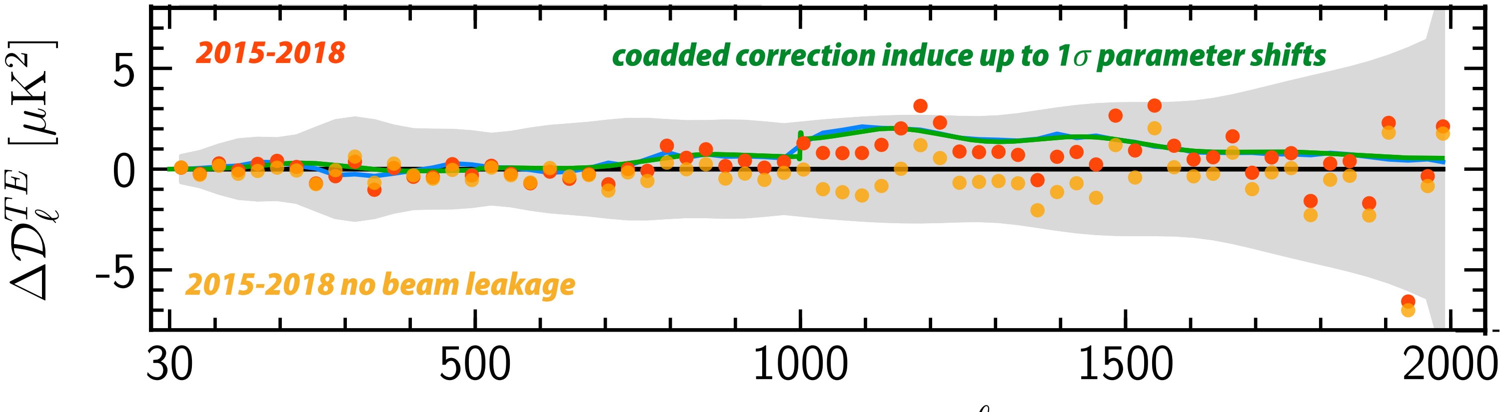
Polarization maps are built using difference between PSB
No Beam deconvolution at the map making step
Differences in beams between detectors means T->E leakage
(at spectrum level, dominant effect is TT->TE and TE->EE)

