# The polarization of the CMB with Planck

## and the reionization of the universe


***Graca Rocha***

JPL, Caltech

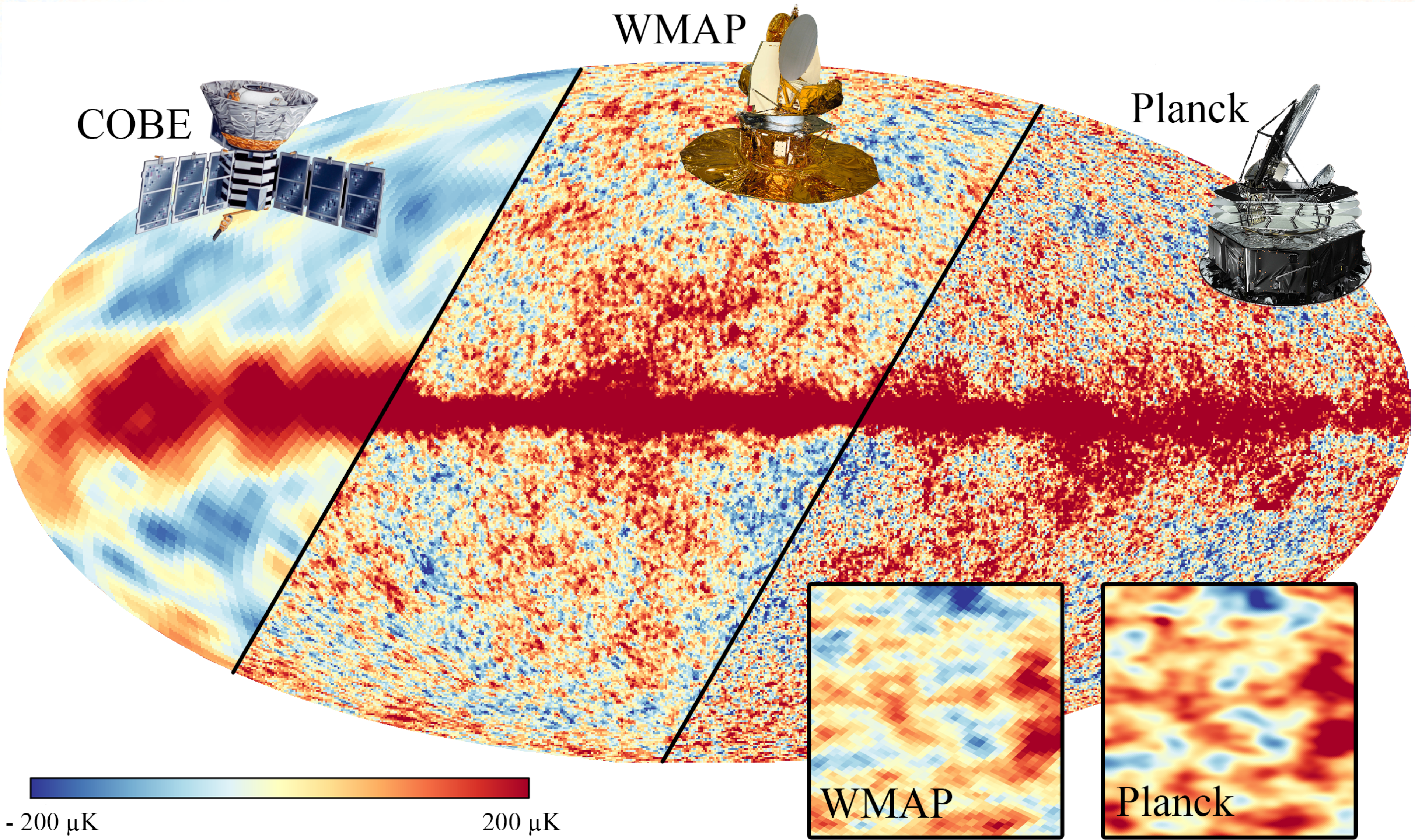
For the *Planck* team


18th July 2017

Nordita, July 2017

**2015 was the *Jubilaeus Annus* for the discovery of the Cosmic Microwave Background.**

We have been enormously privileged to have seen the success of 3 satellite missions and a number of remarkable suborbital experiments dedicated to exploration of the CMB sky.

