Planck systematics

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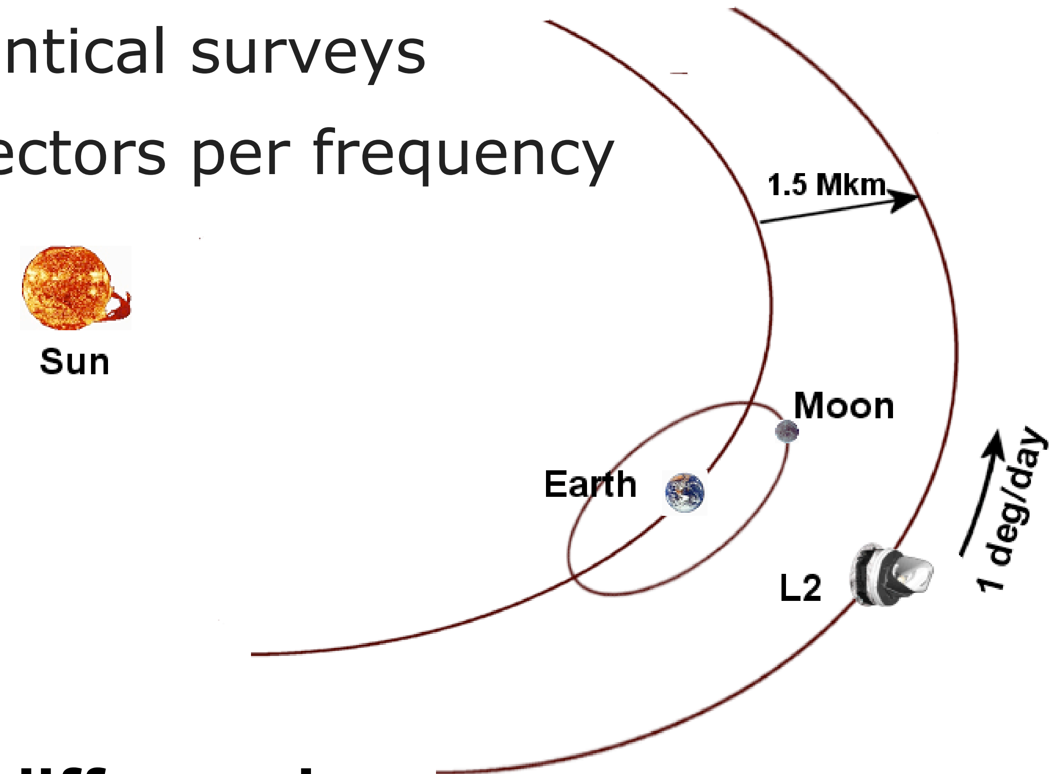
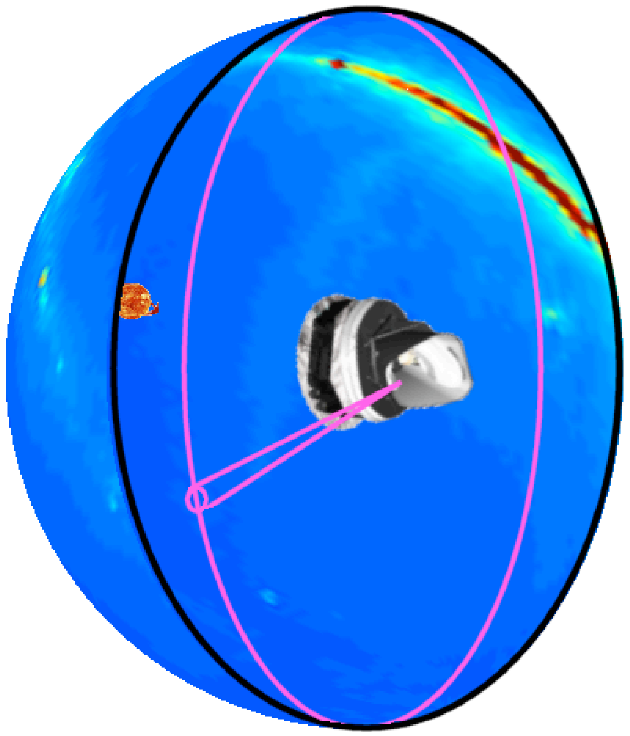
Polarisation measurement

- **we need different angles to measure I,Q,U**

$$m_t = I(\vec{n}) + \rho\Big[Q(\vec{n}).cos(2\psi) + U(\vec{n}).sin(2\psi)\Big]$$