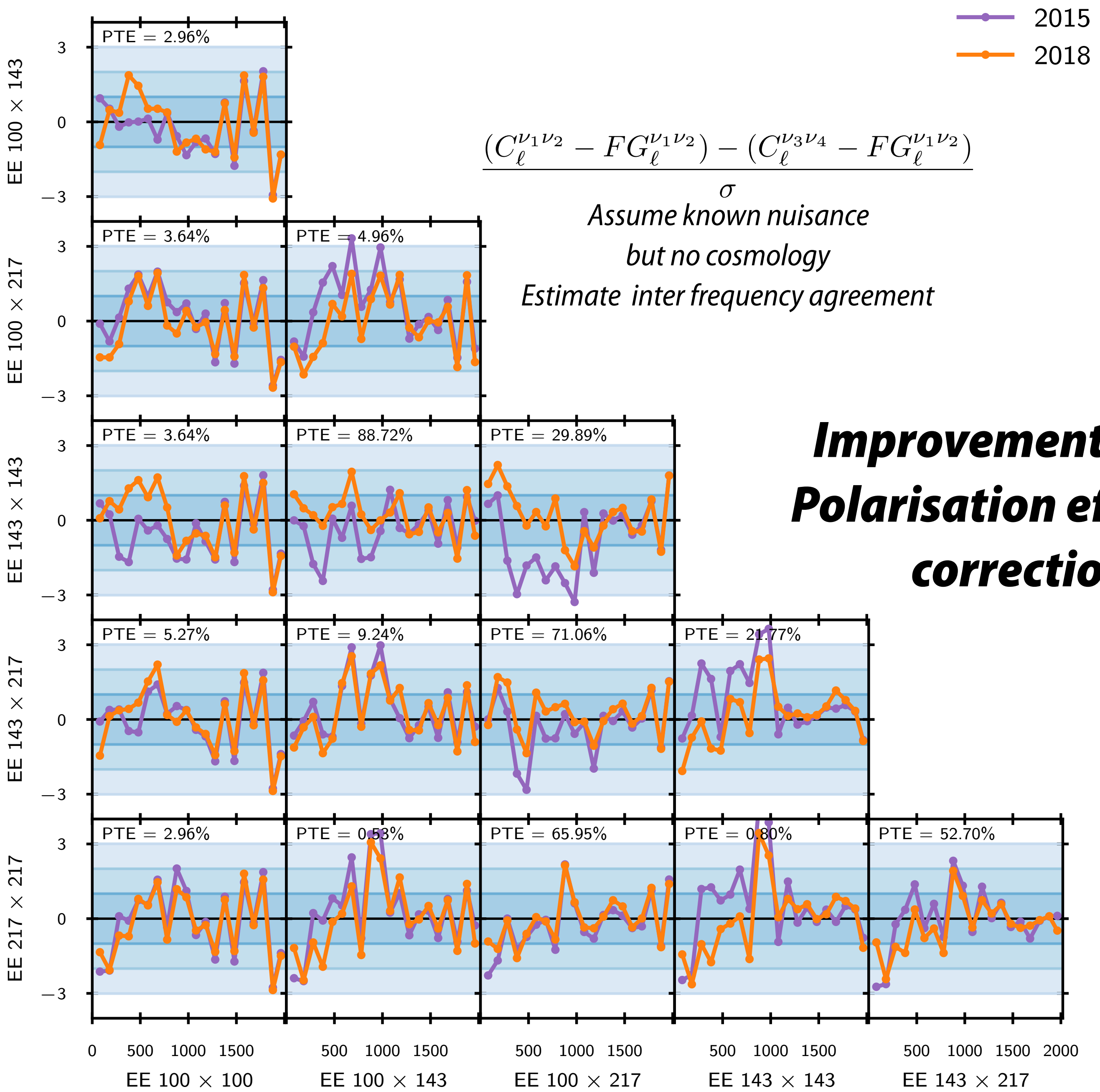


Given Beam and scanning strategy knowledge one can evaluate the amplitude of leakage and correct at the spectrum level (Hivon et al 2017, Quickpol)

Improved inter frequency agreement in TE due to beam leakage correction

$\Delta\chi^2$ ~ 37 on TE , $\Delta\chi^2$ <1 in EE





$$\frac{(C_\ell^{\nu_1\nu_2} - FG_\ell^{\nu_1\nu_2}) - (C_\ell^{\nu_3\nu_4} - FG_\ell^{\nu_1\nu_2})}{\sigma}$$

Assume known nuisance
but no cosmology
Estimate inter frequency agreement

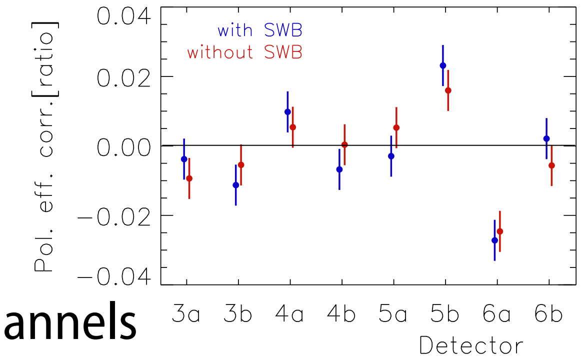
Improvement due to Polarisation efficiency corrections

Improved inter frequency agreement
Overall Chi2 (unbinned coadded) is 1.045 (7% PTE) (compared to TTTEEE+lowE+lensing best fit)

Polarization efficiency corrections

$$d(\mathbf{r},\alpha) = B(\mathbf{r}) \otimes [T(\mathbf{r}) + \rho(Q(\mathbf{r})\cos 2\alpha + U(\mathbf{r})\sin 2\alpha)]$$

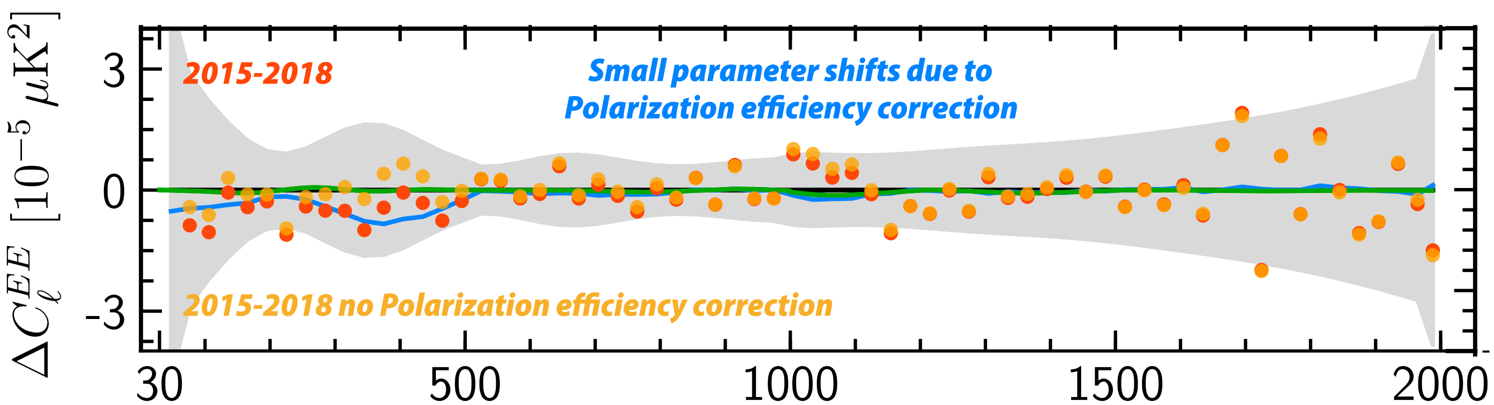
- Estimation of polarisation efficiency correction on dust for the 353 GHz shows percent level errors
  - *Ground based (statistical) errors are 10 times smaller*