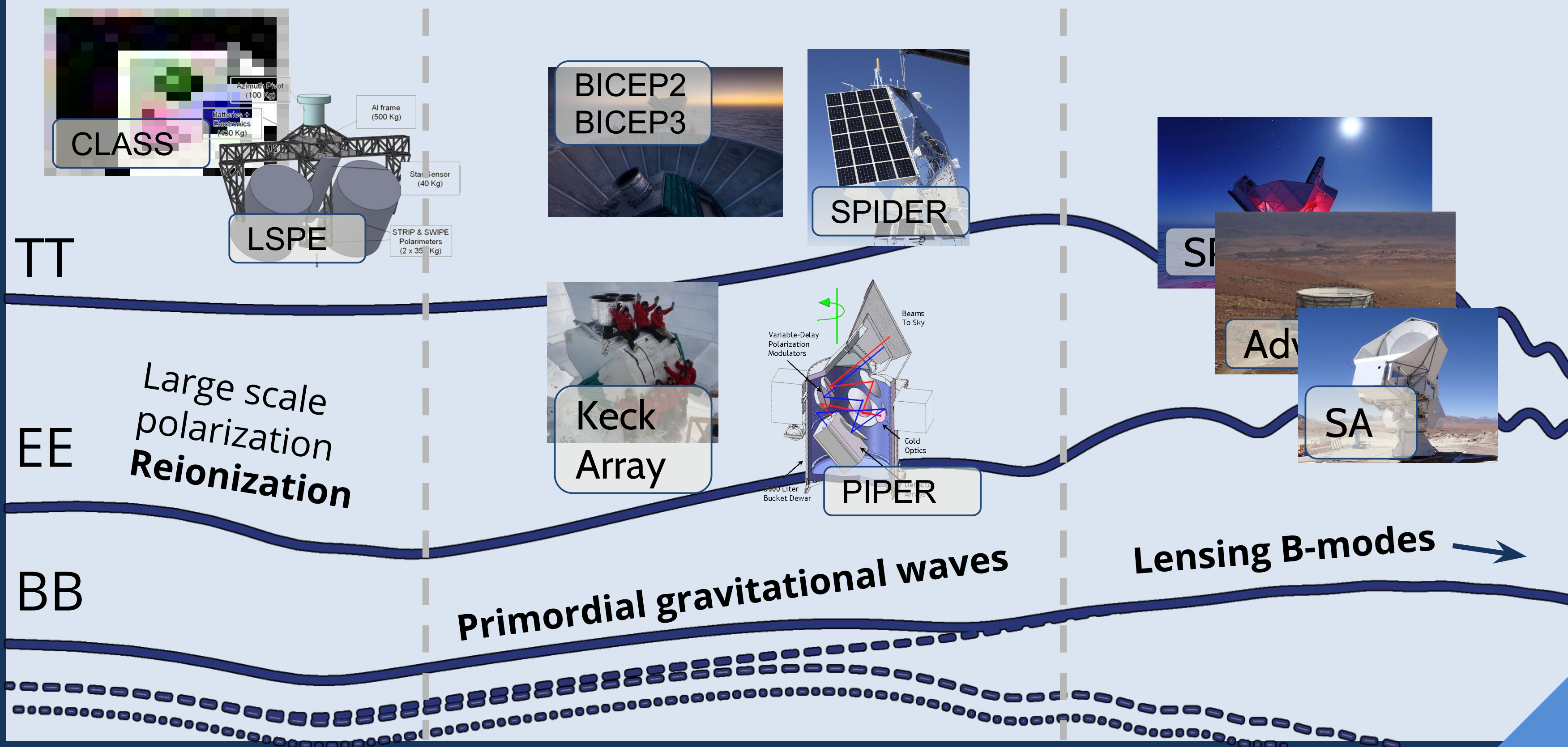


# The observational challenge

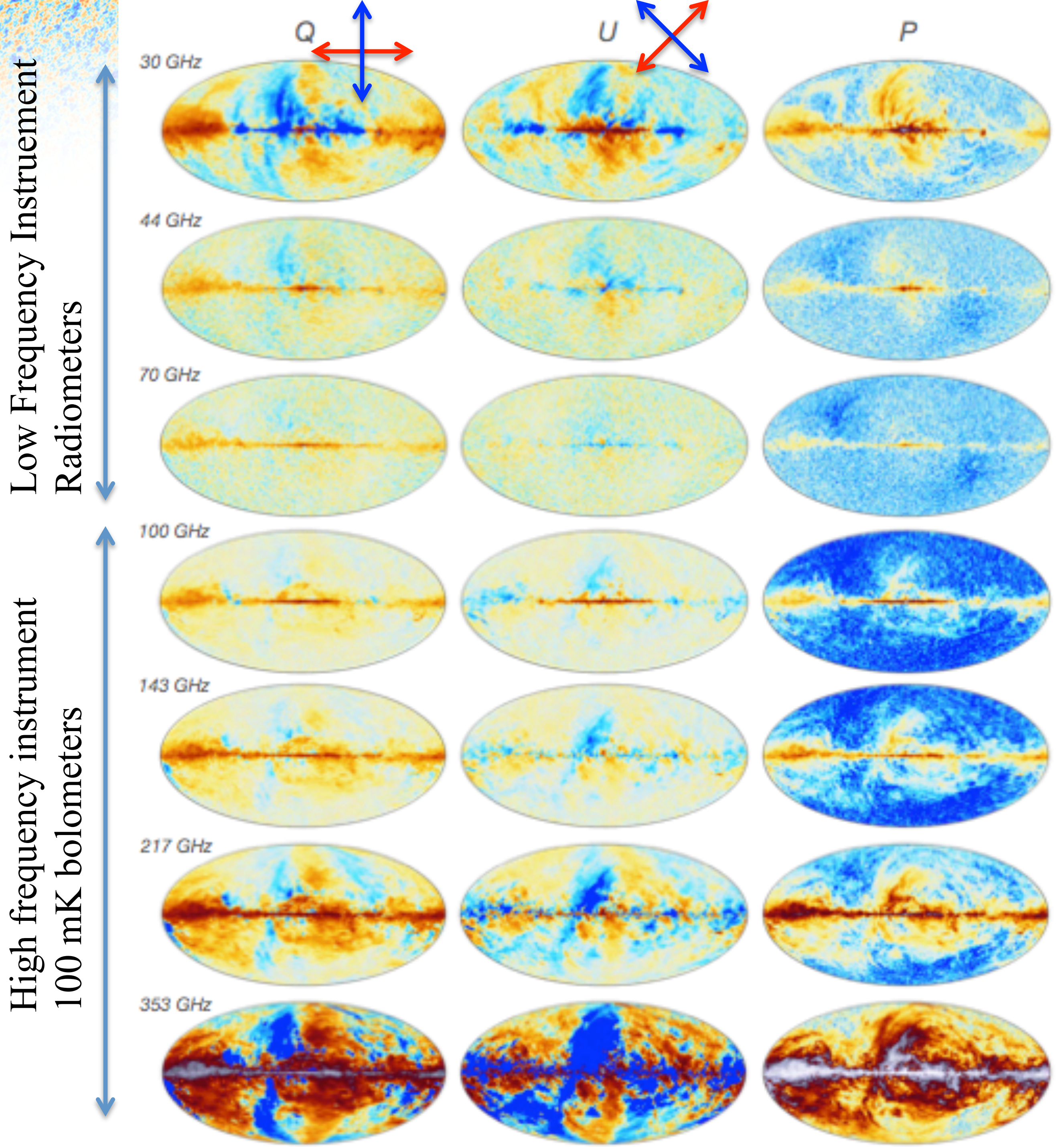
From Jon’s talk

To clearly separate a primordial signal from more local sources we must

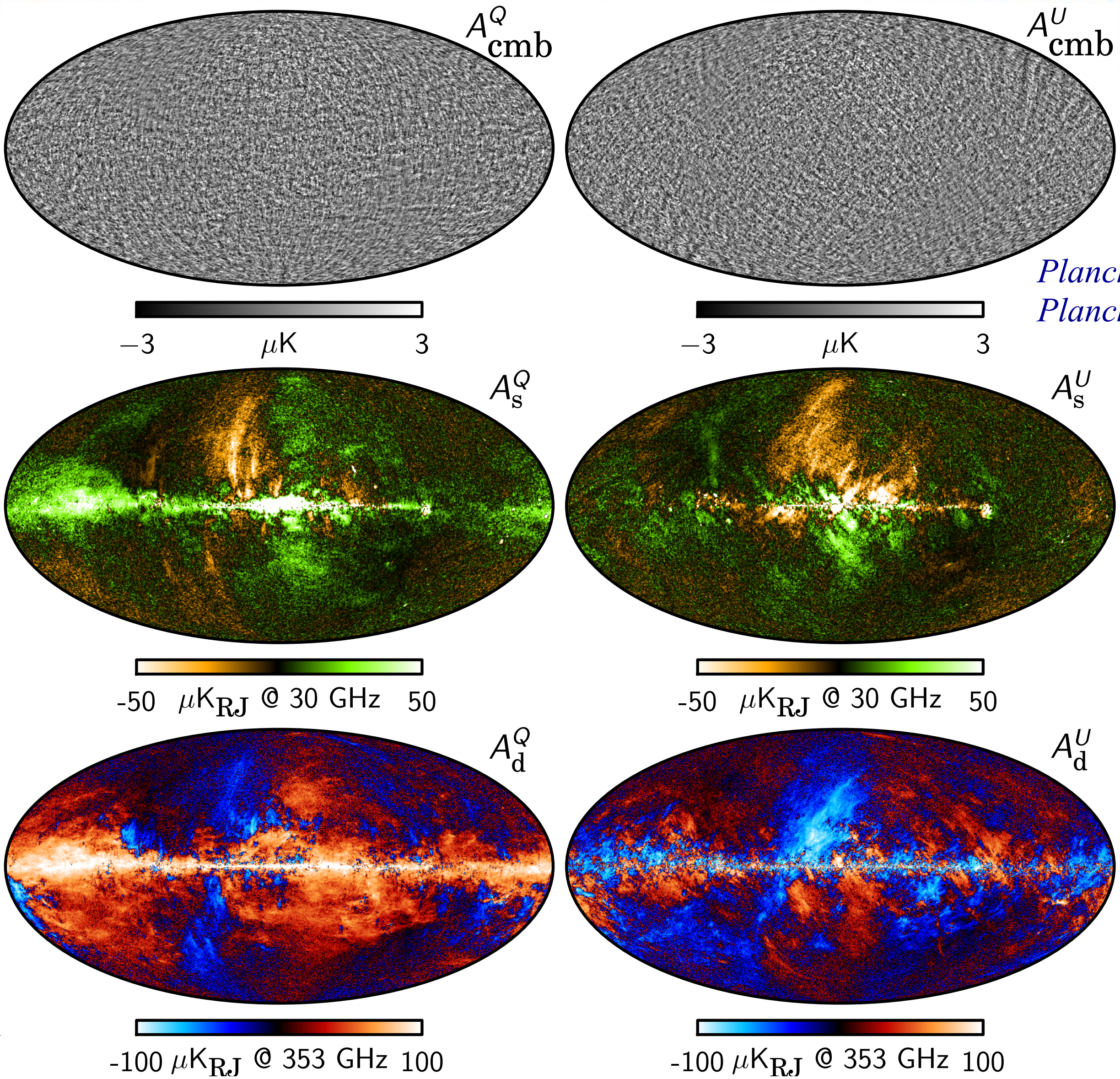
Constrain spectral energy distribution — Verify statistical isotropy — **Probe all angular scales**



**Planck 2015**
**full sky maps of**
**linear polarization**

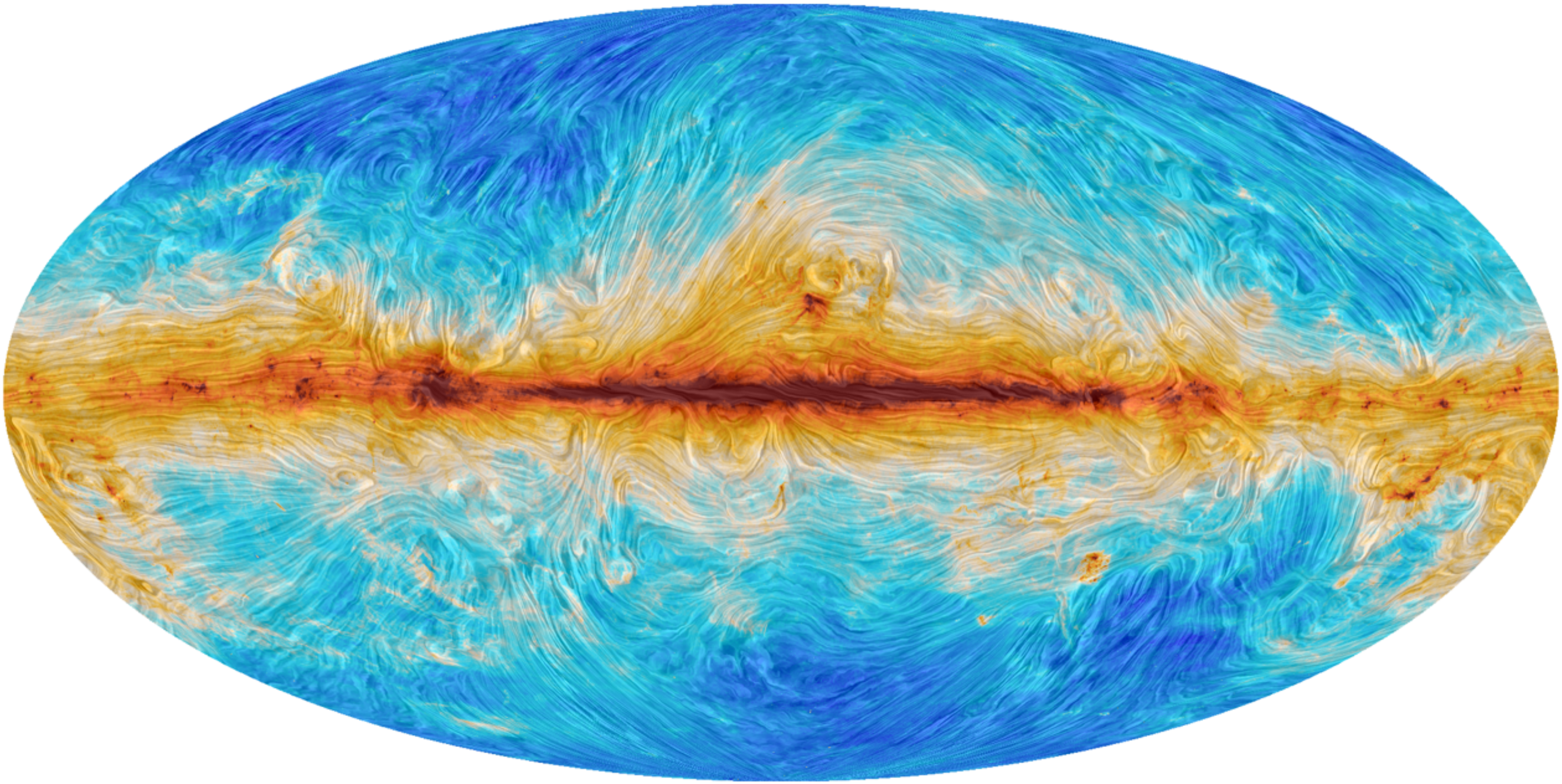


# CMB and Foreground Stokes $Q, U$ Maps

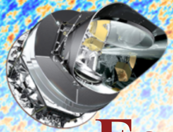



*Planck Collaboration X 2015*
*Planck Collaboration IX 2015*

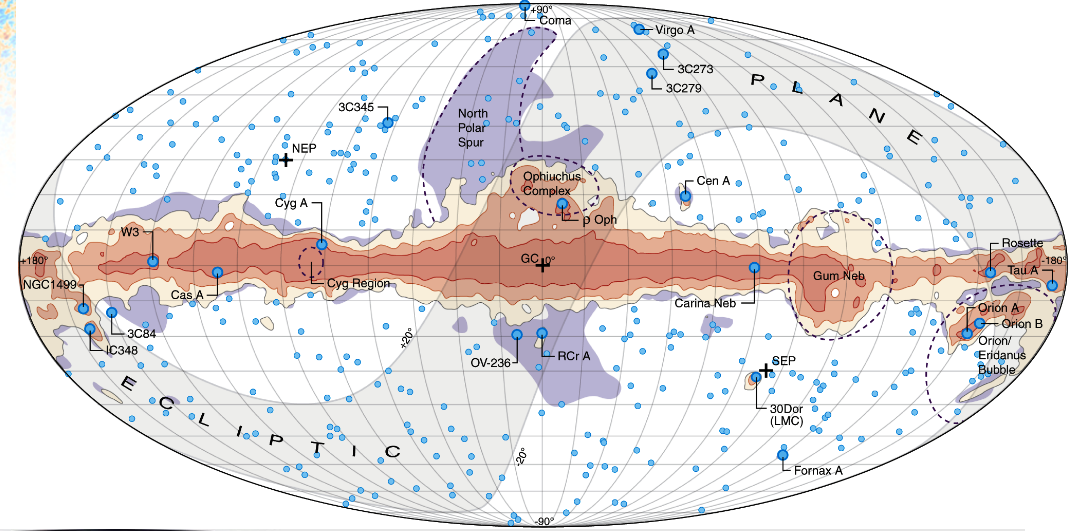
# Dust Temperature and Polarization at 353 GHz

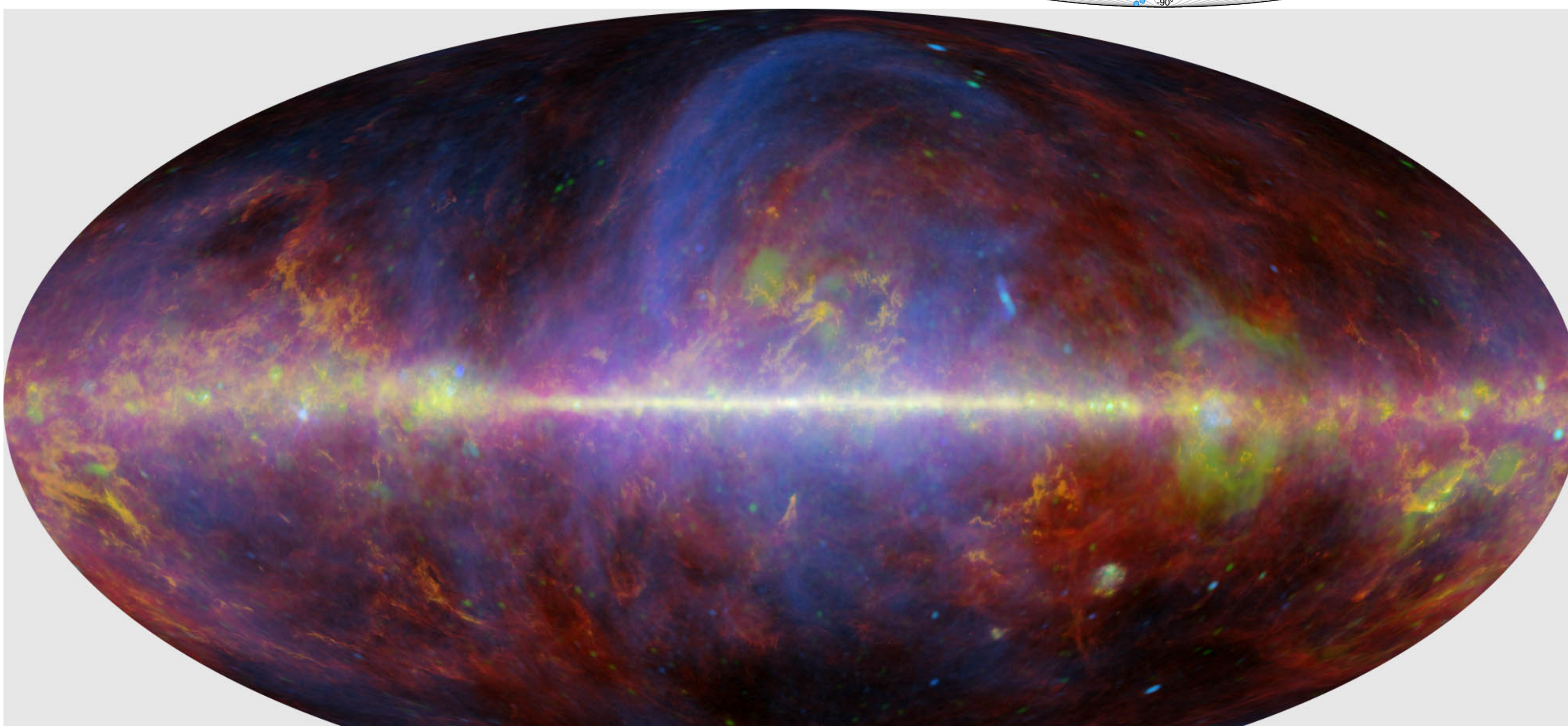


Total intensity encoded in colours
Polarization encoded in shaded striations.
Polarization orientation is at $90^\circ$ from the striations, which indicate the direction of the magnetic field projected on the sky.