- **Planck scanning strategy is such that we have**
  - one orientation of the focal plane / sky pixel / survey
  - 2 pairs of identical surveys
  - 10 to 12 detectors per frequency





- **pair- and time- differencing**
  we combine detectors at 90deg at different time of observation
  - need to have very precise inter-calibration to avoid I,Q,U mixing
  - Intensity signal is ~100 to 1000 times larger than polarisation

PLANCK time-domain systematics

[Planck 2015 results. VIII]

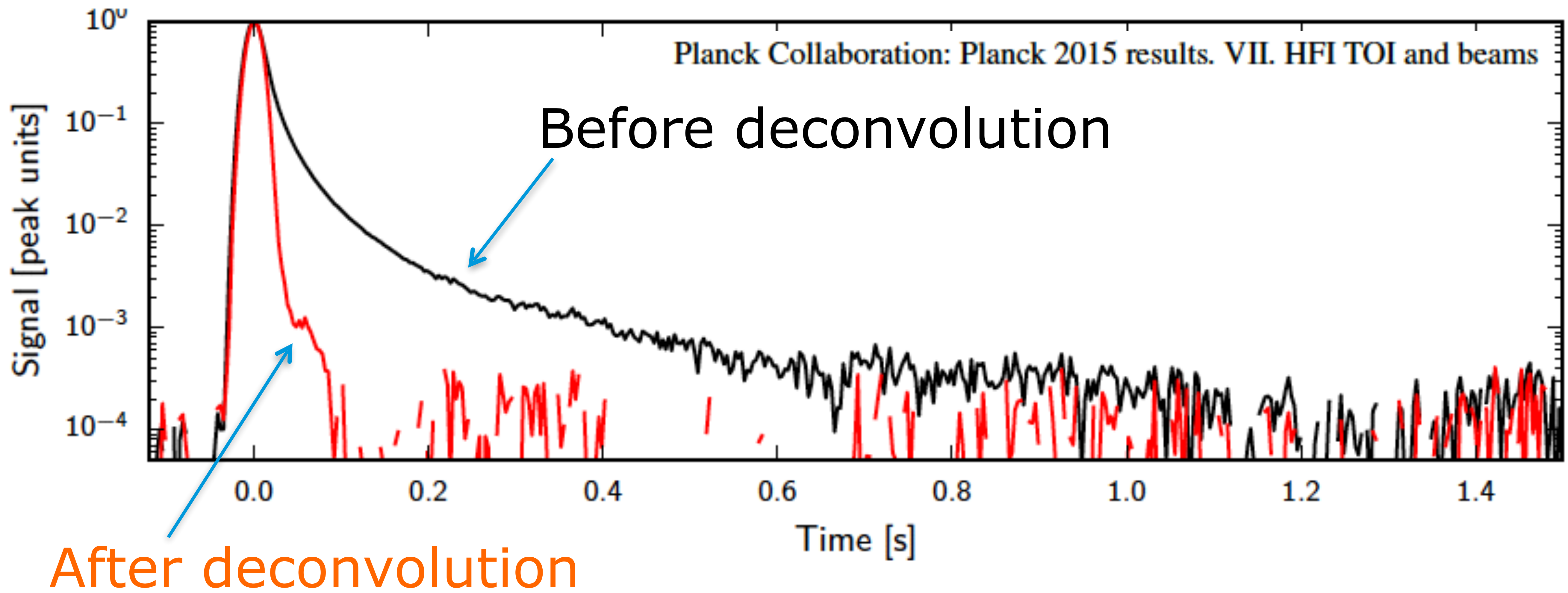
- **detector time response (very long time constants)**
  - seen at map level but not on Jupiter nor glitches
    -> use empirical model
  - impact glitch removal

- **ADC non linearity**

- **4K cooler pick-up**
  - electromagnetic and microphonic interference from the 4K-cooler reaches the readout boxes and wires in the warm service module of the spacecraft and appears in the Planck data as a set of very narrow lines at multiples of 10Hz and at 17Hz
  - correlated with ADC non-linearity