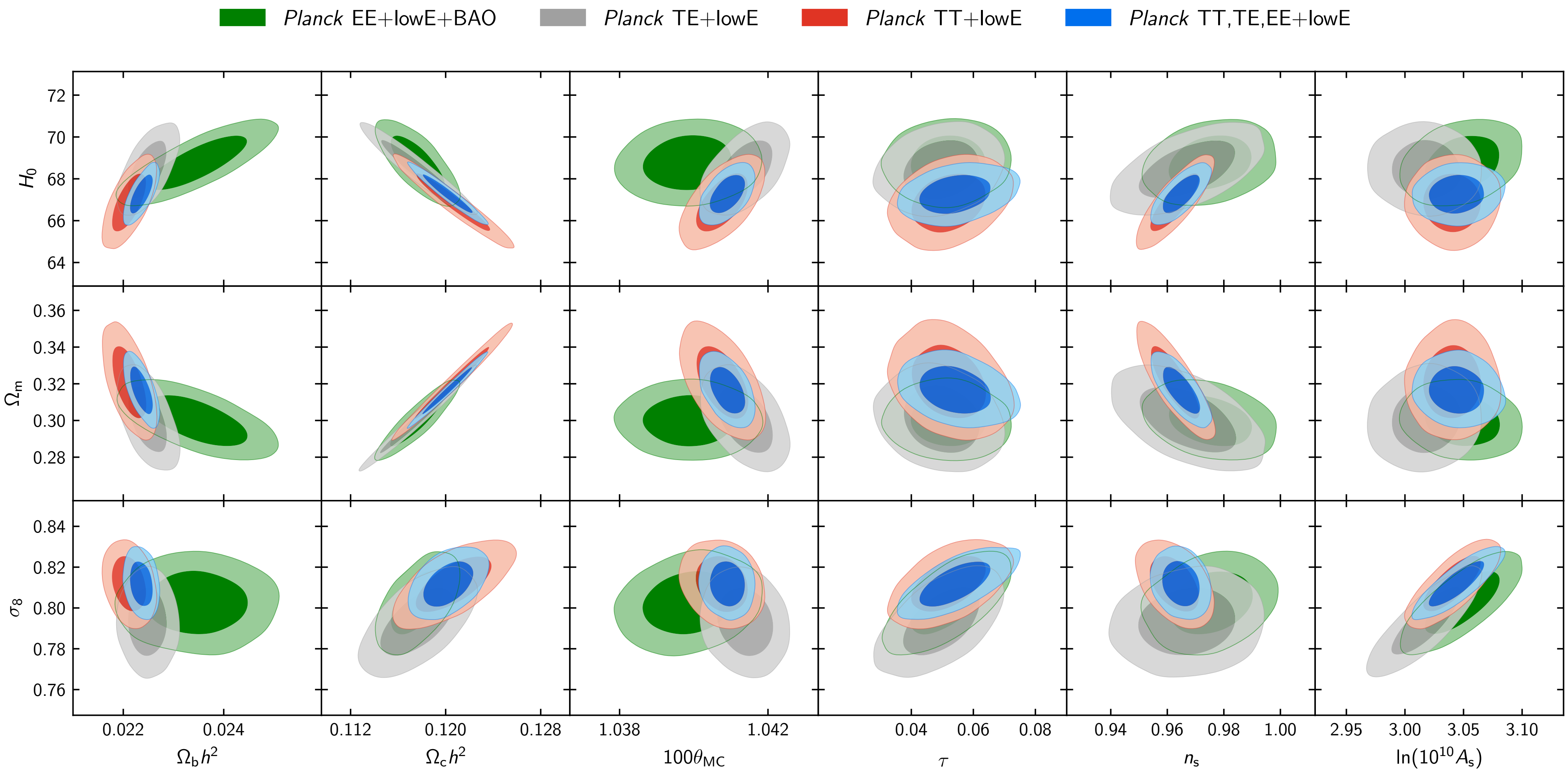


- E map based calibration possible for lower frequency channels
  - *Must take into account dust contamination*
  - *To go beyond intercalibration, and reach % precision one must assume TT cosmology*