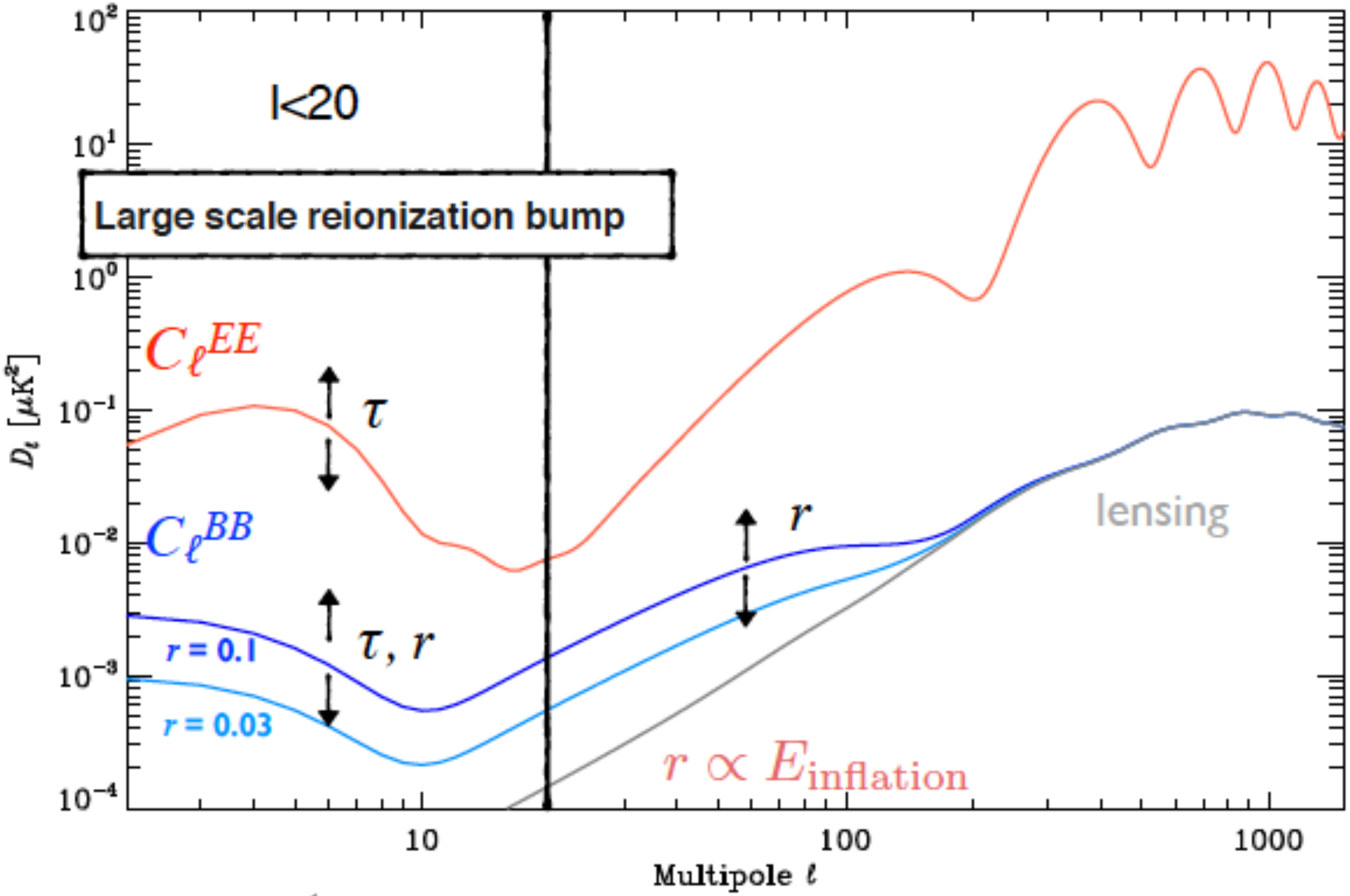
# Four Color Composite Image of the Foreground Sky



Blue—synchrotron; Green—free-free; Yellow—CO; Red—thermal dust

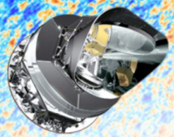
# Large-scale CMB polarization




A. Mangilli

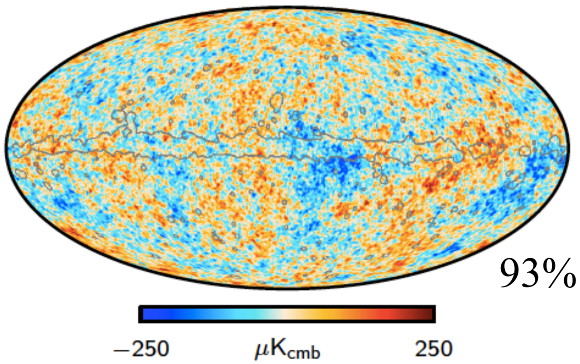
$$\tau(z) = \int_{t(z)}^{t_0} n_e \sigma_T \, c \mathrm{d}t',$$

Small signal confined to low multipoles =>
accurate control of instrumental systematics and
Polarised foreground emission.



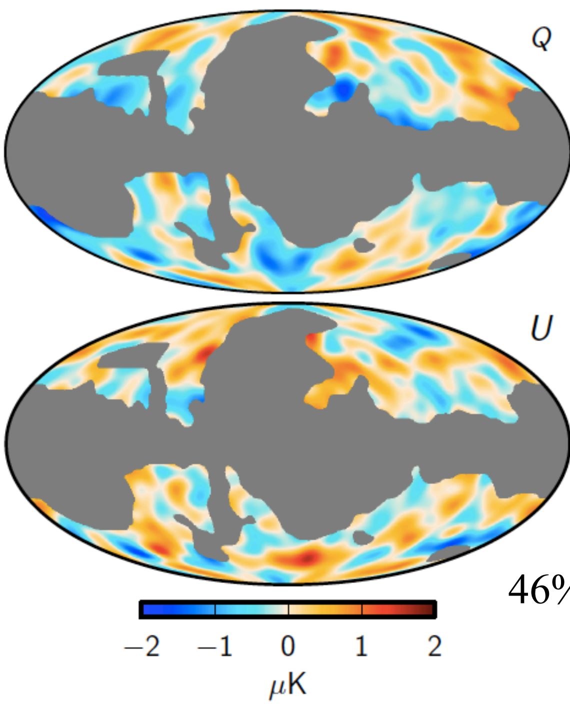
# Measuring the Optical depth of reionized universe (τ) with the CMB – Planck 2015

**Commander T map**




93% sky fraction

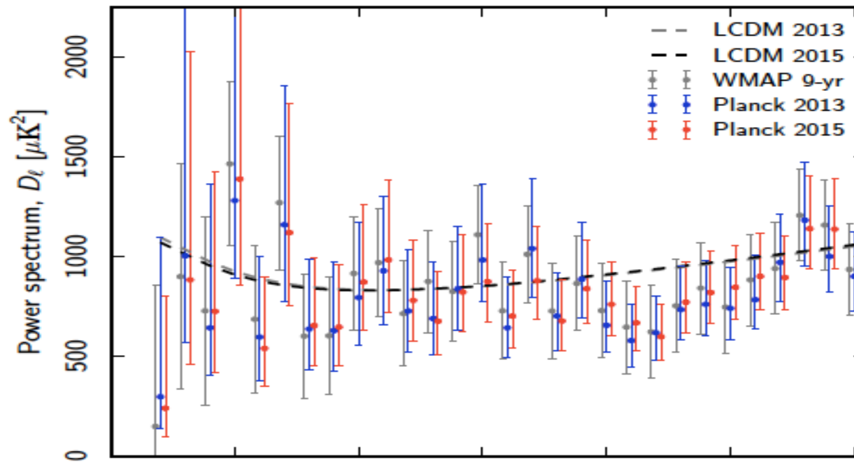
**70GHz pol. Foreground cleaned with 30GHz and 353GHz**