Time response deconvolution
Jupiter crossing

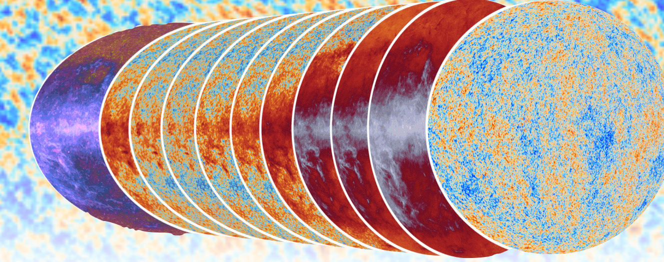
Brendan Crill, B-mode from Space workshop, Dec 14, 2015



Time response function is modeled in Fourier space as a sum of 5-8 lowpass filters time constants vary from 1ms – 1.5s +electronics transfer function

$$F(\omega) = \sum_{i=1,5} \frac{a_i}{1 + i\omega\tau_i}.$$

PLANCK map-making systematics



[Planck 2015 results. VIII]

before projection of several detectors on maps, need to remove

- **instrumental systematic effects**
  - 1/f noise
  - ADC non-linearity corrections
  - gain coefficients (absolute and possibly time-dependent)
  - time constant residuals

- **sky signal not constant in time**
  - zodiacal light
  - orbital dipole (reference for calibration)
  - Far SideLobes

- **sky signal not common to all detectors within a channel**
  - foreground emissions mismatch due to different bandpass