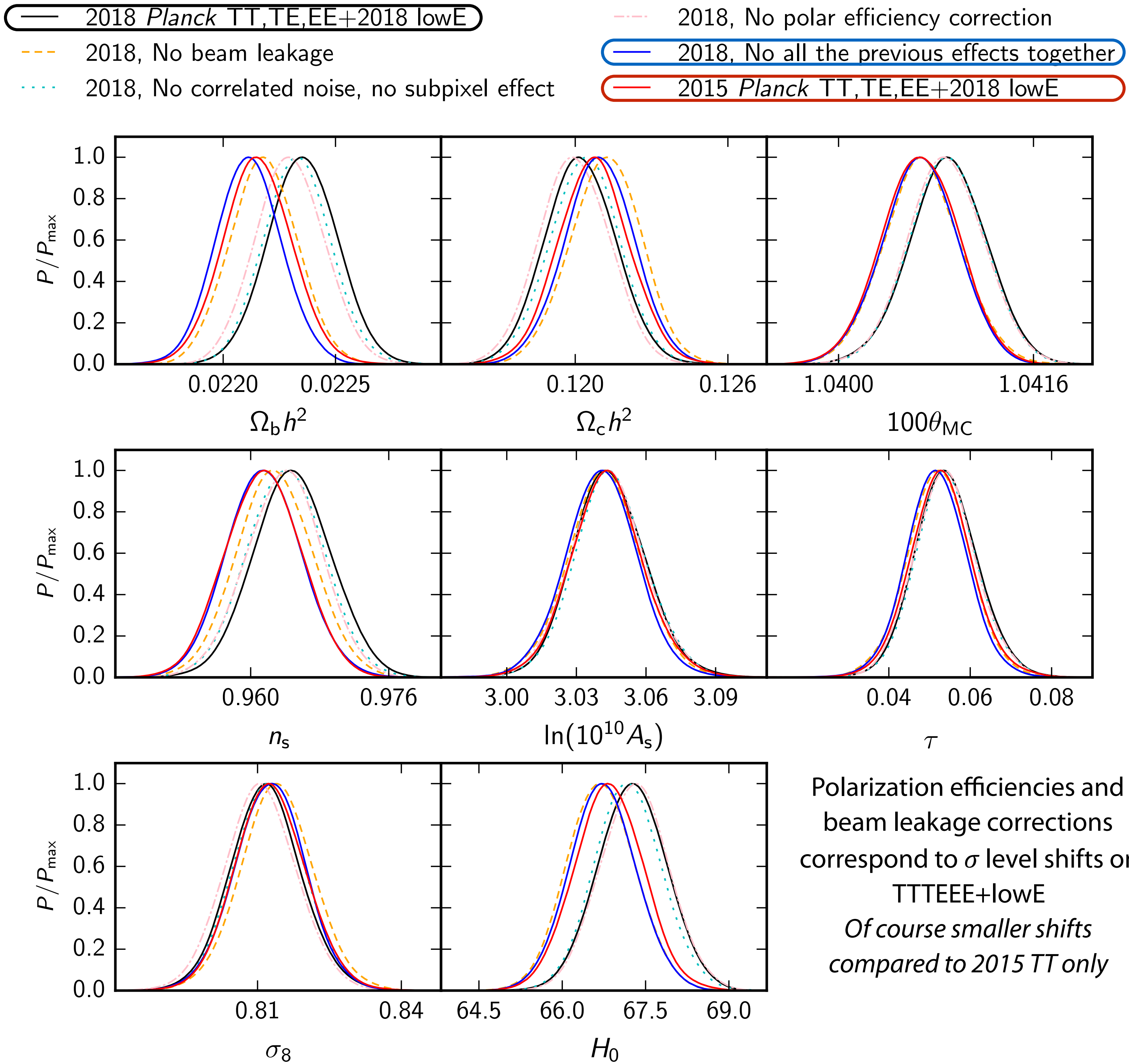
Frequency [GHz]	*EE* first peaks SMICA %	Cosmology driven Camspec %	Cosmology driven Plik %	Combined residuals %
100	+2.4 ± 0.5	+1.3 ± 0.5	+1.0 ± 0.5	+0.7 ± 1.0
143	Ref.	−1.6 ± 0.5	−1.7 ± 0.5	−1.7 ± 1.0
217	+3.6 ± 0.5	+2.5 ± 0.5	+2.0 ± 0.5	+1.9 ± 1.0

$\Delta\chi^2$ ~ 50 on EE, $\Delta\chi^2$ <1 in TE
Improves interfrequency agreement in EE





Planck EE+lowE+BAO
Planck TE+lowE
Planck TT+lowE
Planck TT,TE,EE+lowE
H_0
Ω_m
σ_8
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
τ
n_s
$\ln(10^{10} A_s)$