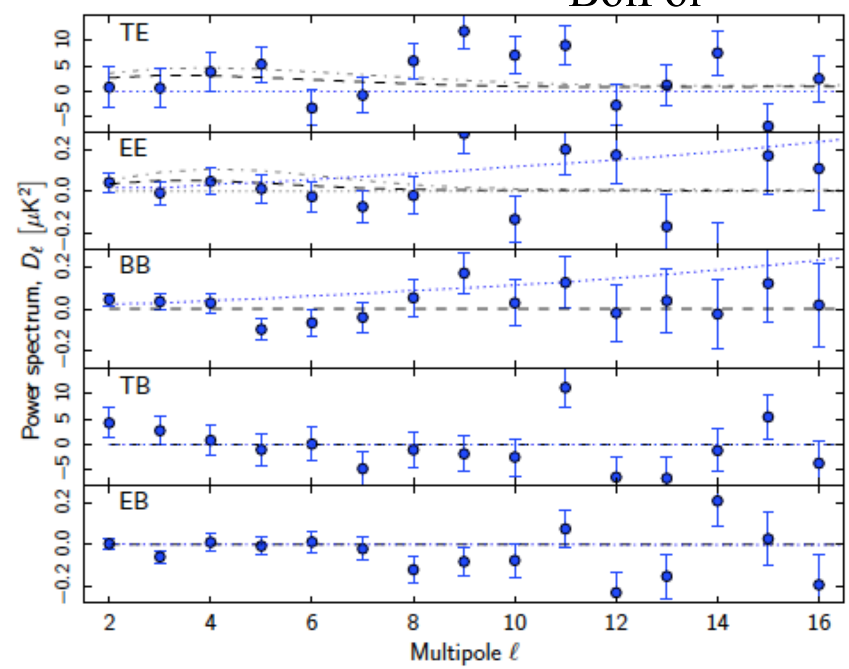

46% sky fraction

*No*

BR



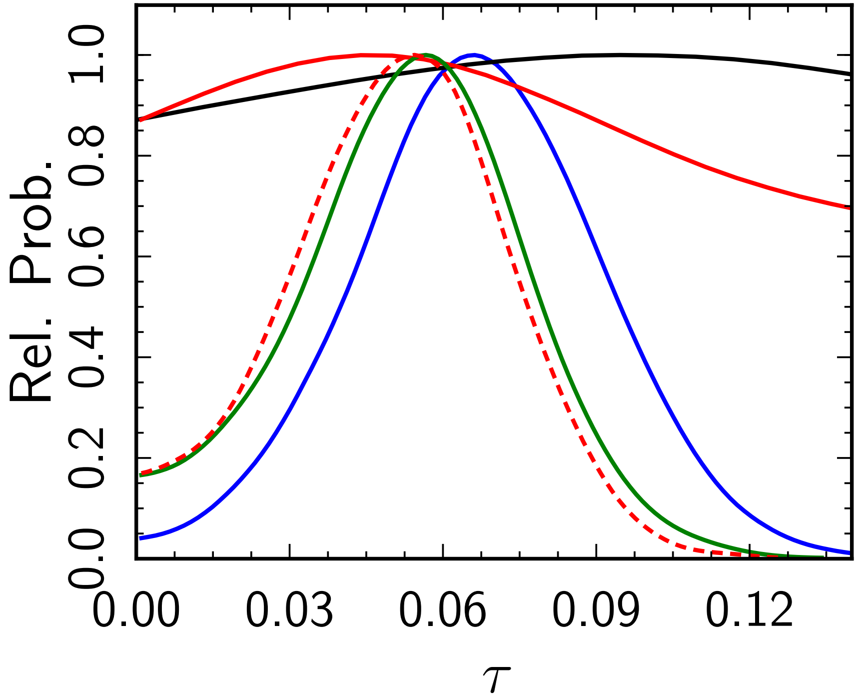

BolPol

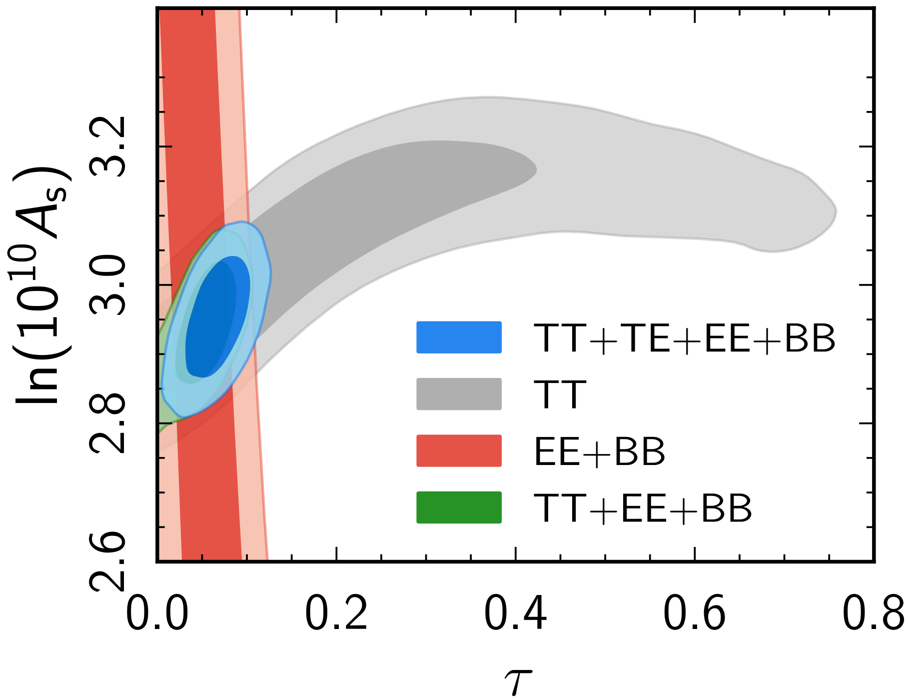


# Measuring the Optical depth of reionized universe ($\tau$) with the CMB – Planck 2015

- Planck low-ell (T,P) Likelihood with all parameters but $\tau$ , $A_s$ and $n_s$ fixed to Planck 2015 Best Fit Model

An example with all parameters but $\tau$ , $A_s$ fixed to Planck 2015 BFM



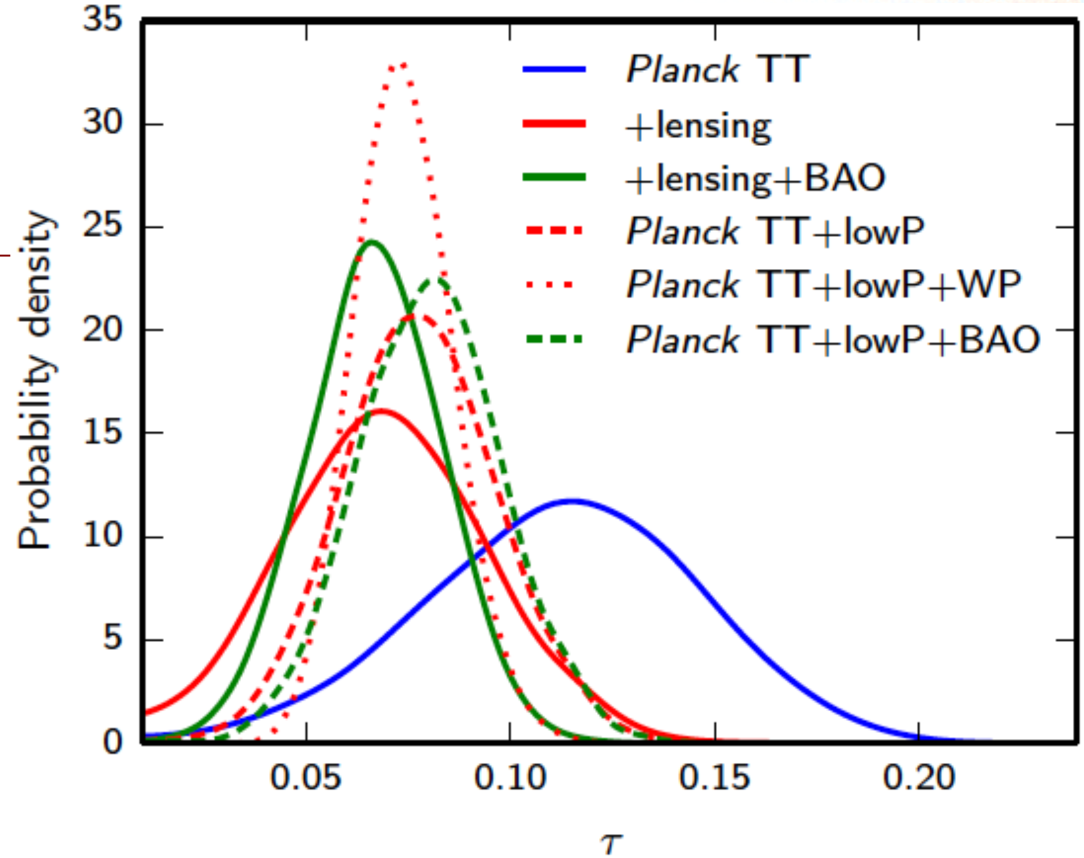

30/70/353 polarization (low-ell) → $\tau = 0.067 \pm 0.022$

# Measuring the Optical depth of reionized universe (τ) with the CMB

- Planck 2015:
  30/70/353 polarization:
  **$\tau = 0.067 \pm 0.022$**

- Planck 2015 polarization (low-ell) + + TT (high-ell)
  **$\tau = 0.078 \pm 0.019$**
- Planck 2015 TT + lensing
  **$\tau = 0.070 \pm 0.024$**
- \+ BAO
  **$\tau = 0.067 \pm 0.016$**

- WMAP9 Hinshaw et al (2013)
  **$\tau = 0.089 \pm 0.014$**
- WMAP9 Dust-cleaned with Planck 353
  **$\tau = 0.075 \pm 0.013$**




Planck 2015 polarization (low-ell) + + TT (high-ell) → **$\tau = 0.078 \pm 0.019$**

# Planck/HFI data and large scale polarization

- In principle, lower noise level in 100, 143, 217 GHz data can improve Planck $\tau$ measurement.
- Polarization power spectra in 2015 release dominated by systematic errors at low multipoles (ell < 30)

- New effort:
  - improved understanding of large angular scale systematics in both HFI and LFI instruments -> improved maps -> improved $\tau$ measurement
  - Simulation effort to characterize systematics remaining in the data
  - New mapmaking procedure

2 papers:

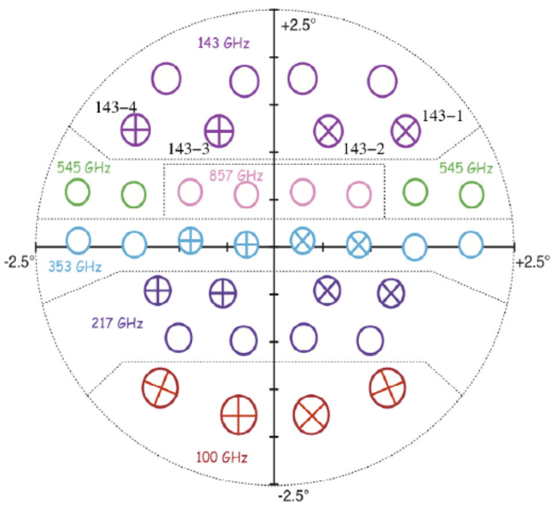
*Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth'*
[2016A&A...596A.107P](#)

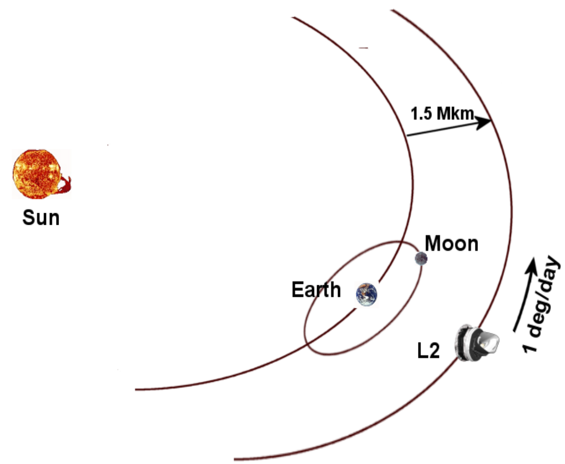
*'Planck intermediate results. XLVII. Planck constraints on reionization history'*
[2016A&A...596A.108P](#)

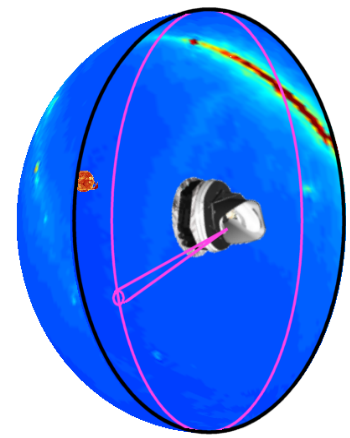
# Planck-HFI 's polarization measurement

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

No instrumental polarization modulation: I,Q,U solved by combining sky measurements from polarization sensitive bolometers at different angles
→ differencing detector signals and by sky modulation.



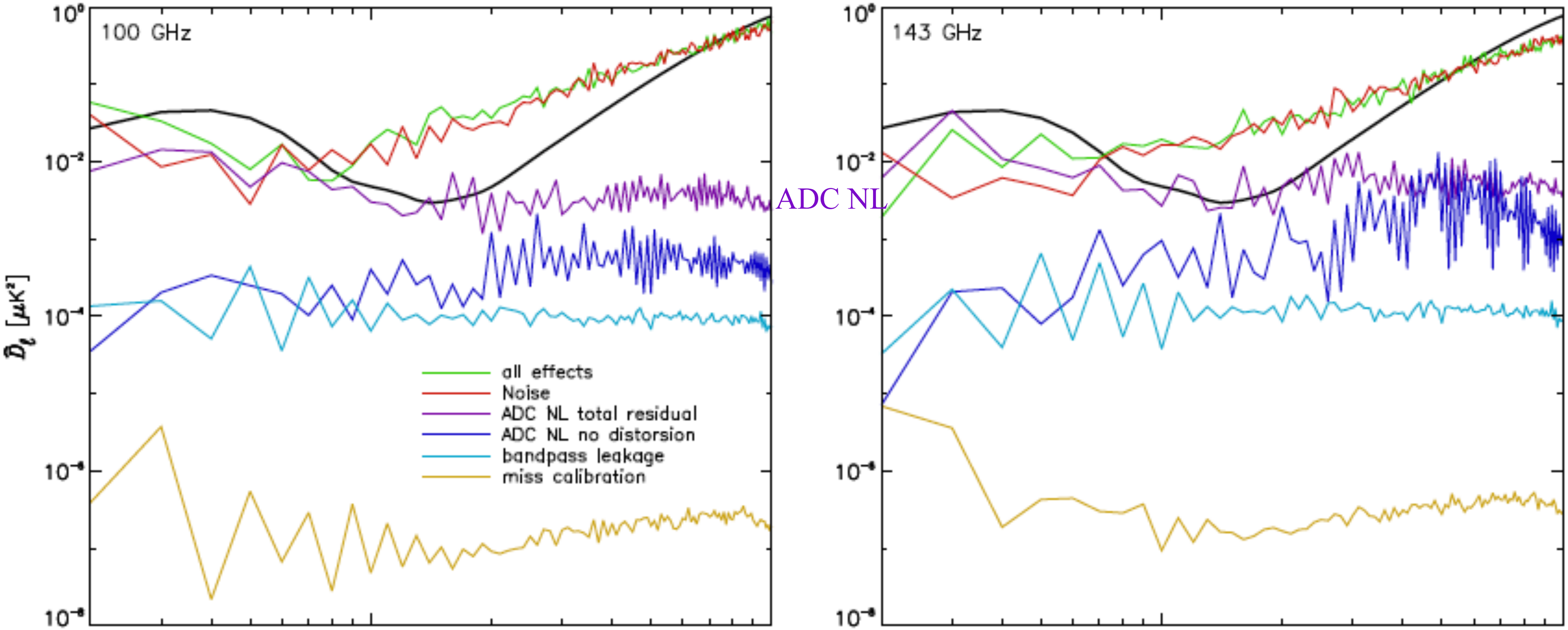



**Much of the sky is poorly sampled in polarization angles: vulnerable to T→P leakage**

- **Characterization of detector-to-detector relative properties + long time scale stability of measurement is critical for large angular scales.**