  - Far SideLobes

PLANCK map-making

[Planck 2015 results. VIII]

- **we include templates of systematics in the map-making**

$$d_t = g\left(\mathbf{A}S + \sum_i \mathbf{\Gamma}^{(\mathbf{i})} T^{(i)}\right) + n_t$$
$$= g\,[\mathbf{A}, \mathbf{\Gamma}] \begin{bmatrix} S \\ T \end{bmatrix} + n_t$$

- **different domains:**
  - time domain (t) / ring domain (r) / pixel domain (p)

- **In practice:**

$$d_t = \mathbf{g_r}\left(\mathbf{I_p} + \rho \mathbf{Q_p} cos2\phi_t + \rho \mathbf{U_p} sin2\phi_t + D_t + \sum \mathbf{f_i} T_p^{(fg)_i} + \sum \mathbf{c_i} T_t^{(TF)_i}\right) + \mathbf{o_r} + n_t$$

$\rightarrow$

g **gains non-linear system → gain linearization**
I,Q,U **sky signal**
f **bandpass mismatch coefficients**
c **transfer function residual coefficients**
o **1/f offsets**

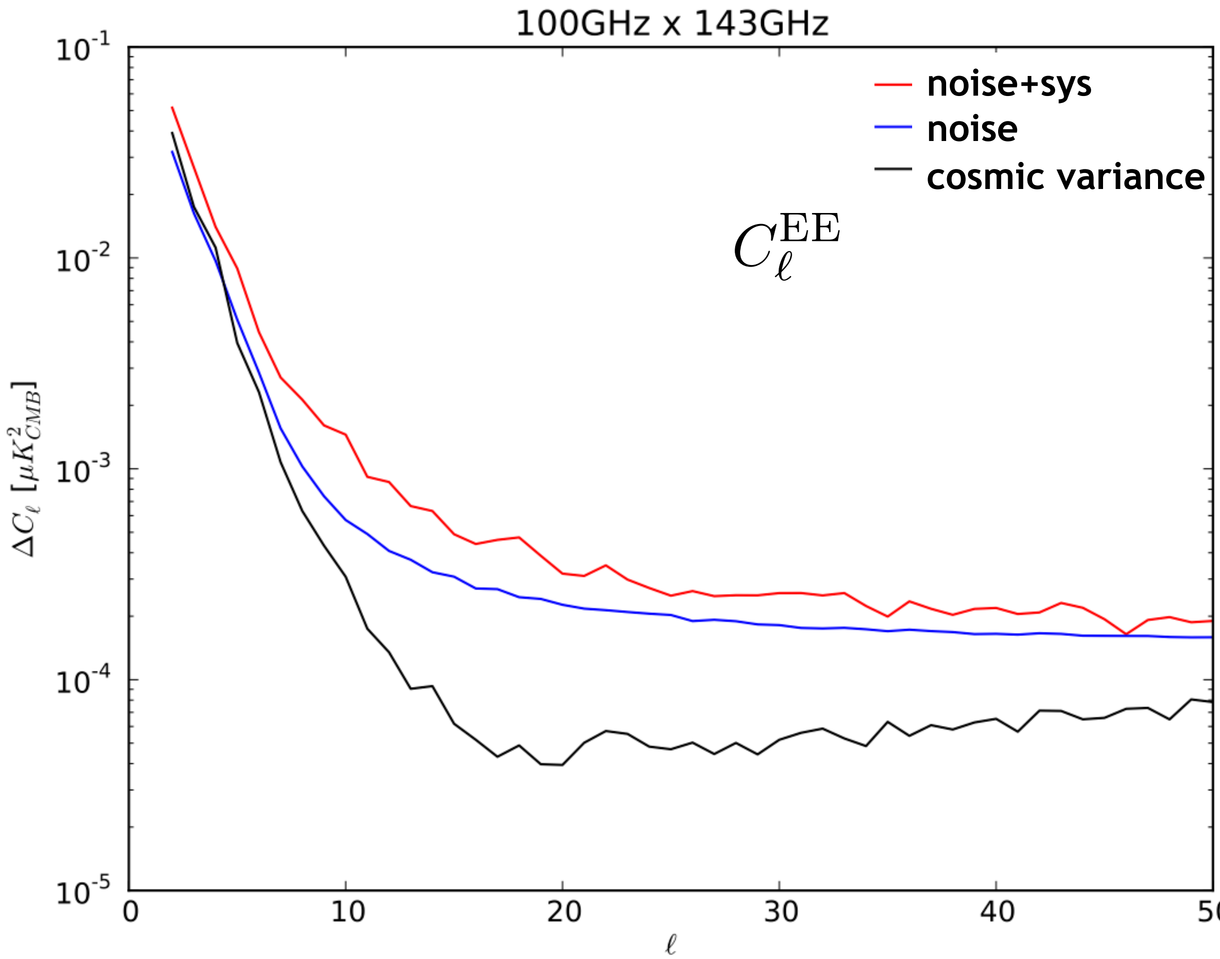
PLANCK polarization systematics
at low-ℓ