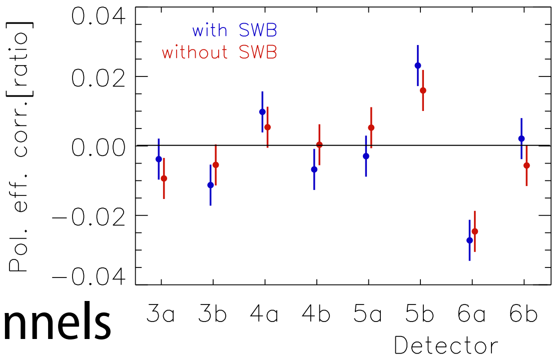


Polarization efficiencies and beam leakage corrections correspond to σ level shifts on TTTEEE+lowE

Of course smaller shifts compared to 2015 TT only

Polarization efficiency corrections

$$d(\mathbf{r},\alpha) = B(\mathbf{r}) \otimes [T(\mathbf{r}) + \rho(Q(\mathbf{r})\cos 2\alpha + U(\mathbf{r})\sin 2\alpha)]$$



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Frequency [GHz]	*EE* first peaks SMICA %	Cosmology driven Camspec %	Cosmology driven Plik % (Baseline)	Combined residuals %
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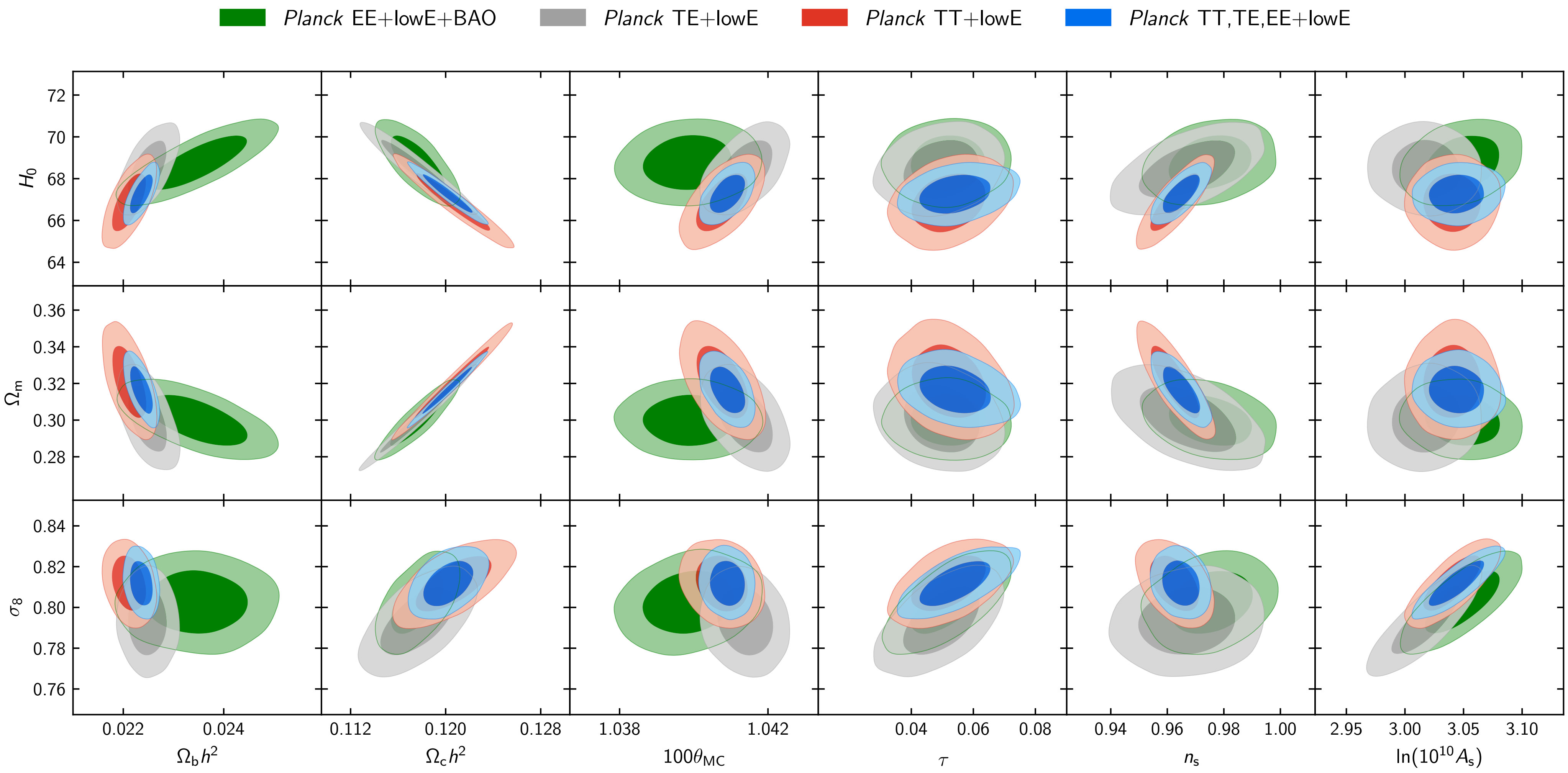
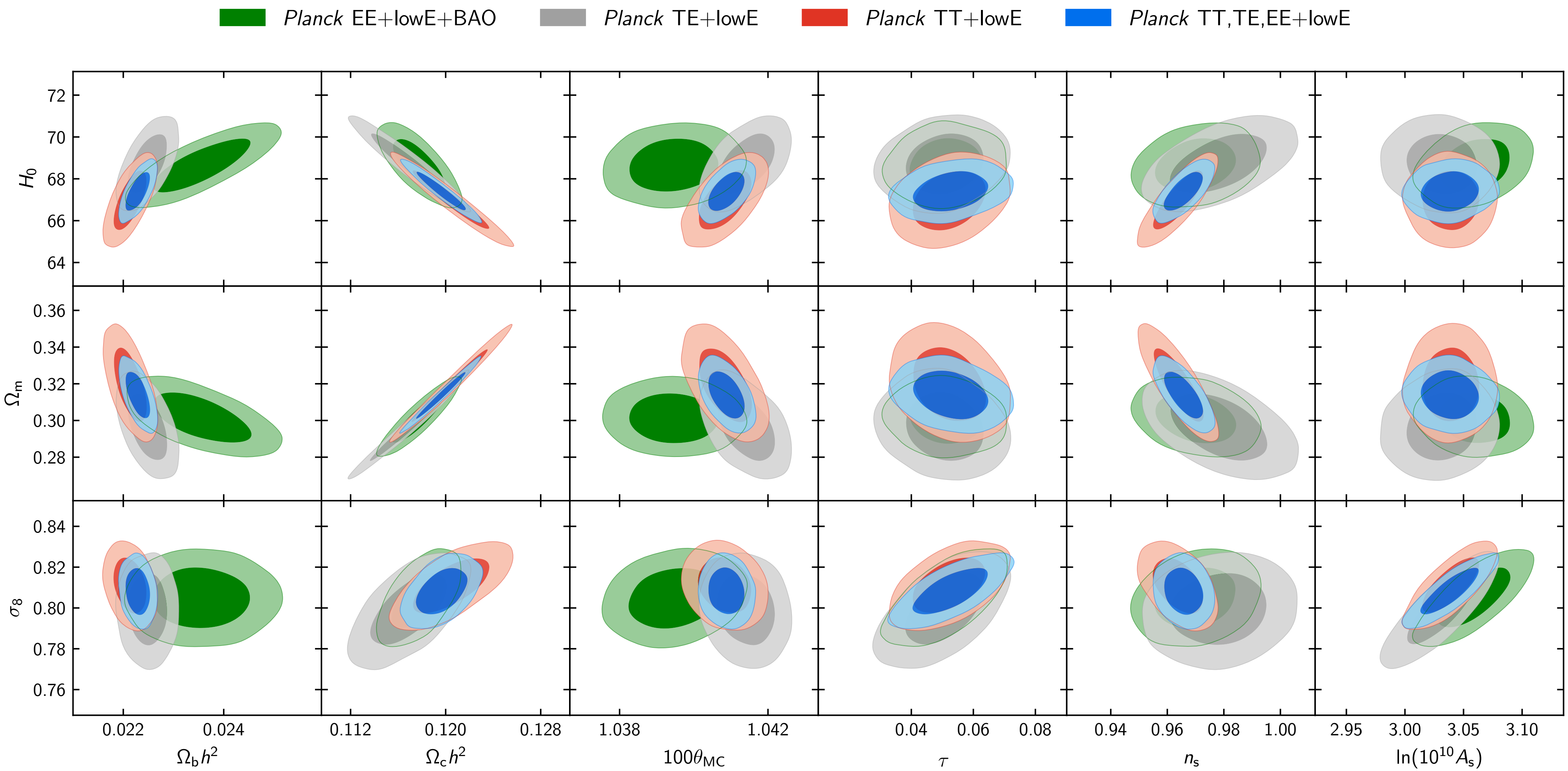
217	+3.6 ± 0.5	+2.5 ± 0.5	+2.0 ± 0.5	+1.9 ± 1.0