# Simulated systematics propagated to EE-spectra for HFI




**Systematics at low ell in HFI channels dominated by ADC nonlinearity**

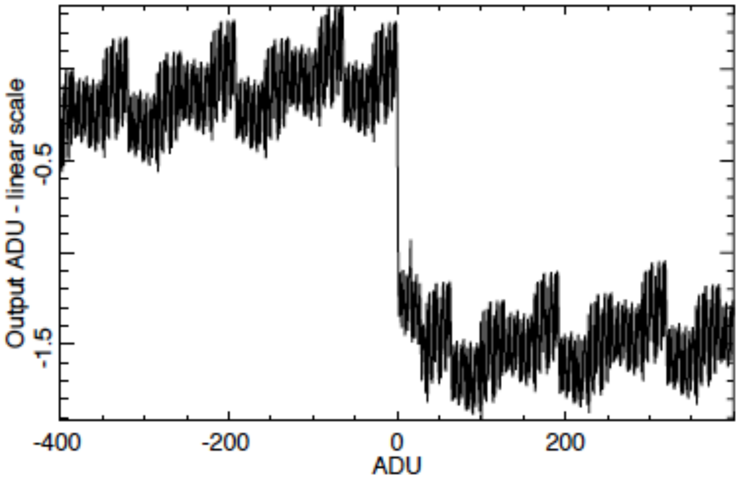
Purely instrumental -> Analog-to-Digital Converter (ADC) nonlinearity; Time response residuals; Relative gain between detectors; Possible time-variable gain

Scan-strategy related -> Far sidelobe pickup; Zodiacal light emission; Bandpass mismatch T → P leakage

ADC nonlinearity: **Can be (mostly) corrected by applying a time-variable linear gain correction.**

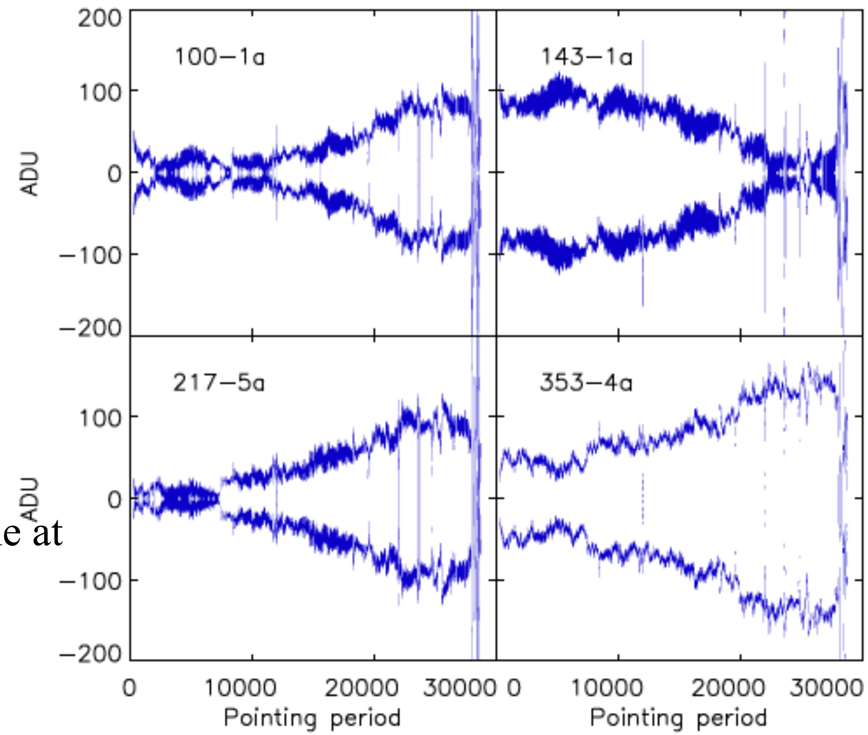
# ADC nonlinearity in HFI

**Nonlinearity near mid-range**




A perfectly linear device would be a horizontal line at zero

**Typical modulated signal level and baseline throughout mission**

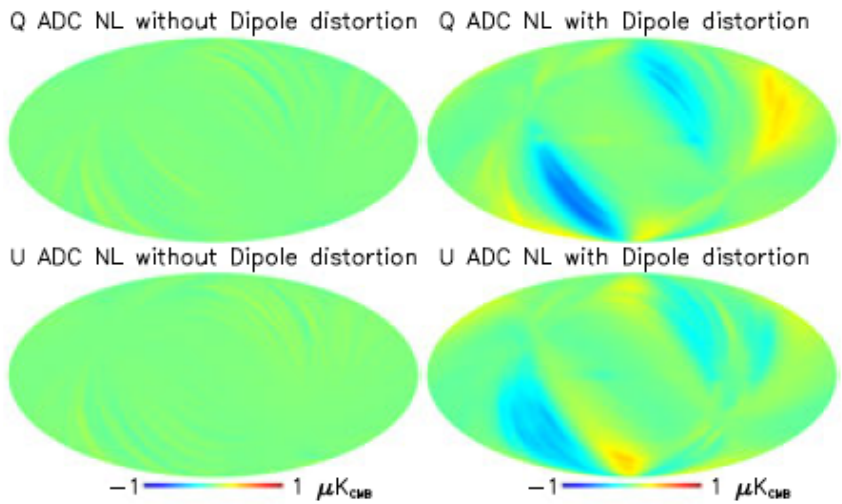


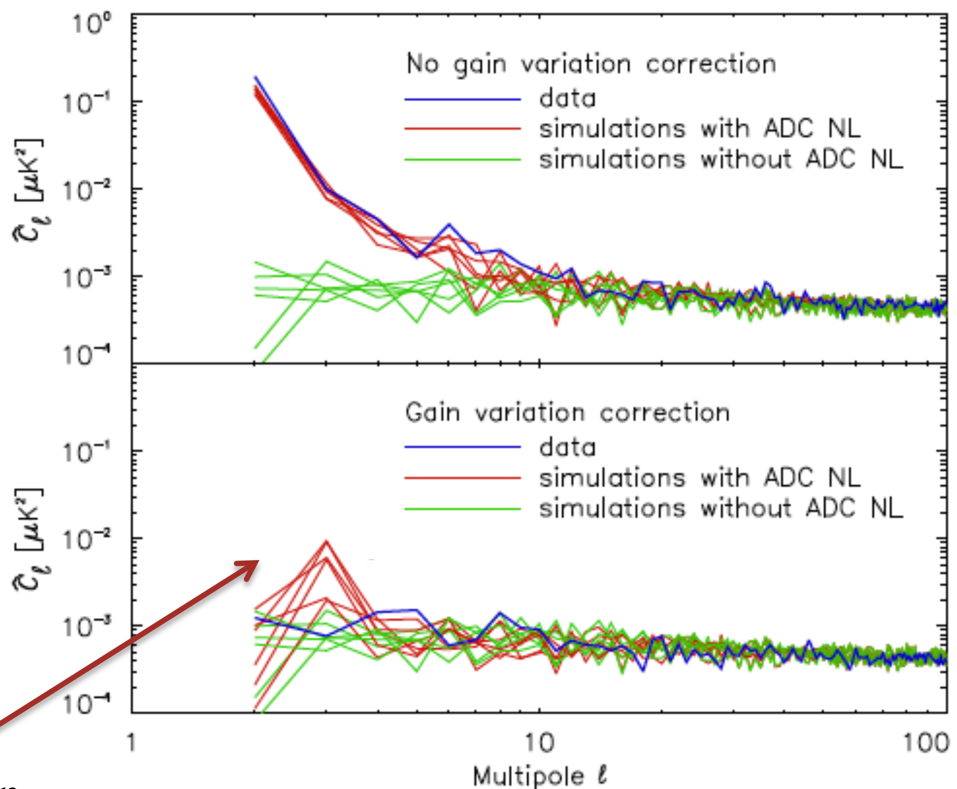

Huge effort during HFI warm mission to characterize ADCs.

- ✧ Major improvements between 2013 and 2015 releases
- ✧ But some residual effects remain

# Simulated effects of residual ADC nonlinearity

Can be (mostly) corrected by applying a time-variable linear gain correction. However dipole signal is distorted: signal leaked from ell=1 to higher ell (affects mostly ell=2 and 3)

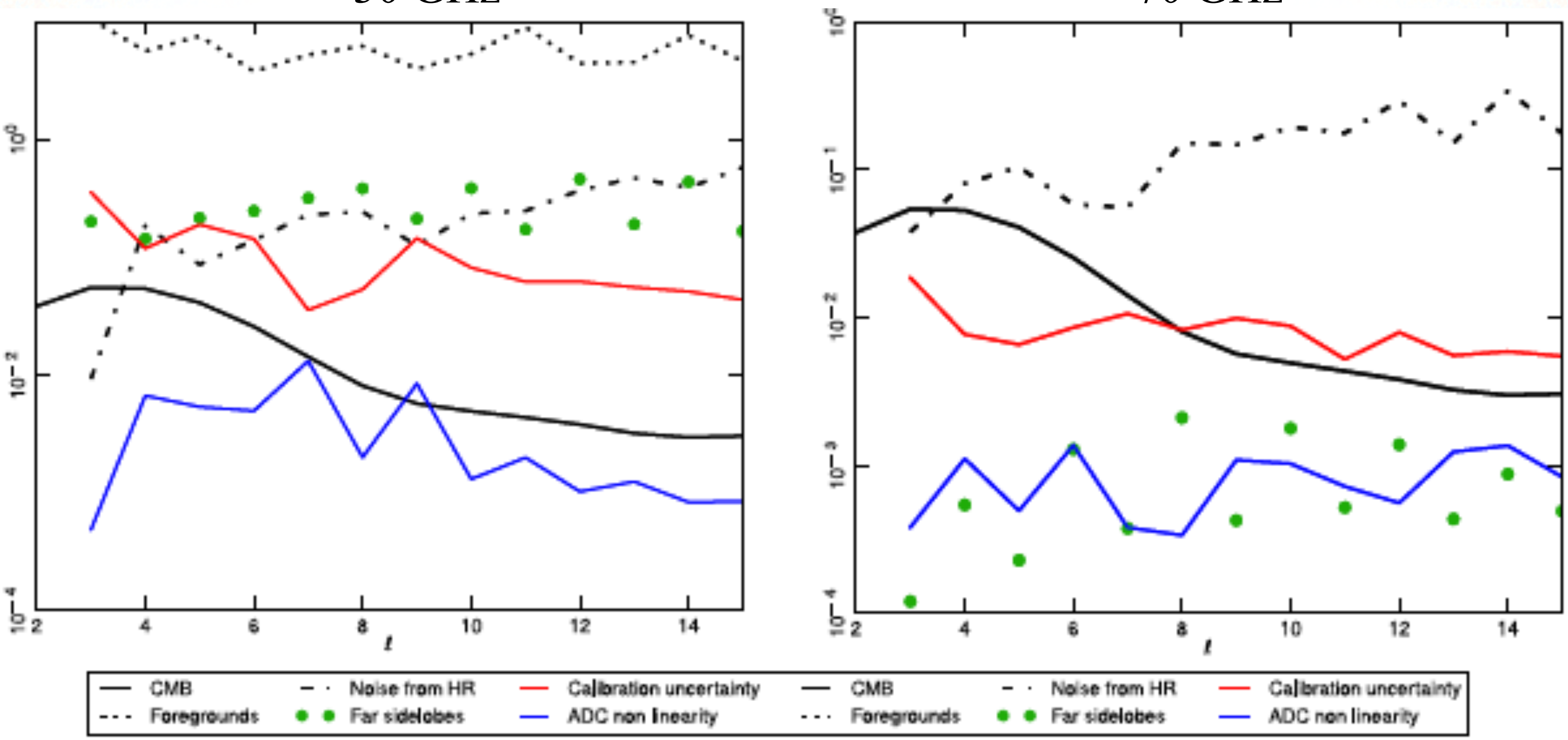



Efficiency of the new mapmaking residual gain variation correction

# Simulated LFI systematics in EE spectra

30 GHz 70 GHz




**Systematics at low ell are mostly dominated by**

- **calibration uncertainty**
- **far sidelobe pickup at 30 GHz**

# Removal of Systematic Errors

Extend data model to solve for systematic effects while also solving for I, Q, U on the sky:

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

Time variable gain (mostly corrects ADC nonlinearity)