[Planck intermediate results. XLVII (2016)]

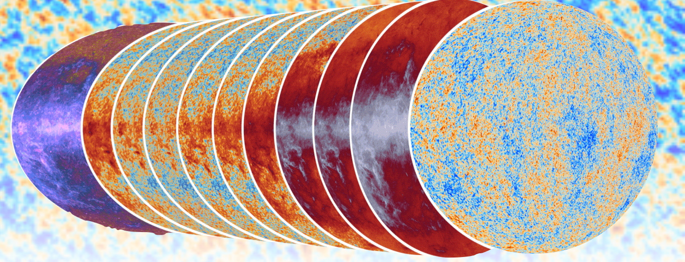
- **Instrumental systematics**
  - 1/f noise residuals
  - glitches (increase the 1/f)
  - inter-calibration leakage
  - time-constant residuals
  - ADC non-linearity residuals
- **Foreground systematics**
  - cleaning residuals
- **Need for simulations !**
- **PLANCK 100 E2E simulations**
  - **no bias** on 100x143
  - error budget extended by a factor ~**1.5 due to systematics** uncertainties

those residuals are in $\ell^{-\alpha}$

but not directly correlated between frequencies



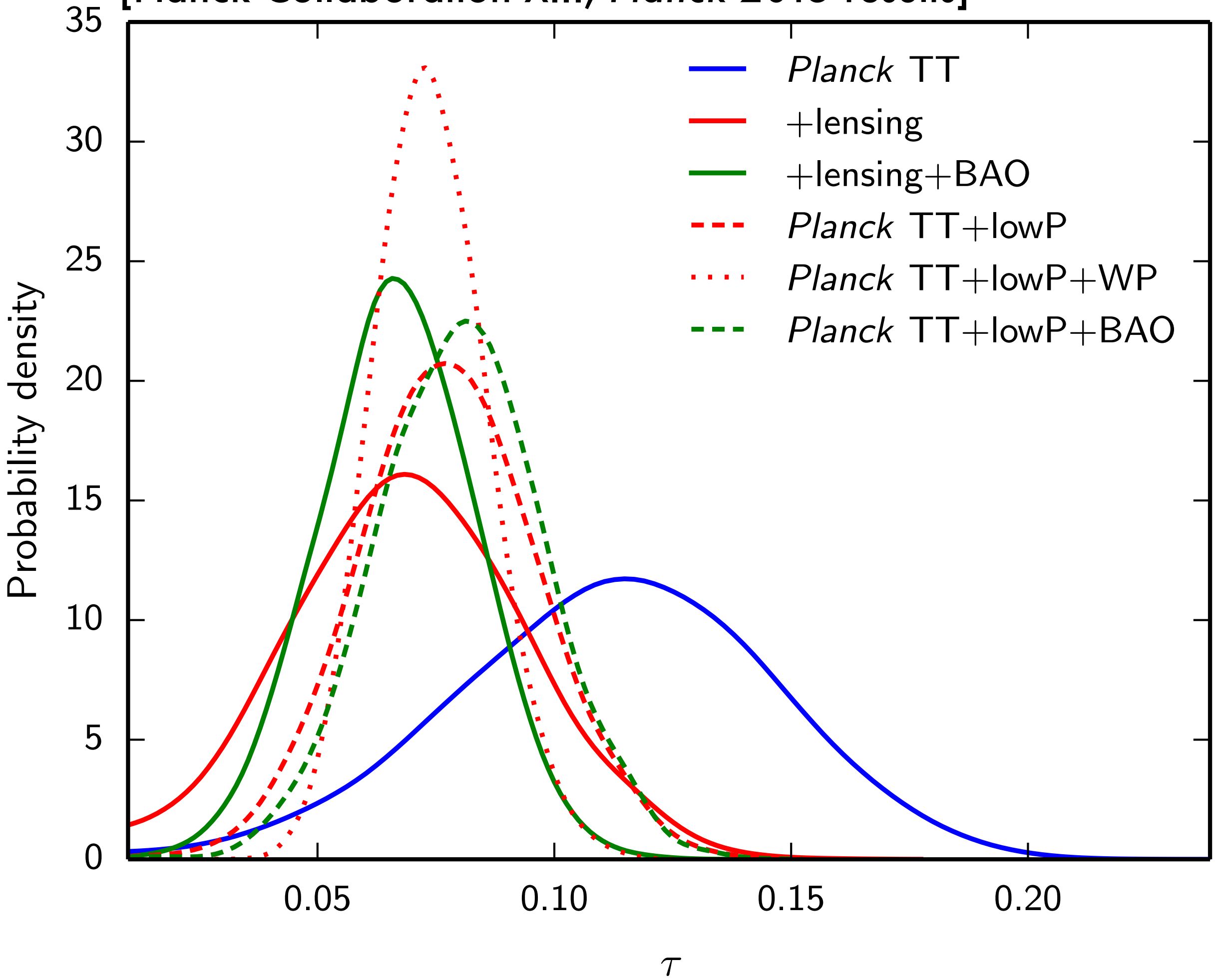
reionization optical depth (history)



[Planck intermediate results. XLVII (2016)]

From CMB data:

[Planck Collaboration XIII, *Planck* 2015 results]



1. **WMAP 9yr**
   - τ = 0.089 ± 0.014
2. **Planck 2013**
   - τ = 0.089 ± 0.014 (TT with WMAP Polar)
   - τ = 0.075 ± 0.013 (TT with WP&Planck dust)
3. **Planck 2015**
   - τ = 0.078 ± 0.019 (TT + lowP)
   - τ = 0.066 ± 0.016 (TT + lowP + lensing)
   - τ = 0.067 ± 0.016 (TT + lensing + BAO)
4. **Planck HFI EE low-ℓ**
   - τ = 0.058 ± 0.012 (TT + **lowHFI**)
     (lollipop)

$$\tau = \mathbf{0.058 \pm 0.012} \begin{pmatrix} \pm\, 0.009\ (\mathrm{stat}) \\ \pm\, 0.003\ (\mathrm{sys}) \end{pmatrix}$$