$\Delta\chi^2 \sim 50$ on EE, $\Delta\chi^2 < 1$ in TE
Improves interfrequency agreement in EE

- Assuming different ***effective*** polarization efficiency correction in TE and EE
  - *@143GHz, TE correction differs by 2σ (compatible with 1). $\Delta\chi^2 = 10$.*
  - *Parameters shifts by ~0.5σ (TTTEEE)*
- Effect of *spectrum-based* polarization efficiency correction explored in alternative likelihood

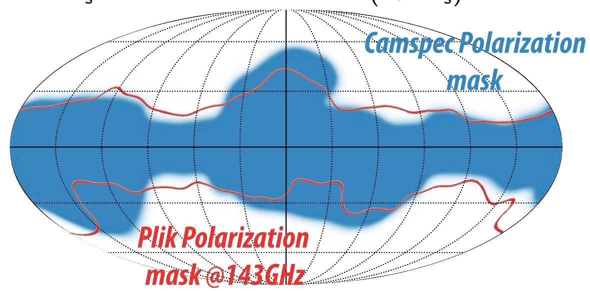


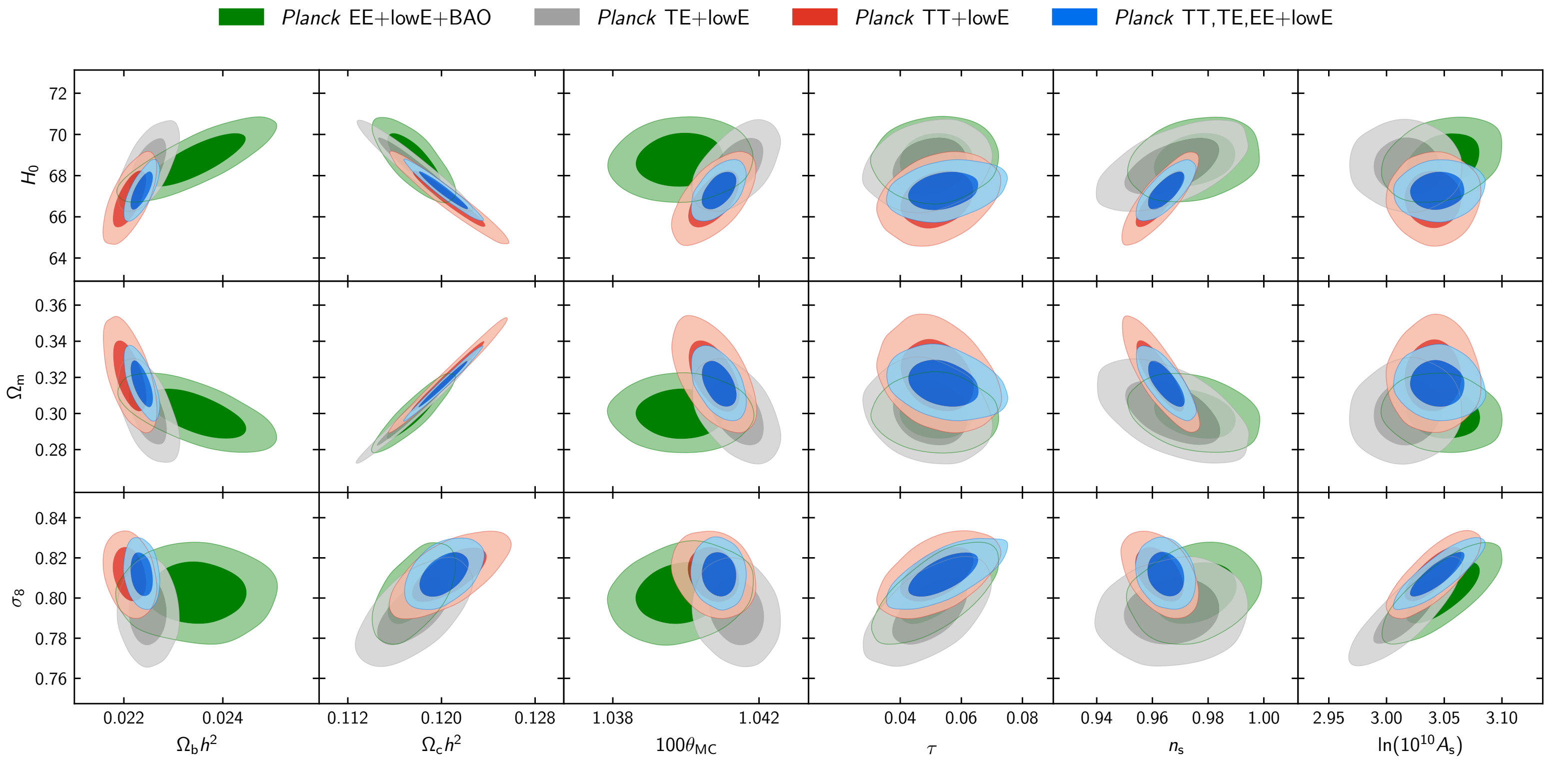
Plik - Baseline



Camspec - Alternative

Spectrum based polarisation efficiency correction
Different polarisation mask



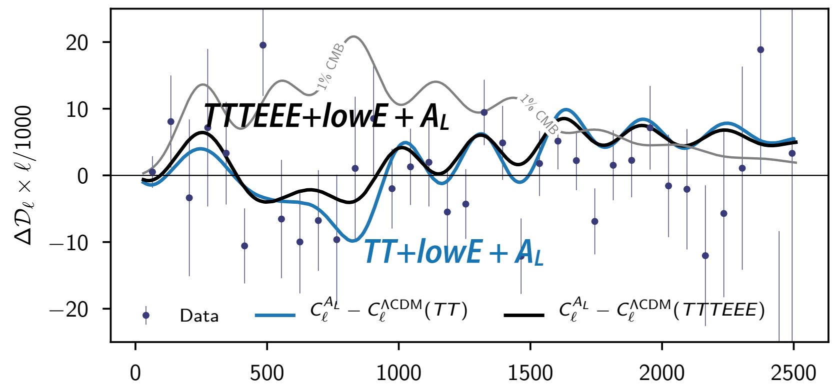


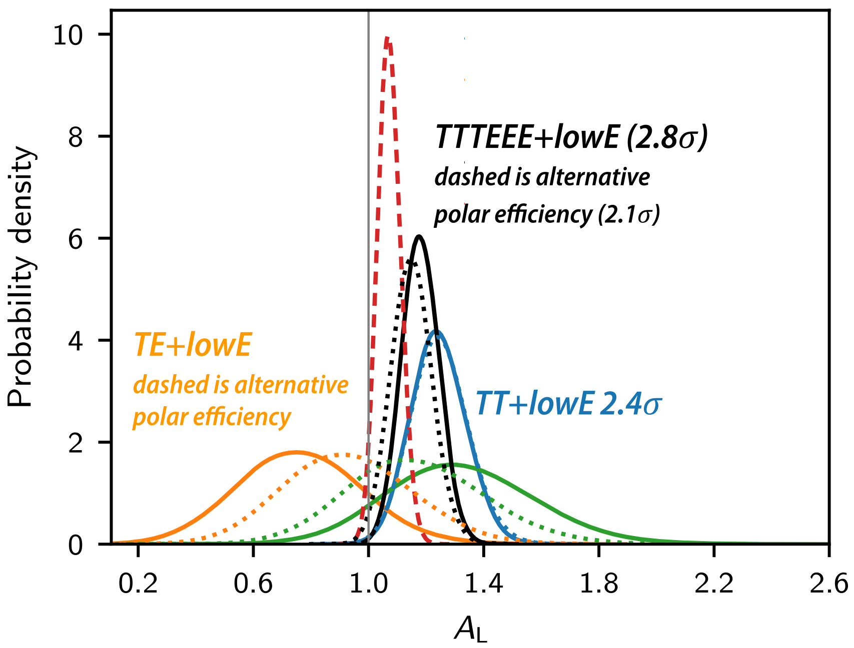
Parameter	`Plik` best fit	`Plik` [1]	`CamSpec` [2]	$([2]-[1])/\sigma_1$
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1
$\ln(10^{10}A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2
		Baseline		

Exploration of alternative data selection *(polarization mask)*, **methodology and calibration** *(polarization efficiency correction)* **result in <0.5σ shifts**

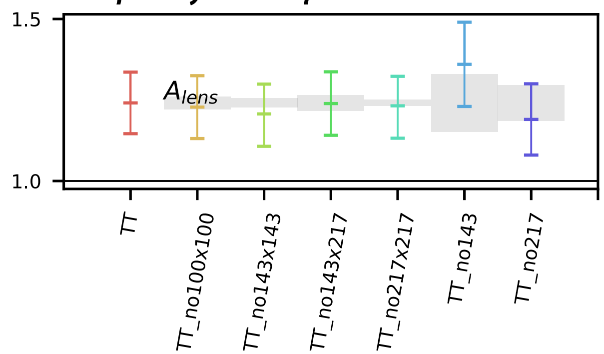
Persistance of *curiosities*