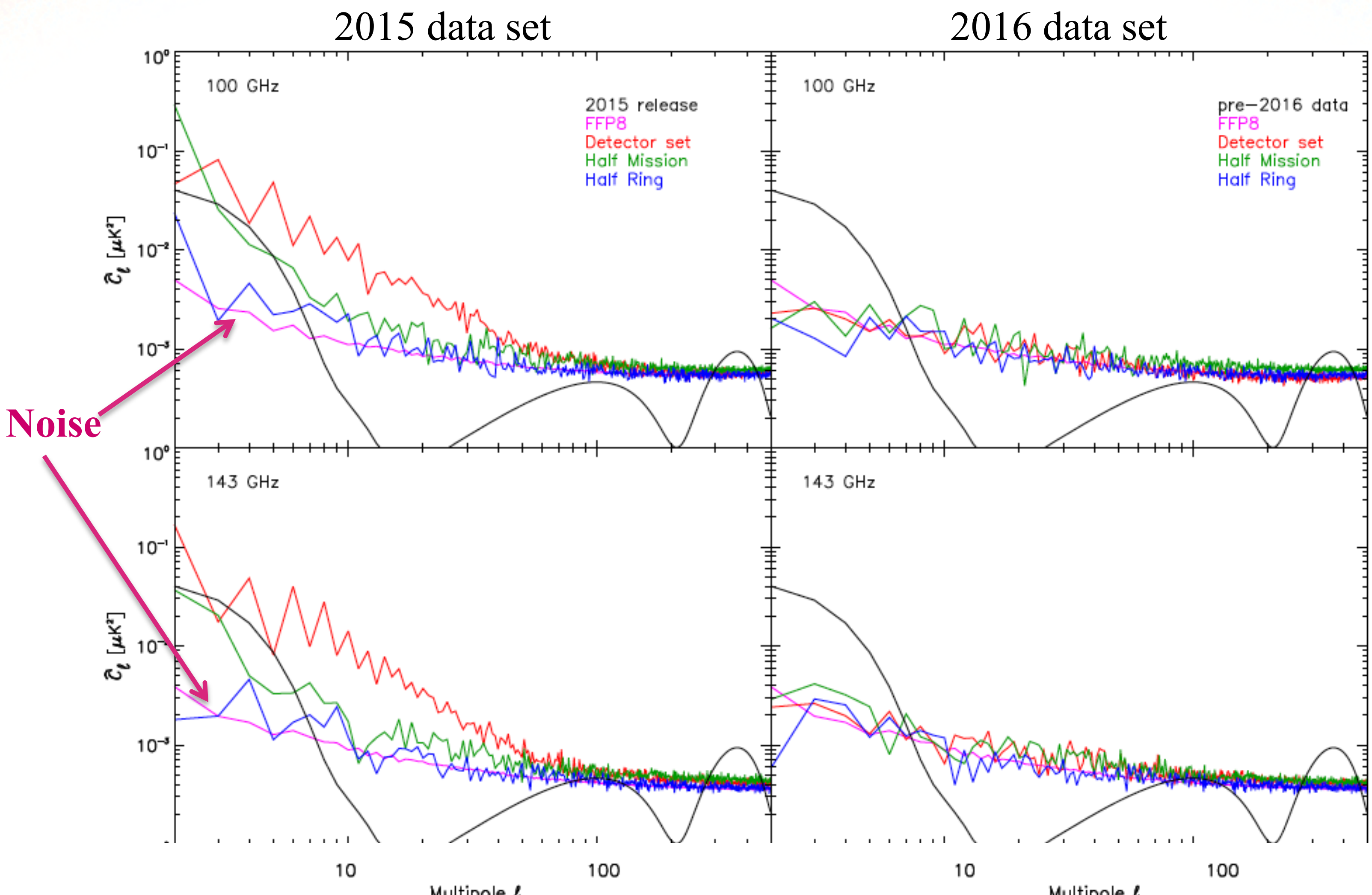
Residual dipole

Bandpass mismatch: leaks foreground T to P

Residual transfer function templates. Zodi templates

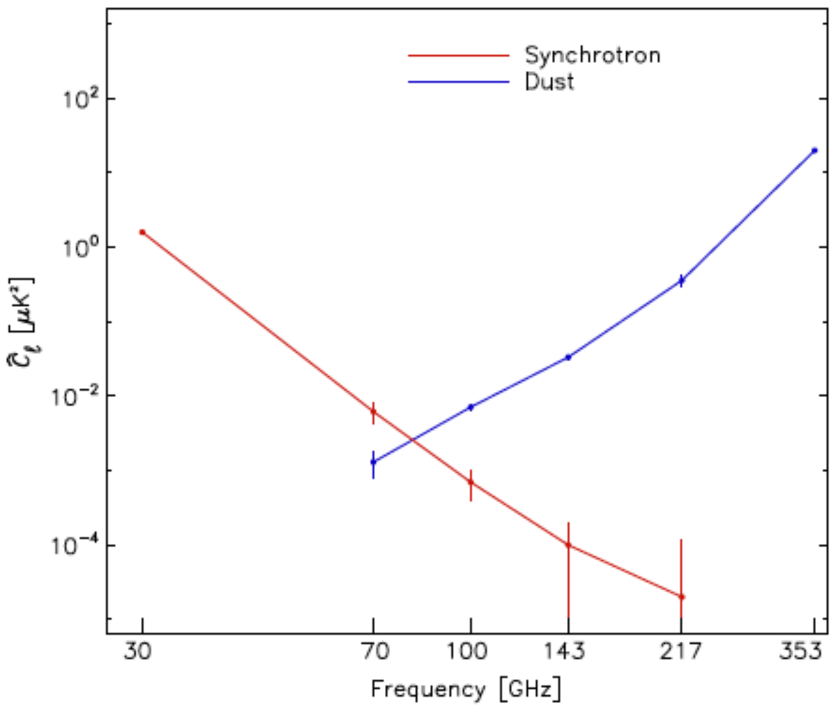
Destriper offset: remove 1/f noise

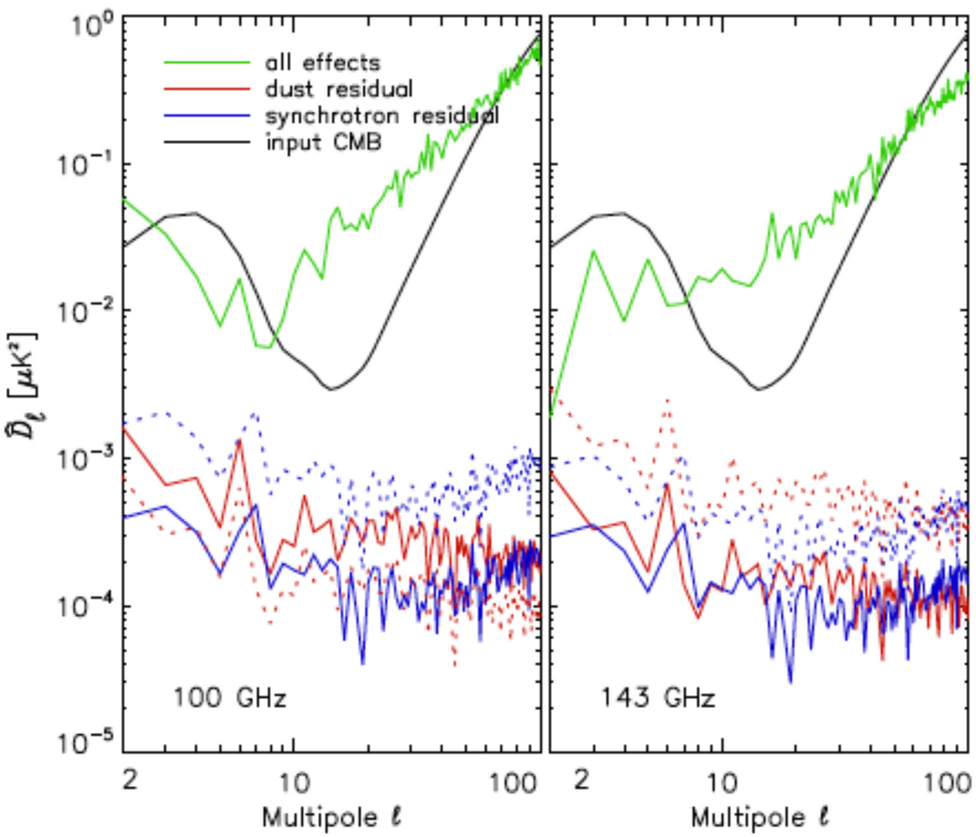
# Null tests: great improvement in self-consistency of maps

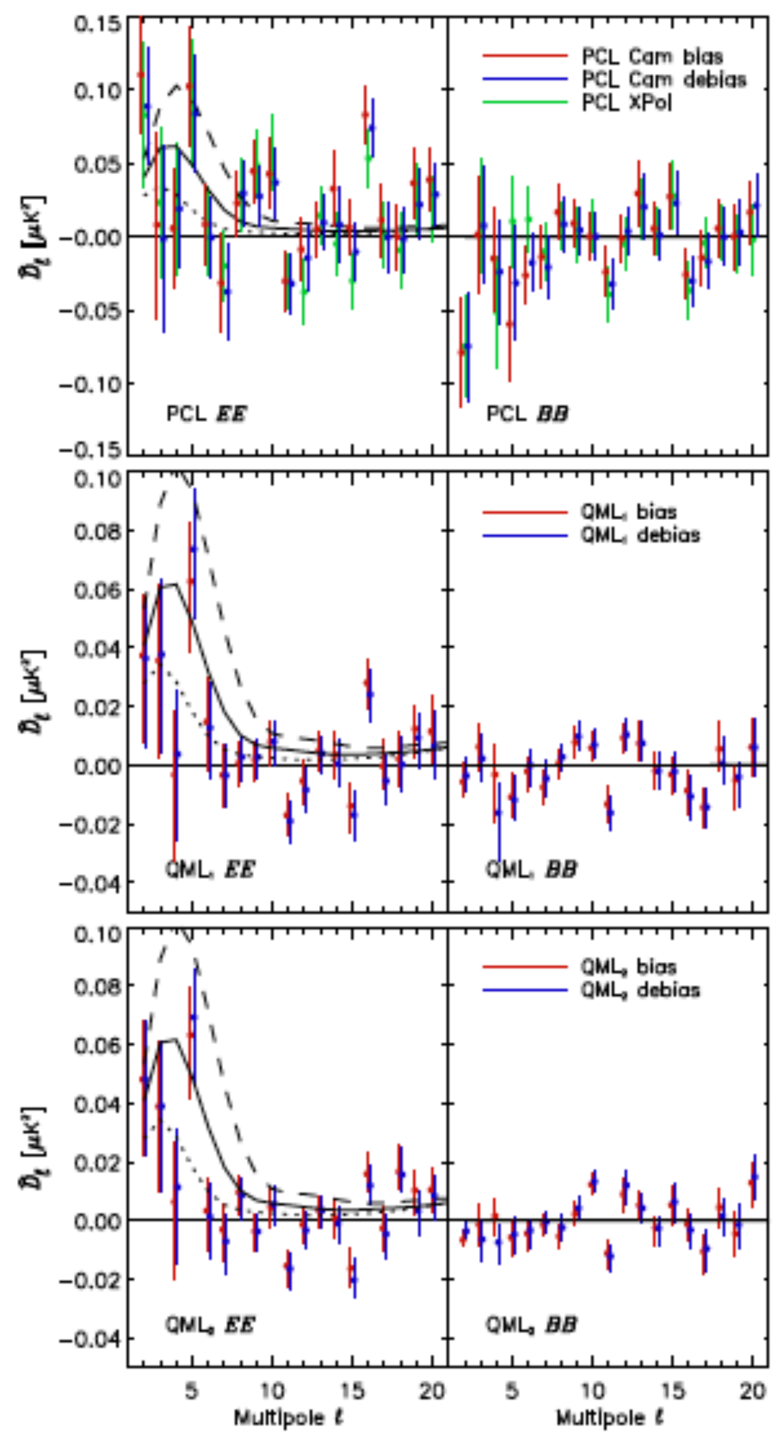


## ILC with 30 GHz for synchrotron and 353 GHz for dust

50% sky fraction
Ell=4 EE power



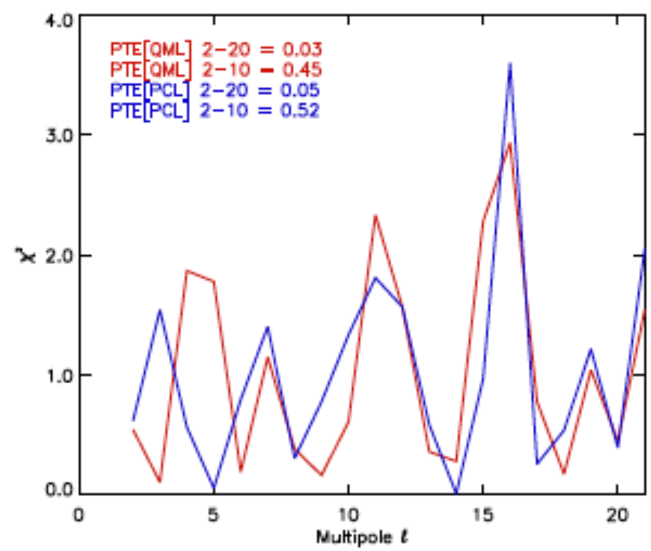



# 100x143 spectra

- Main results: Use 100 x 143 (foreground cleaned)
- Cross checks from 100 x 70 and 143 x 70, 100x100 and143x143 autospectra for crosschecks.
- Use multiple spectral estimator techniques
  - Pseudo-Cl (PCL) - *Lollipop*
  - Quadratic Maximum Likelihood (QML)
- Use instrumental simulations to compute and subtract bias due to systematics (very small), and to construct pixel-pixel noise covariance
- Simulation based Likelihood - *SimBal*