PLANCK major systematics
at high-ℓ

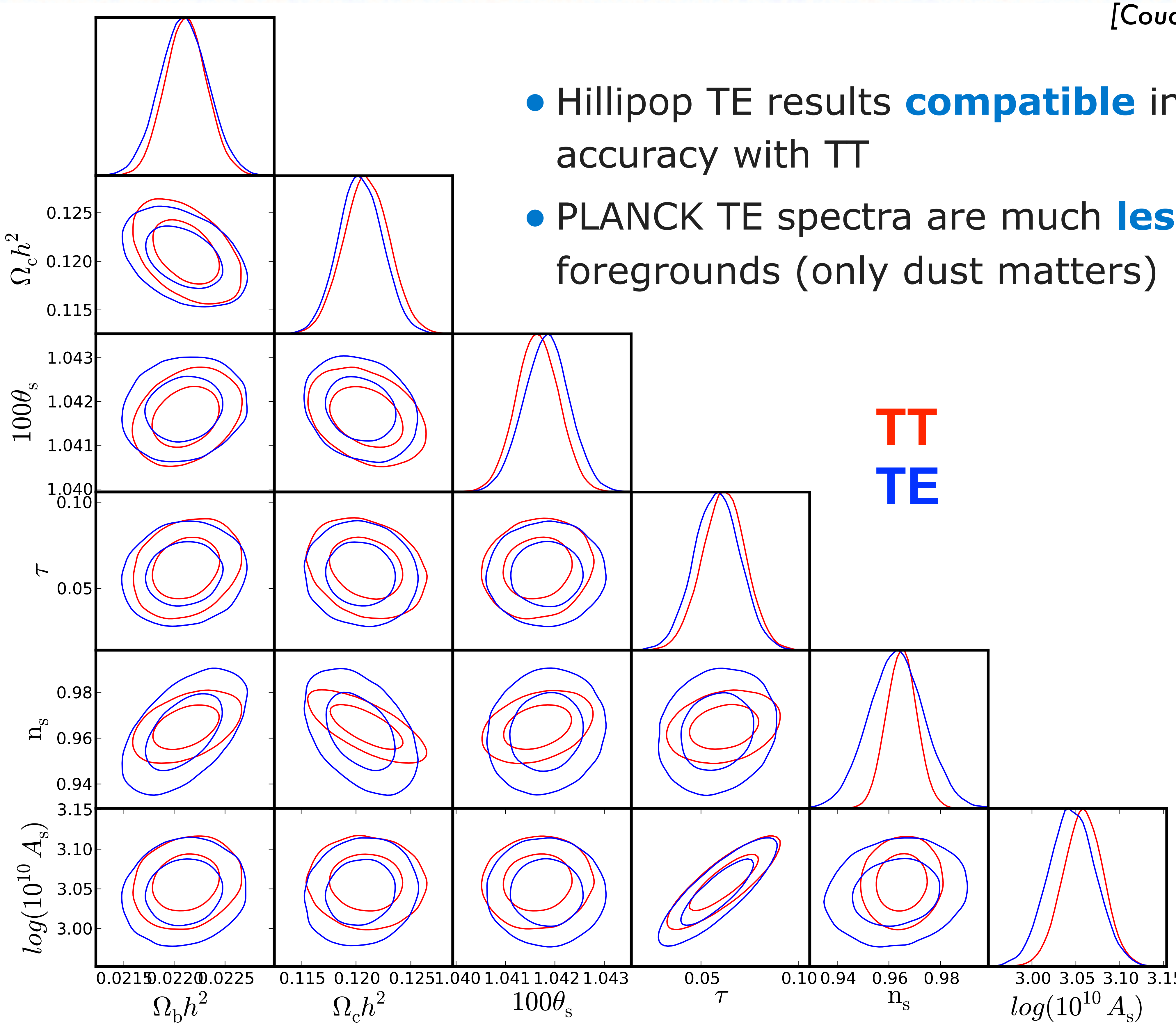
- **Instrumental systematics**
  - beam leakage due to beam mismatch
  - calibration uncertainty
  - cosmic rays inducing correlated noise

- **Foregrounds systematics**
  - impact of free parameters in likelihood
  - impact of the choice of the foreground modeling

- **Need for simulations !**
  - hard to perform because lack of knowledge on the physical processes of the foregrounds
  - PLANCK made extensive use of **jack-knives**
  - comparison with different foreground modelings or different data set (TE)

likelihood TE: temperature-polarisation

[Couchot et al. A&A 602 A41 (2017)]



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

TT
TE

Cosmology with the CMB (& systematics)

- **major Planck systematic residuals**
  - ADC non-linearity (affecting inter-calibration and inducing E-B leakage)
  - residual long-time constant
  - unidentified cross-correlation noise affecting TE auto-power spectra

- **the major consequence is that systematics are becoming no longer negligible in the error budget**
  - as a consequence, we need massive Monte Carlo to
    - check for biases
    - propagate properly the uncertainties
  - this has been underestimated in PLANCK

- **This is difficult**
  - because of the lack of current knowledge on the Galactic emissions (emission law with frequency are not measured with enough accuracy and difficult to simulate)
  - massive amount of data available

- **This can make some differences especially for extension on ΛCDM models**