Residual to ΛCDM best fit TTTEEE





Frequency/cross spectrum removal test



- C_l^{TT}, l>800 compatible with extra smoothing of the peaks and degenerate with extra lensing
  - A_L=1.18±0.065 (2.8σ) TTTEEE+lowE
  - A_L=1.15±0.072 (2.1σ) TTTEEE+lowE (alternative Polar Efficiency)
  - ***A_L=1.243±0.096 (2.4σ) TT+lowE*** *(baseline and alternative)*
- ***TT effect is common to all frequencies***
  - Increased by low-l TT lack of power
  - Degenerate with FG
- Cannot be explained by
  - *Calibration*
  - *Aberration*
  - *Residual transfer function*
  - *4K lines*
  - *l=1460 dip*
  - *Correlated noise*

A solid legacy release

- ***We have improved all parts of the data analysis and hybrid approximation***
  - Extra products for more validation
- ***HFI polarization can now be used for cosmology at all scales***
  - tighter constraints, in particular for tau
- Limitations
  - 2σ discrepancies in the polar efficiency correction models and 0.5σ level corresponding shifts in parameters (TE)
  - ***Agreement within 0.5σ on ΛCDM between different calibration models!***
  - Alens, l>800 l<800, driven by TT and not going away
- *Paper and code release later this year*