Black lines - Model for $\tau$=0.05 (dotted), 0.07(solid) and 0.09 (dashed)

QML computed with two different simulation sets



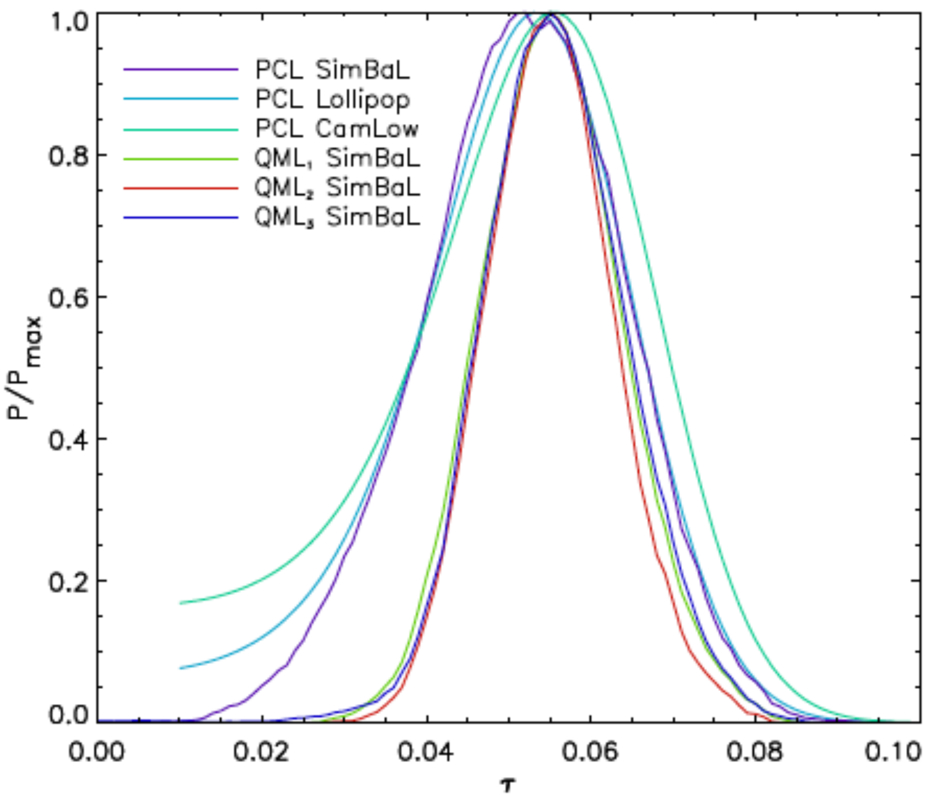


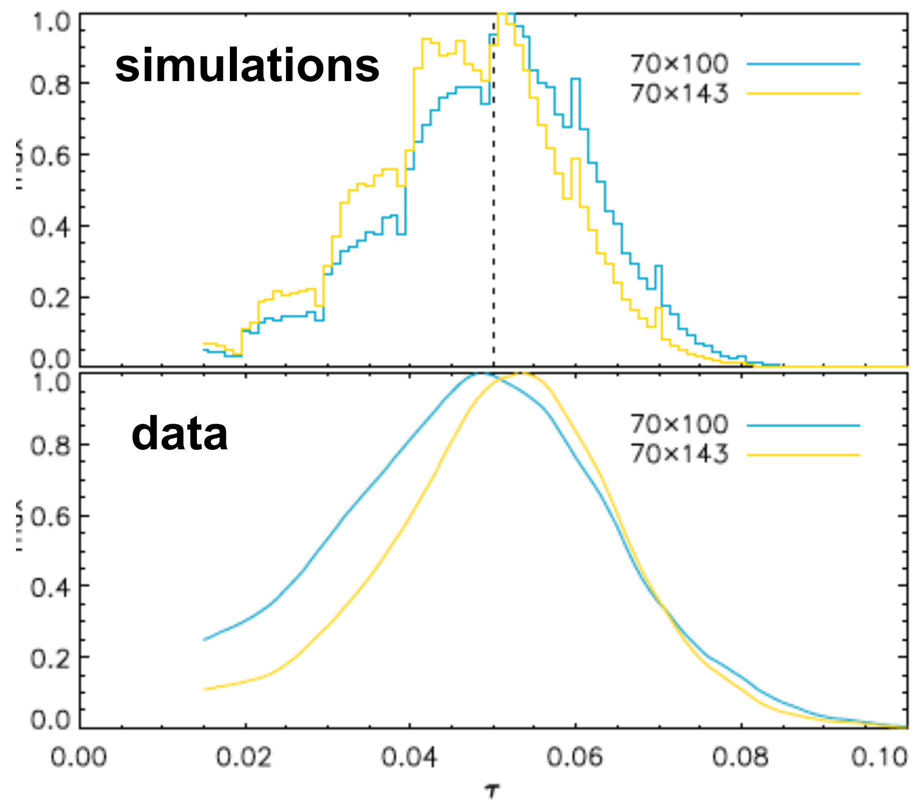

*Graca Rocha*

# Tau results

Instrumental cross-check: HFI x LFI

**100x143** **70x100 70x143**

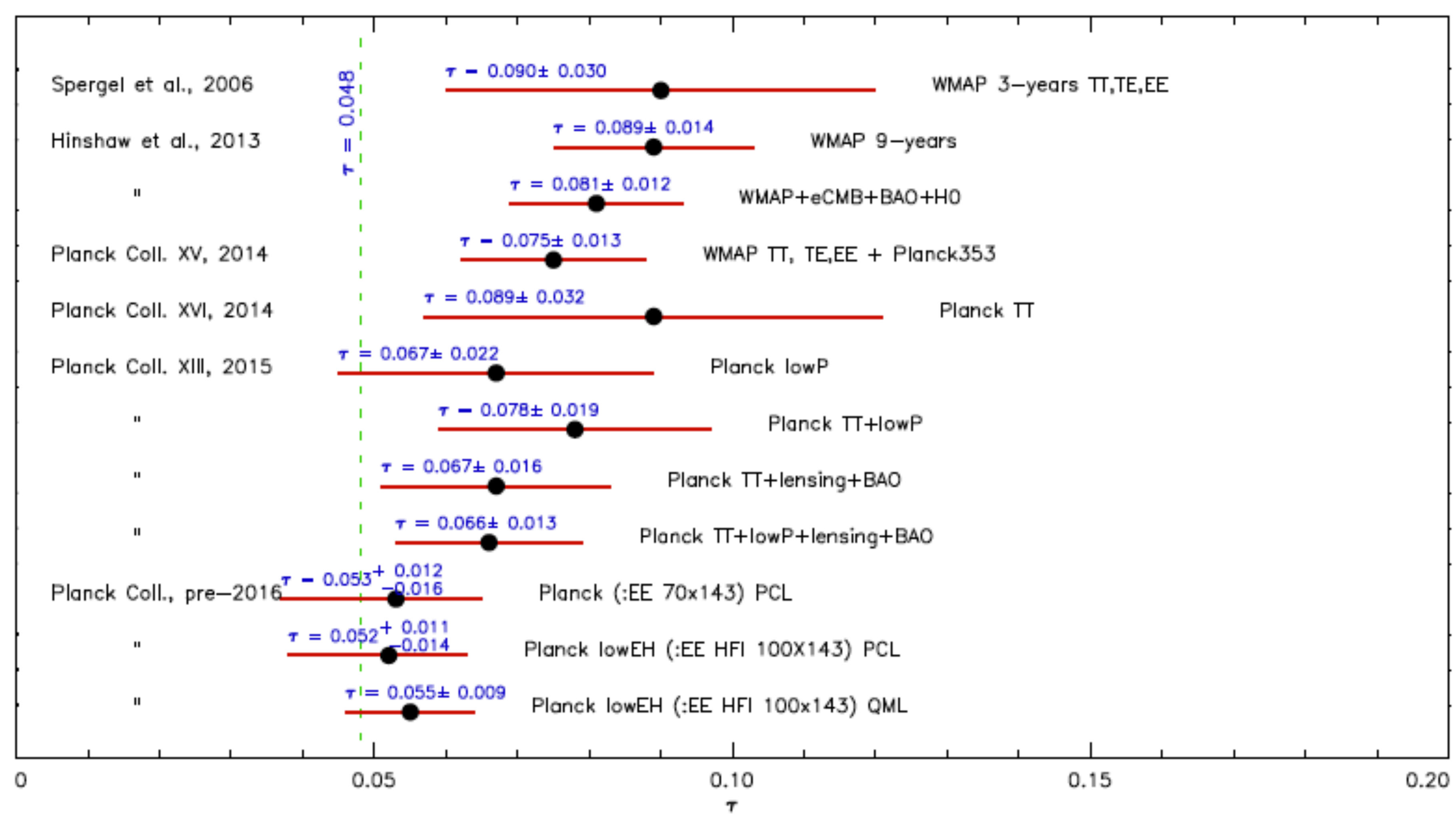



QML spectra : $0.055^{+0.009}_{-0.009}$

$$\tau = 0.049^{+0.015}_{-0.019} \text{ for the } 70\times100 \text{ cross-spectra}$$
$$\tau = 0.053^{+0.012}_{-0.016} \text{ for the } 70\times143 \text{ cross-spectra}$$

# Summary of tau results



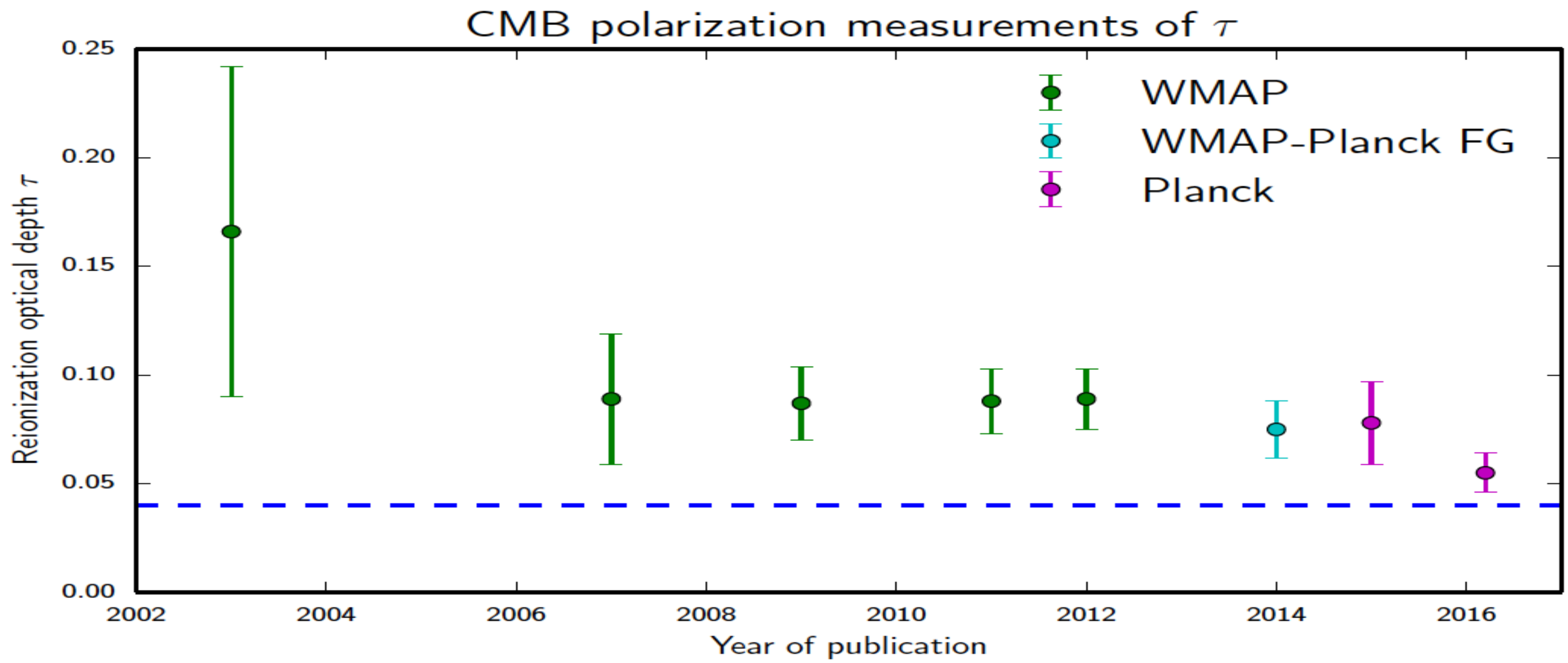

Given lower limit from astrophysics (Gunn-Peterson), $z_{re}$~6, ie, τ ~0.038

New Planck/HFI result has 95% CL upper limit τ < 0.072

$z_{re}$ ~7.7 to 8.8 (depending on the model of reionization)

The Universe is ionized at less than the 10% level above z ~10

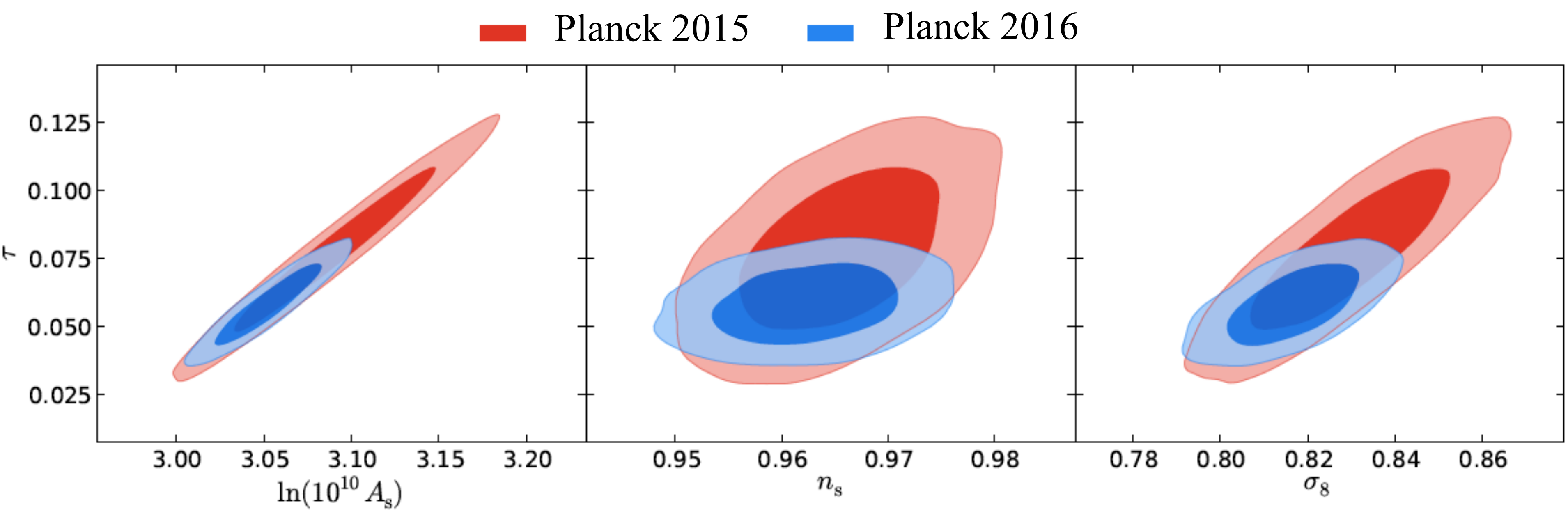
# Timeline of tau results



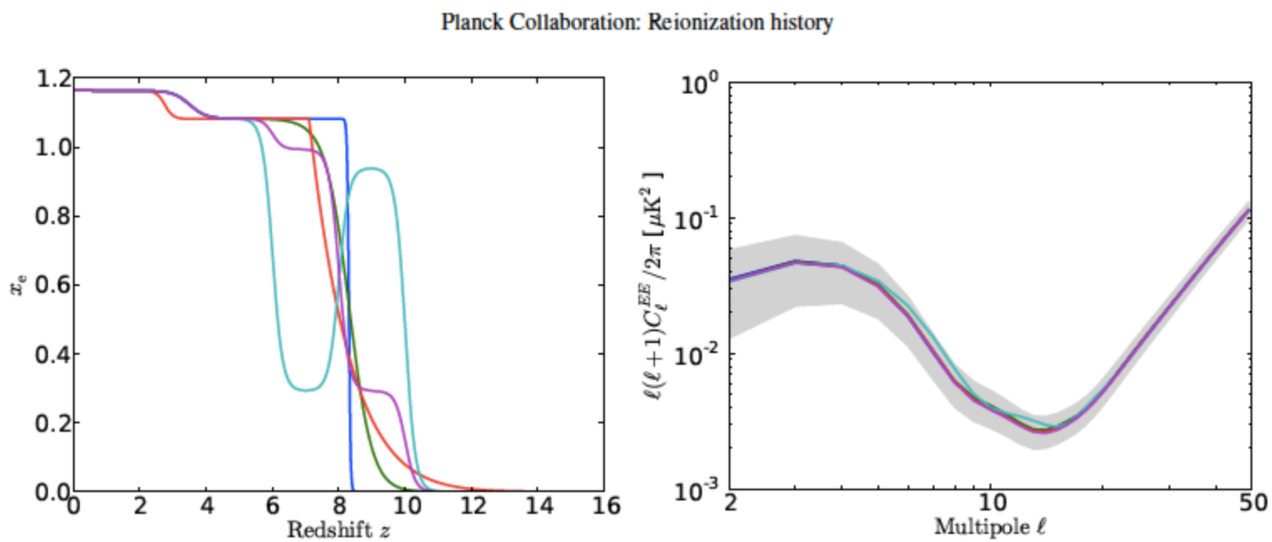

Given lower limit from astrophysics (Gunn-Peterson), $z_{re}$~6, ie, $\tau$ ~0.038
New Planck/HFI result has 95% CL upper limit $\tau < 0.072$
$z_{re}$ ~7.7 to 8.8 (depending on the model of reionization)
The Universe is ionized at less than the 10% level above z ~10

# Effects on other ΛCDM cosmological parameters

- Impact on scalar amplitude of the spectra, $A_s$, and tilt, n:
  - Main degeneracy is with primordial scalar $A_s$ → $\sigma_8$ comes down (by 1 σ)
    - *but not enough to resolve discrepancy with Planck cluster abundance measurement*
  - Slight degeneracy with $n_s$, which shifts down slightly



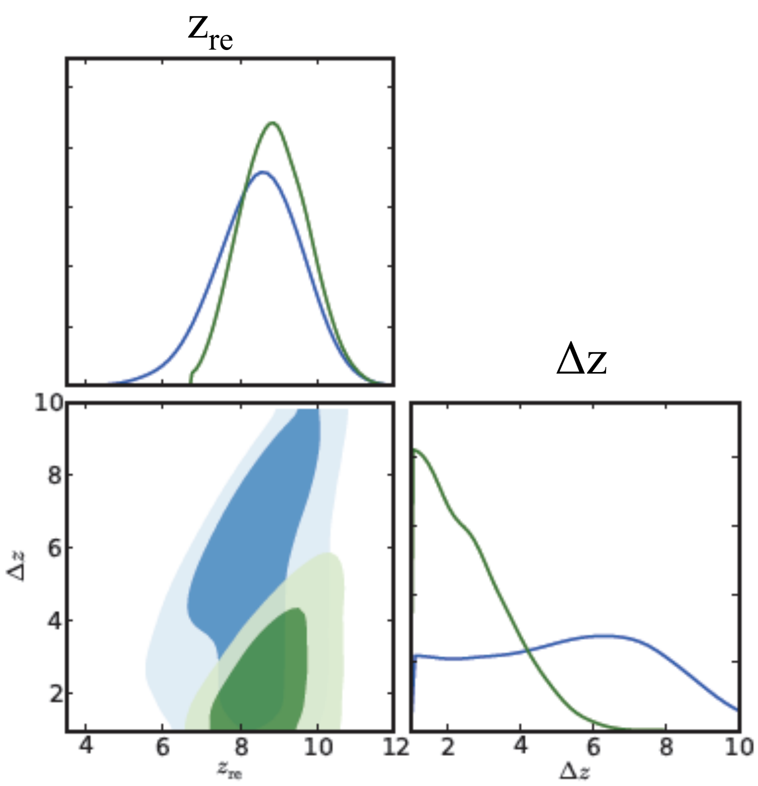
# Impact on models of early galaxy evolution and star formation

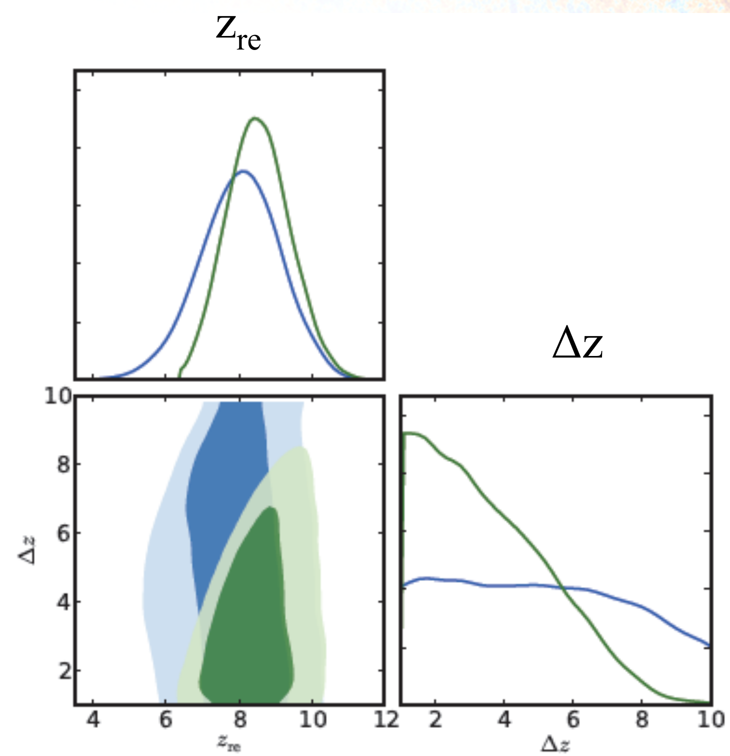



Left: Evolution of the ionization fraction for several functions with same τ=0.06
Green and Blue are for redshift-symmetric instantaneous (z = 0.05) and extended reionization (z = 0. 7), respectively;
Red is an example of a redshift asymmetric parameterization;
Light Blue and Magenta are examples of an ionization fraction defined in redshift bins, with two bins inverted between these two examples.
Right: corresponding EE power spectra with cosmic variance in grey.

All models have the same optical depth τ = 0.06 and are essentially indistinguishable at the reionization bump scale.

# Impact on models of early galaxy evolution and star formation




redshift-symmetric parameterization

redshift-asymmetric parameterization

Green after imposing prior z_end >6

# Conclusions

- The Planck team has made huge improvements in understanding and cleaning of systematic errors in HFI and LFI instruments:
  - Internal consistency of maps on large angular scales is much improved
  - Improved simulations and removal of systematic effects allow detection of signature of reionization in large scale E-mode angular power spectrum.

- Reionization optical depth τ lower than previous measurements:
  - $\tau = 0.055 \pm 0.009$ based on 100x143, foreground-cleaned with 30 and 353 GHz
  - Still limited by systematics:
    - cosmic variance limited error bars over 50% of the sky: 0.006 → some room for improvement in final 2017 release or beyond..

- Two papers on:
  - Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth'
  - *2016A&A...596A.107P*
  - 'Planck intermediate results. XLVII. Planck constraints on reionization history'
  - 2016A&A...596A.108P: