The Planck low-ell power spectra and likelihood

Paolo Natoli

Università di Ferrara

on behalf of the Planck Collaboration

Background

- ✓ The low ell likelihood requires dedicated methodology because approximations that work well at high ell typically fail at low ell
- ✓ Including low ell polarization is important to break the degeneracy between the scalar amplitude A_s and the optical depth at reionization τ (beyond what can we done with CMB lensing).
  - It can also help constraining the tensor to scalar ratio r through B modes
- ✓ In 2013, we used Planck in low ell temperature, but WMAP in low ell polarization, because Planck polarization was not ready
- ✓ In 2014, we are using Planck LFI 70 GHz as the low ell polarization baseline

Methodology

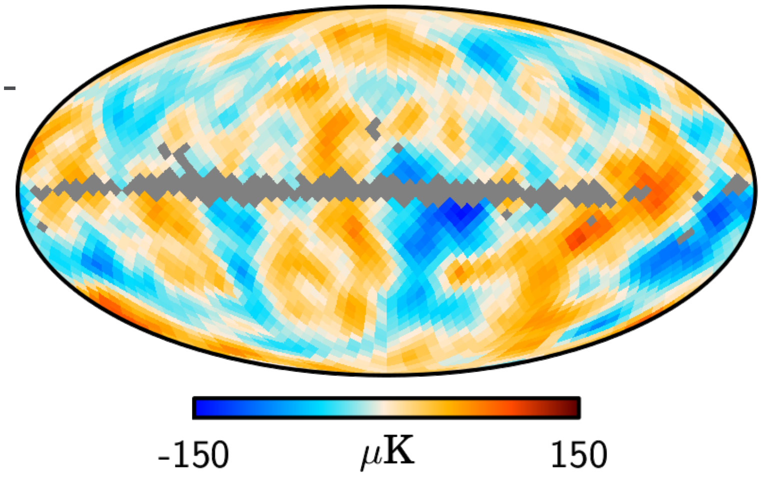
1. Multivariate Gaussian likelihood in the m=[T,Q,U] maps, with CMB signal plus noise covariance matrix M :

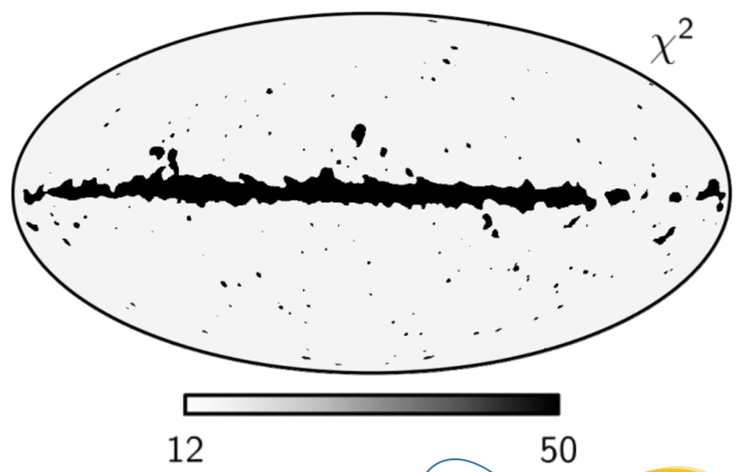
$$\mathcal{L}(C_\ell) = P(\mathbf{m}|C_\ell) = \frac{1}{2\pi^{n/2}|\mathbf{M}|^{1/2}} \exp\left(-\frac{1}{2}\mathbf{m}^t\,\mathbf{M}^{-1}\mathbf{m}\right)$$

2. T,Q,U maps are cleaned of foreground emission and residual systematics:
   a. In T, Commander multiband CMB solution
   b. In Q,U polarized CMB is provided by Planck 70 GHz, after template fitting for polarized synchrotron and dust, based on Planck 30 and 353 GHz, and their polarization leakage corrections.
3. Covers the range $2 \leq \ell \leq 29$

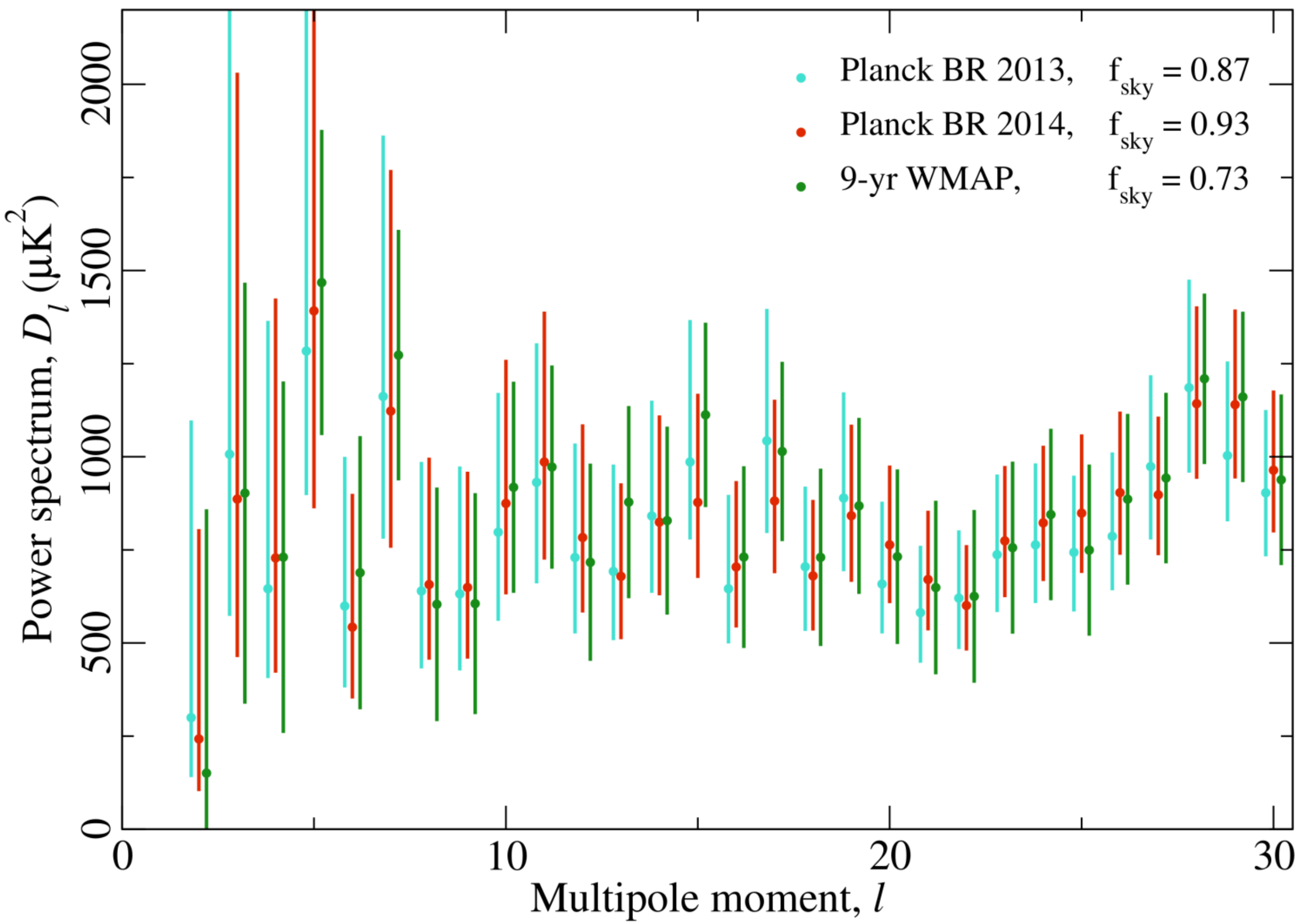
Low-l Commander temperature map

- As in 2013, the low-l temperature likelihood is based on the foreground-cleaned Commander map
- But unlike 2013, the 2014 map also incorporates the 9-year WMAP data and the 408 MHz Haslam map
  - More frequencies $\Rightarrow$ better fg model $\Rightarrow$ more clean sky
  - See Wehus' talk tomorrow for more details
- Analysis chain:
  1. Perform component separation at 1° resolution
  2. Define narrow χ^2–based processing mask to remove obvious residuals
  3. Fill mask with a constrained Gaussian realization
  4. Smooth to 440' FWHM, and repixelize at N_{side}=16
  5. Define proper χ^2–based confidence mask at N_{side}=256
     - **This year f_{sky} = 0.93, which is up from 0.87 in 2013**
  6. Downgrade mask, and apply to N_{side}=16 map
     - Range of different χ^2 thresholds considered; no systematic biases or trends found in power spectrum until $f_{sky} \approx 0.97$





Low-l Commander temperature spectrum



All TT spectra shown here are computed with the Blackwell-Rao estimator from temperature data alone

The low-l Planck 2014 TT spectrum is on average ≈1.5% higher than the 2013 spectrum, primarily because of revised dipole calibration

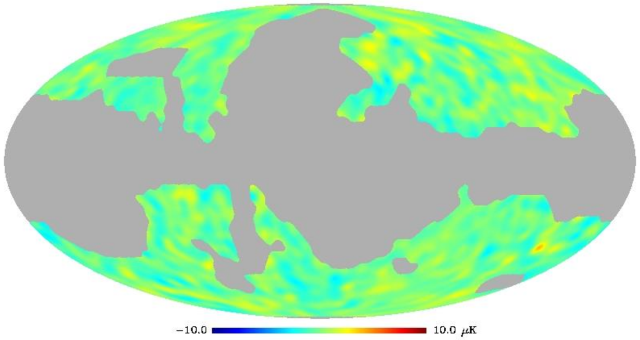
⇓

Excellent agreement with WMAP

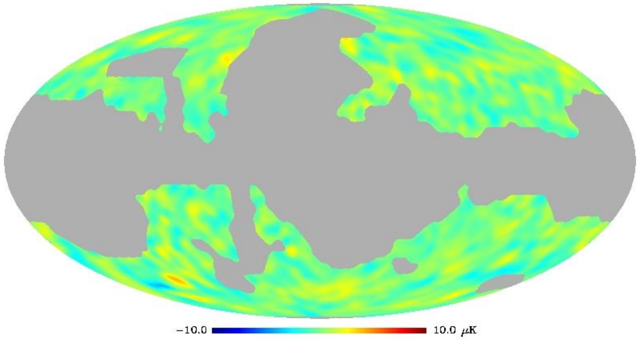
Preliminary

Polarized CMB from 70 GHz

1. Low ell CMB polarization in Planck 2014 comes from 70 GHz.
2. Out of eight surveys, we exclude from the dataset survey 2 and 4 because the exhibit unusual B mode excess, presumably connected with sidelobe contamination.
3. Templates (30 and 353) are built from full mission data.
4. Working resolution is nside = 16, down sampled from high resolution through noise weighting. No smoothing is applied in polarization
5. The analysis mask retains 47% of the sky.



Stokes Q



Stokes U

Preliminary

Polarized template subtraction

1. Foreground removal is based on a simple model, which assume that α and β are constant over the sky:

$$m_{Q,U} = \frac{1}{1-\alpha-\beta}(m_{70} - \alpha m_{30} - \beta m_{353})$$

2. Coefficients are derived minimizing the pixel space $\chi^2 = m^T C^{-1} m$, with C a dense, CMB signal plus noise covariance matrix
   a. Using a brute force Gaussian likelihood evaluation yields consistent estimates.
3. The clean map noise covariance matrix is derived as:

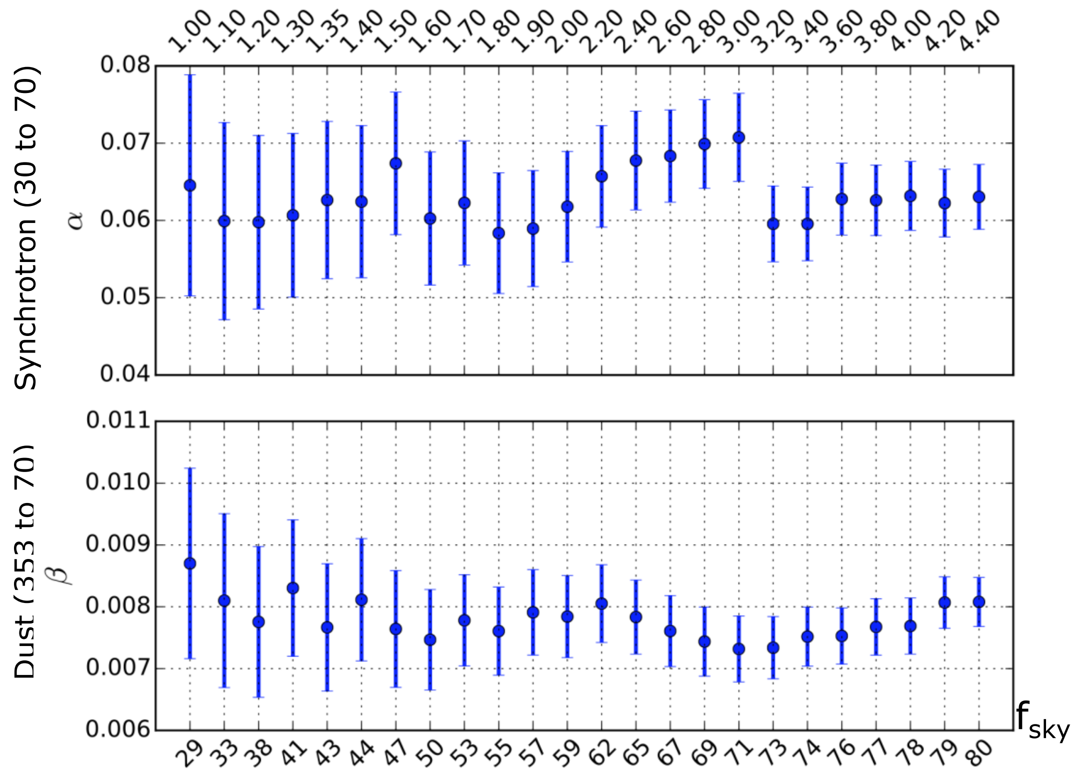
$$N = \frac{1}{(1-\alpha-\beta)^2}(N_{70} + \sigma_\alpha^2 m_{30} m_{30}^T + \sigma_\beta^2 m_{353} m_{353}^T)$$

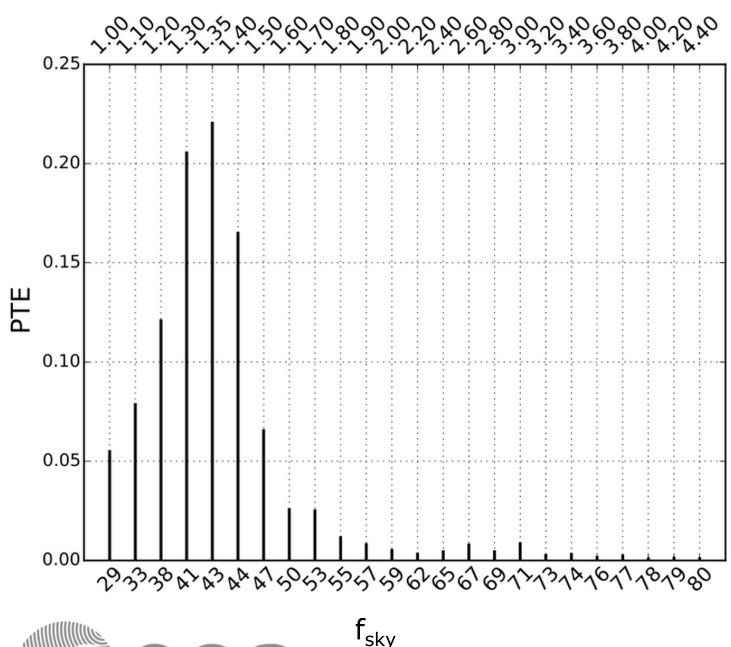
4. Propagating noise matrices from the templates has negligible impact.

Stability of best fit scalings with f_{sky}

planck

- ✓ Galactic masks are built thresholding polarized intensity at 30 and 353 GHZ
- ✓ Scaling coefficients for appear rather stable below $f_{sky} \sim 60\%$.. Variations within errors does not influence the power spectra much.
- ✓ We compute pixel space $P(\chi^2 > \chi^2_{obs})$ as a goodness of fit criterion.





- ✓ At $f_{sky} < 50\%$ fit becomes acceptable. We settle for 47%
- ✓ Usability of larger sky fractions may be hampered by crude approximations used for FG removed. More general component separation should perform better in 2015
- ✓ For $f_{sky} = 47\%$ the physical scalings are:

α_{synch} **= - 3.4 ± 0.2**

β_{dust} **= 1.50 ± 0.08**

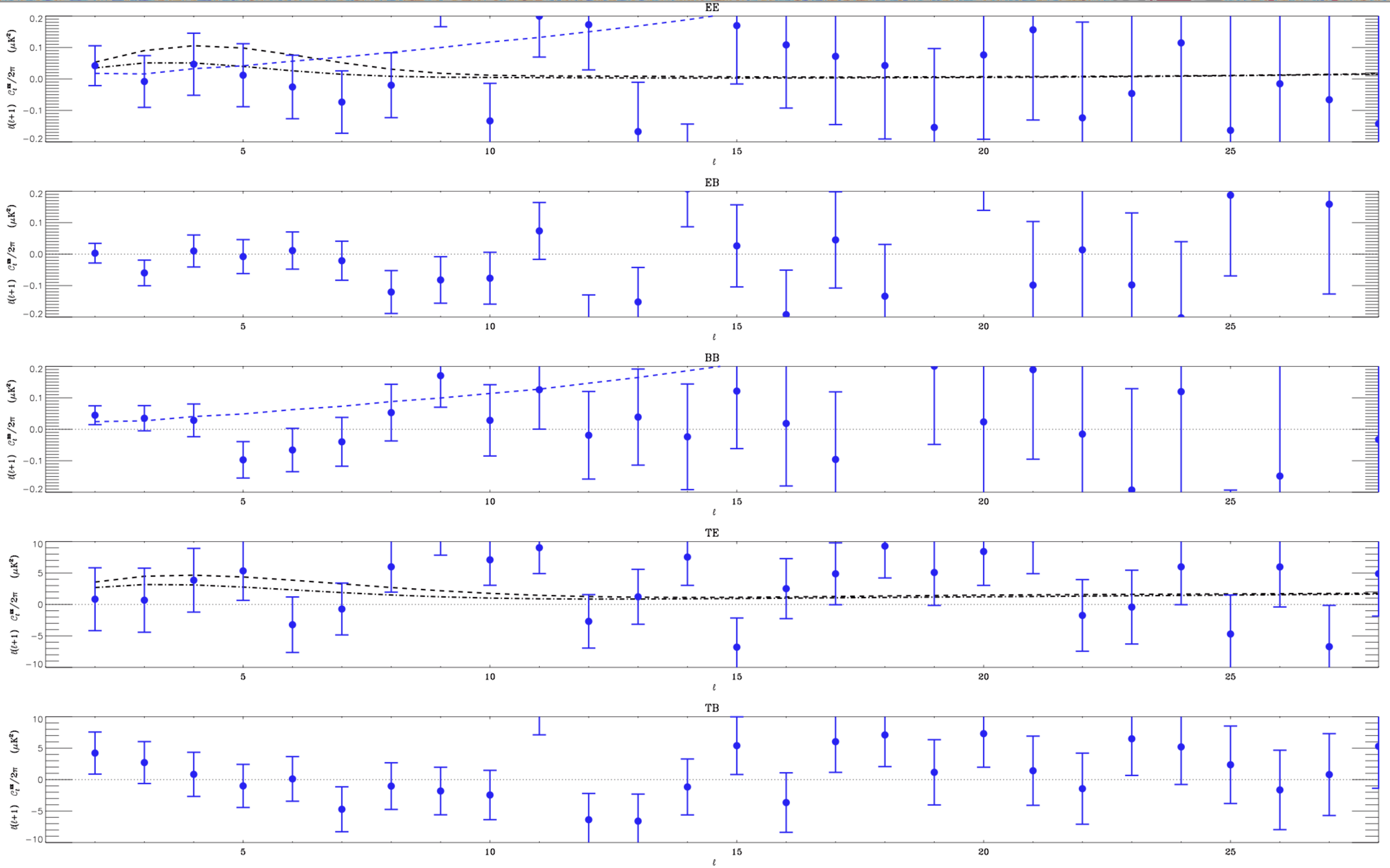
esa

Preliminary

PLANCK LFI

HFI PLANCK

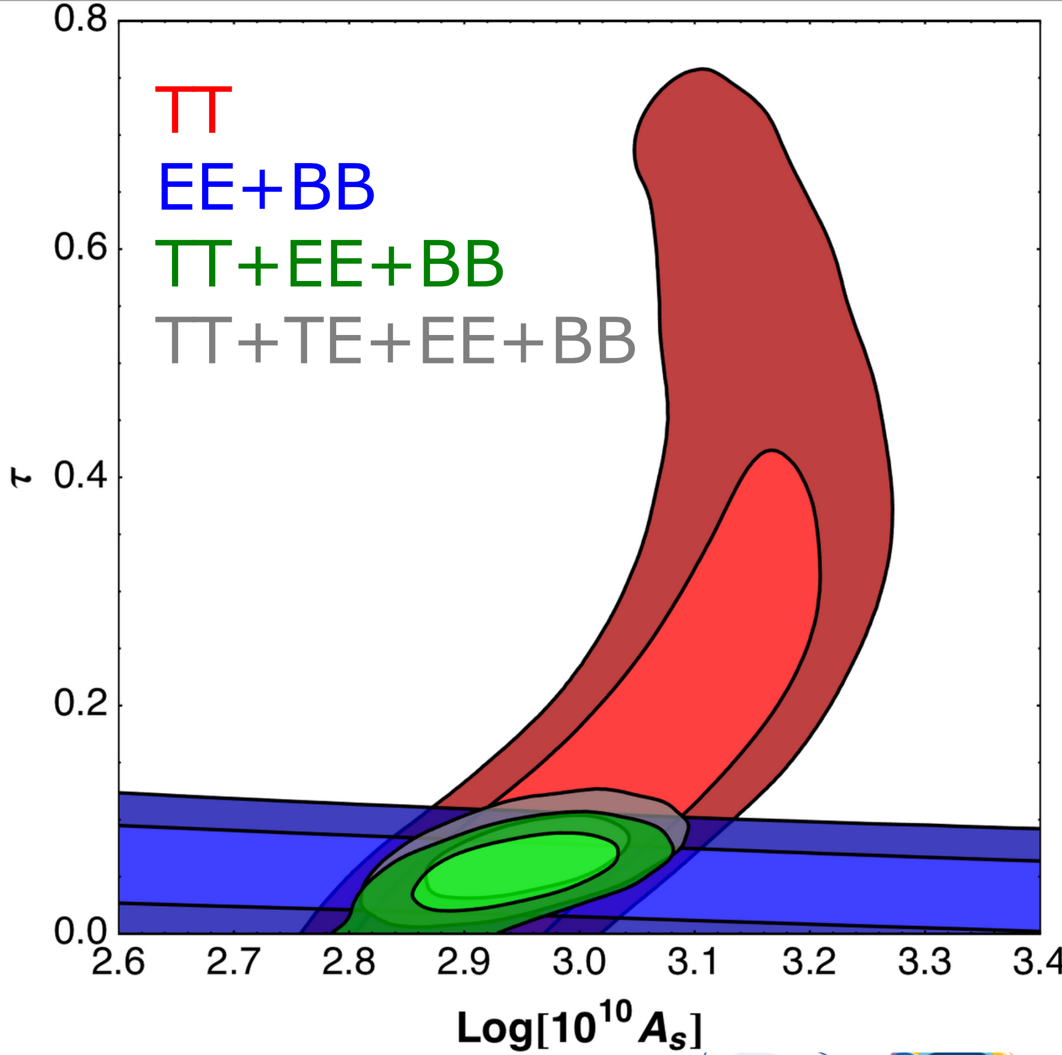
Low ell power spectra



Preliminary

Two parameters (τ, As) from 2<ell<29 only

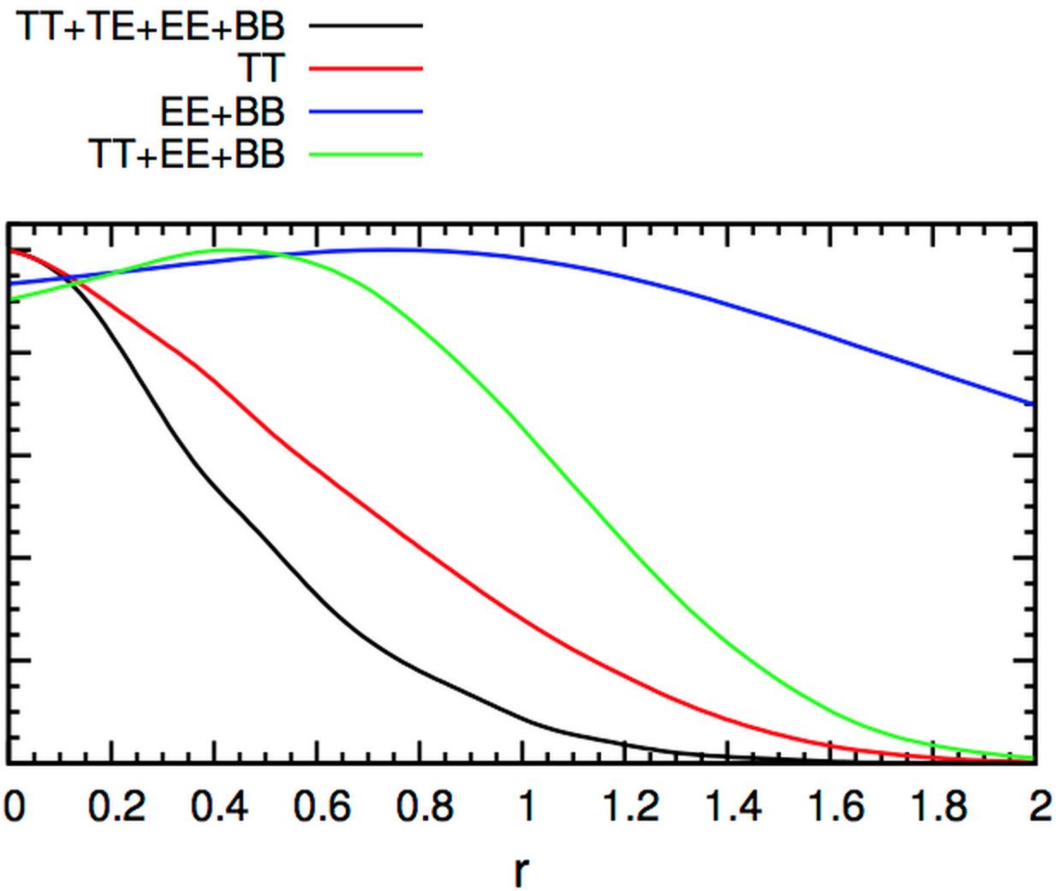
- ✓ Temperature mainly contains information on A_s, not τ
- ✓ Polarization mainly contains information on τ not A_s
- ✓ The two orthogonal bounds combine nicely to constrain both
- ✓ Adding TE reinforces the τ detection



Preliminary

Tensor to scalar ratio r from 2<ell<29 only

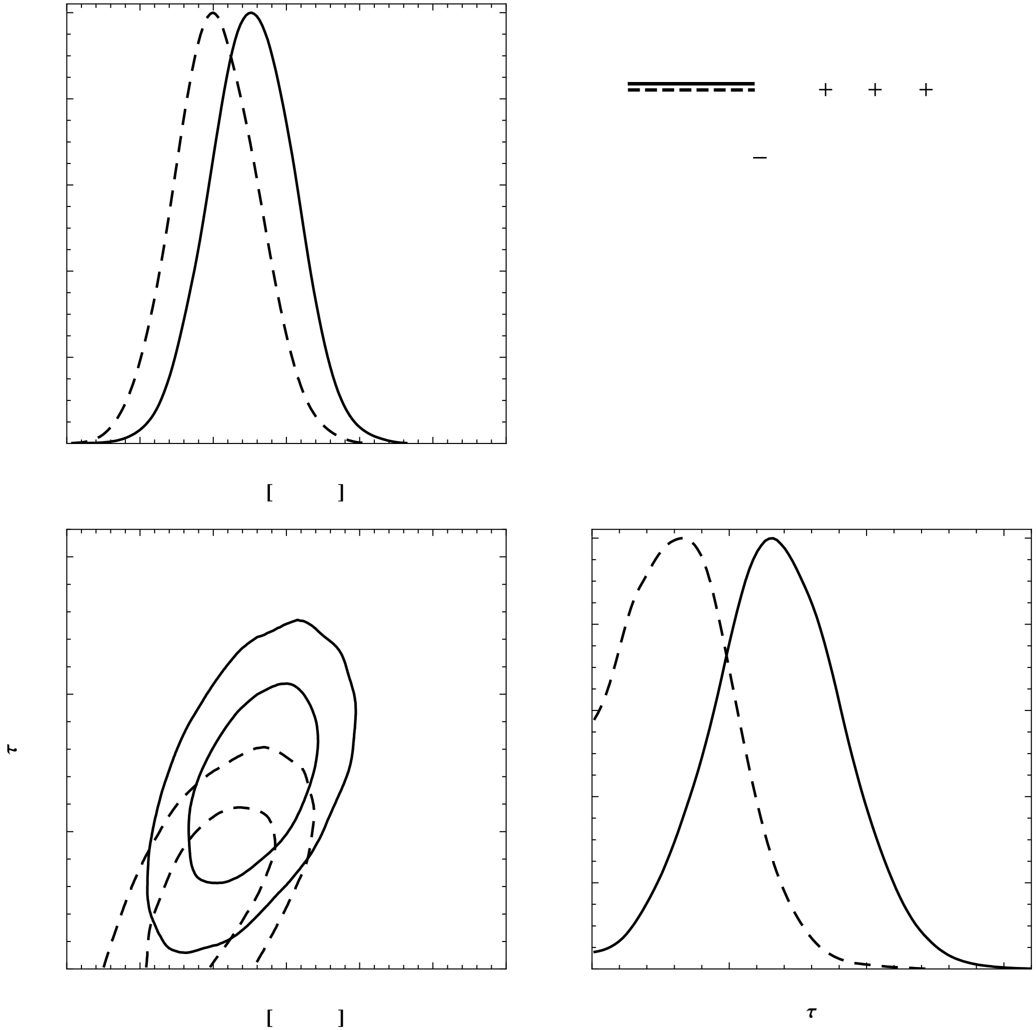
- ✓ This obtained is sampling also on A_s and τ
- ✓ All other parameters fixed to 2014 best fit
- ✓ Limit on r using polarization is stronger than with temperature only



Preliminary

Consistency: suppose we exchange E and B

1. A $\pi/4$ rotation sends Q -> -U, U-> Q and E -> -B, B -> E. Do we still measure τ? No!
2. This happens also with TT+TE+EB, but the effect is less evident, so another hint that TE is relevant.



Preliminary

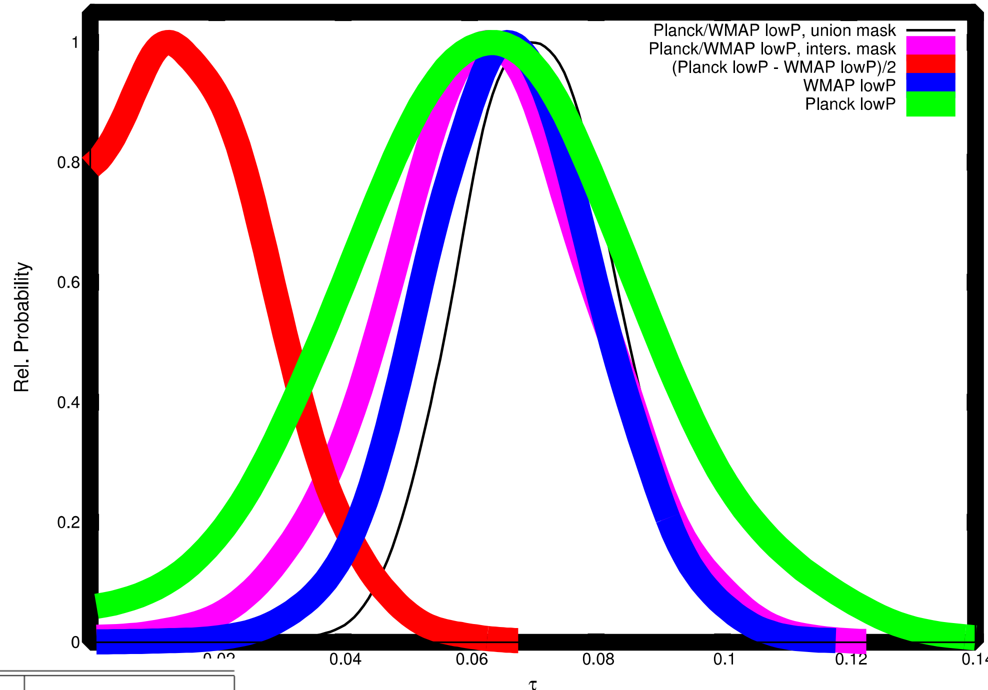
WMAP-9 with 353

1. In 2013 we used WMAP-9 for the release low ℓ likelihood. Dust cleaning for this dataset was based on a model. When analyzed with Planck TT, this yielded $\tau = 0.089 \pm 0.013$. This value is confirmed when using WMAP-9 public low ell products with Planck 2014.
2. In the 2013 likelihood paper we used a preliminary version of 353 polarization as a dust template. This lowered τ by 1σ to $\tau = 0.075 \pm 0.013$.
3. We have used the 2014 Planck 353 to clean again WMAP-9 Ka+Q+V, keeping WMAP K band as a synchrotron template (Planck 70 uses 30 GHz) and the WMAP processing and analysis masks (P06, fsky ≅ 0.74)
4. From this new dataset and Planck TT 2014 we get $\tau = 0.071 \pm 0.013$.

Preliminary

WMAP 9 and Planck 70: parameters

- ✓ TT here is always Planck 2014
- ✓ The τ signal disappears in the null map
- ✓ WMAP and Planck 70 yield consistent estimates
- ✓ We thus can combine them

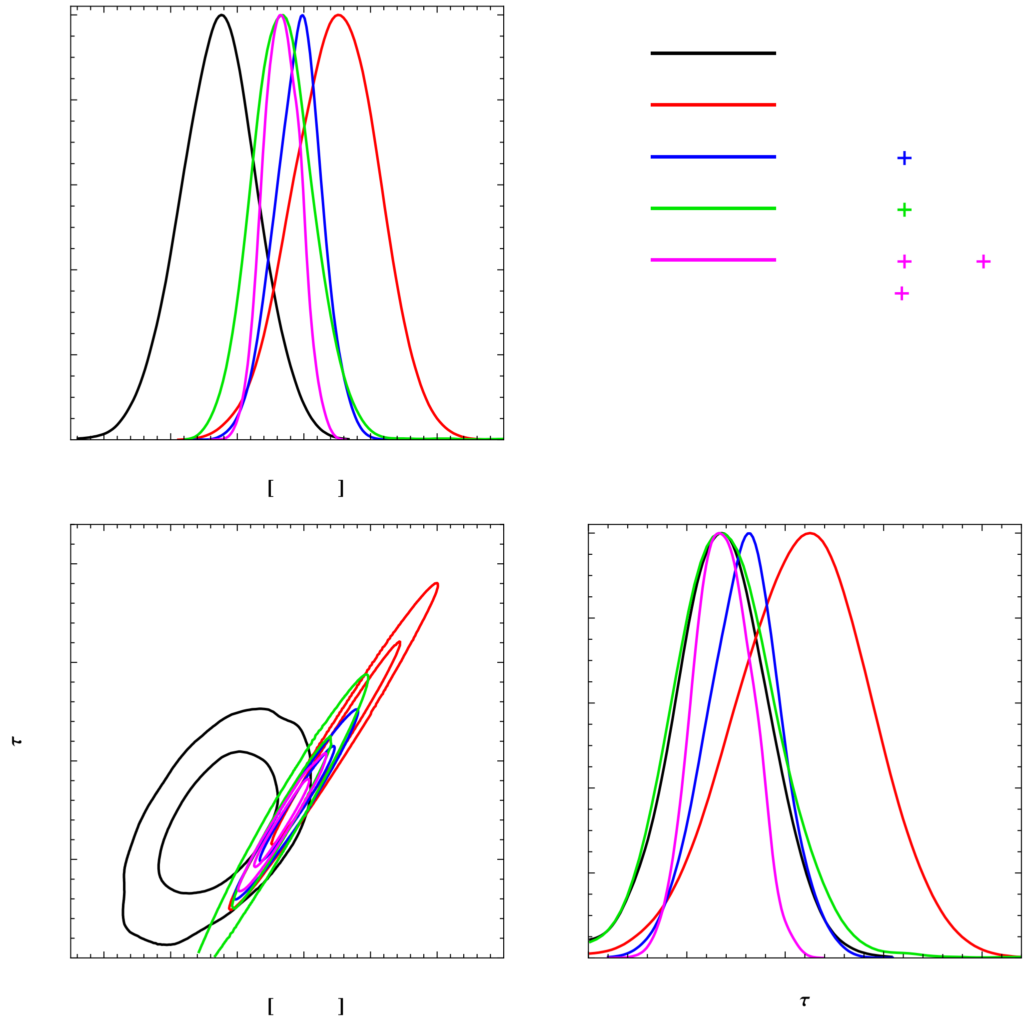


Parameter	Planck lowP +Planck lowT	Planck lowP +PlanckTT	WMAP lowP +Planck lowT	WMAP lowP +PlanckTT	Planck/WMAP lowP +Planck lowT	Planck/WMAP lowP +PlanckTT
τ	$0.064^{+0.022}_{-0.023}$	$0.077^{+0.019}_{-0.018}$	$0.067^{+0.013}_{-0.013}$	$0.071^{+0.012}_{-0.012}$	$0.071^{+0.011}_{-0.013}$	$0.074^{+0.012}_{-0.012}$
z_{re}	$8.5^{+2.5}_{-2.1}$	$9.8^{+1.8}_{-1.6}$	$8.9^{+1.3}_{-1.3}$	$9.3^{+1.1}_{-1.1}$	$9.3^{+1.1}_{-1.1}$	$9.63^{+1.1}_{-1.0}$
$\log[10^{10} A_s]$	$2.79^{+0.19}_{-0.09}$	$3.087^{+0.036}_{-0.035}$	$2.87^{+0.11}_{-0.06}$	$3.076^{+0.022}_{-0.022}$	$2.88^{+0.10}_{-0.06}$	$3.082^{+0.021}_{-0.023}$
r	[0, 0.90]	[0, 0.11]	[0, 0.52]	[0, 0.096]	[0, 0.48]	[0, 0.10]
$A_s e^{-2\tau}$	$1.45^{+0.24}_{-0.14}$	$1.878^{+0.010}_{-0.010}$	$1.55^{+0.16}_{-0.10}$	$1.879^{+0.011}_{-0.010}$	$1.55^{+0.14}_{-0.11}$	$1.879^{+0.010}_{-0.010}$

Preliminary

Low and high ell

- ✓ Low/high ell tension still present in 2014, but less prominent
- ✓ It also affects τ: high ell TT prefer an higher value
- ✓ Planck TT + low P and Planck TT + lensing are very compatible.



Preliminary

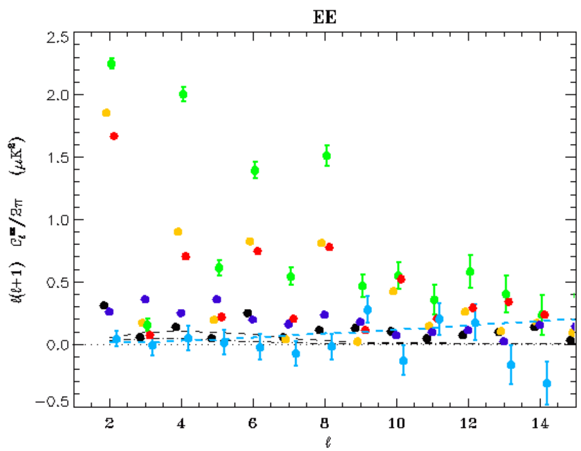
Conclusions

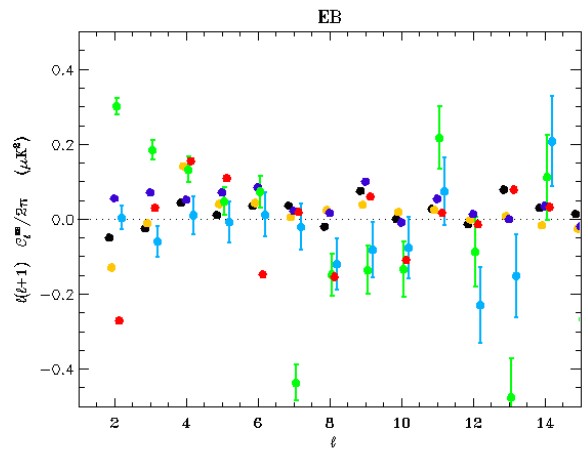
1. Planck baseline low ell likelihood for 2014 is based on 70 GHz, with 30 and 353 GHz as cleaning templates
2. There is good consistency with WMAP-9 low ell polarization, when the latter is cleaned using 353.
3. Estimates of tau from low ell polarization and lensing are also compatible.
4. Planck can do much better than what is presented here. Planck HFI alone has already reached a sensitivity on τ of the order of 0.006 (three times better): results were however not deemed stable enough to be presented. There is also good hope from multifrequency polarized component separation.

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

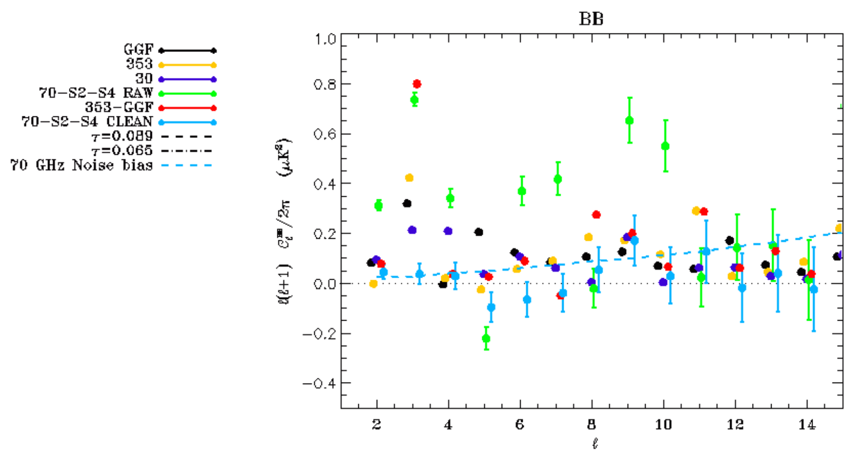
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

From frequency maps to clean maps



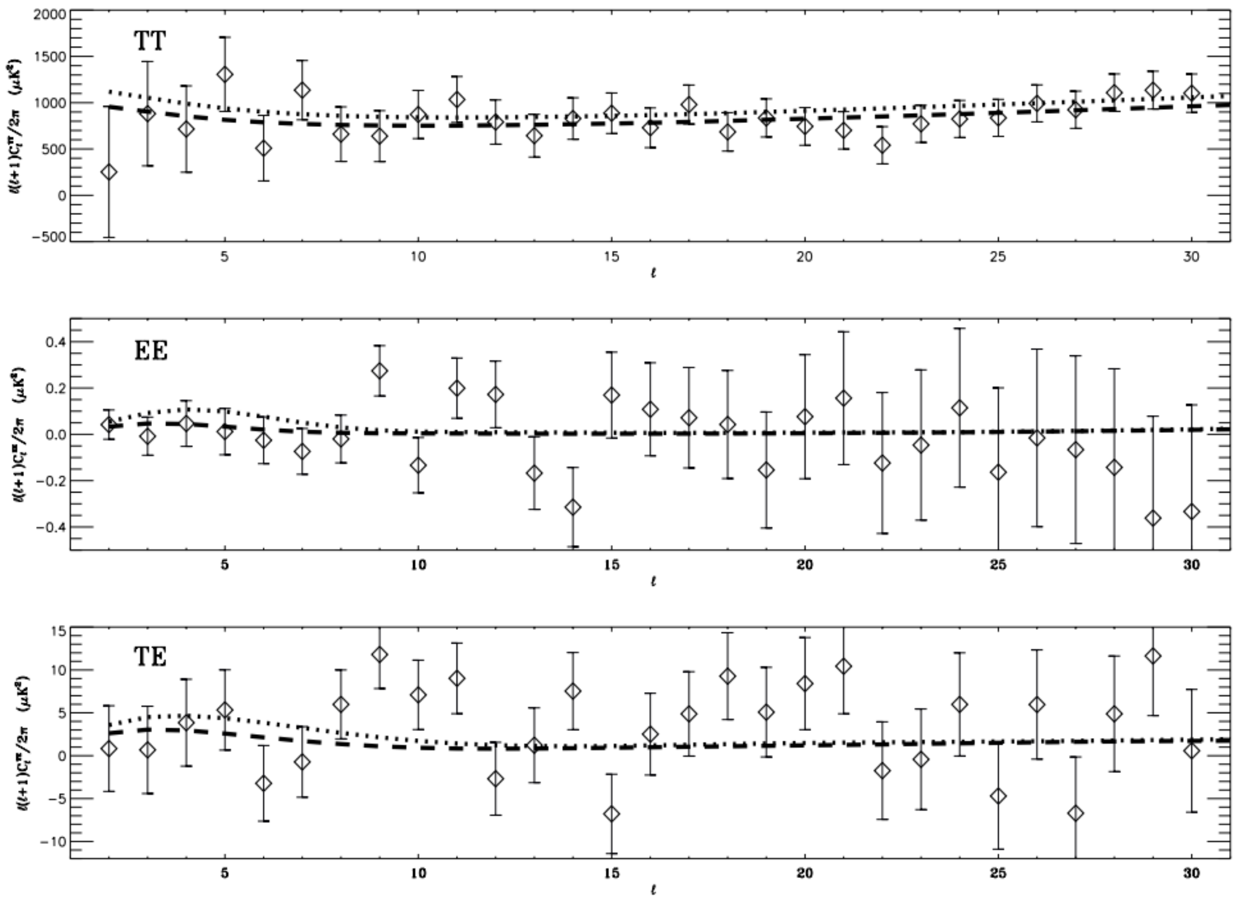


[REDO AND MAKE MORE READABLE
- REMOVE GGF RELATED SPECTRA
- ONLY LOW TAU MODEL?



Low ell power spectra 1/2

[REDO WITH ALL SIX SPECTRA IN ONE SLIDE]

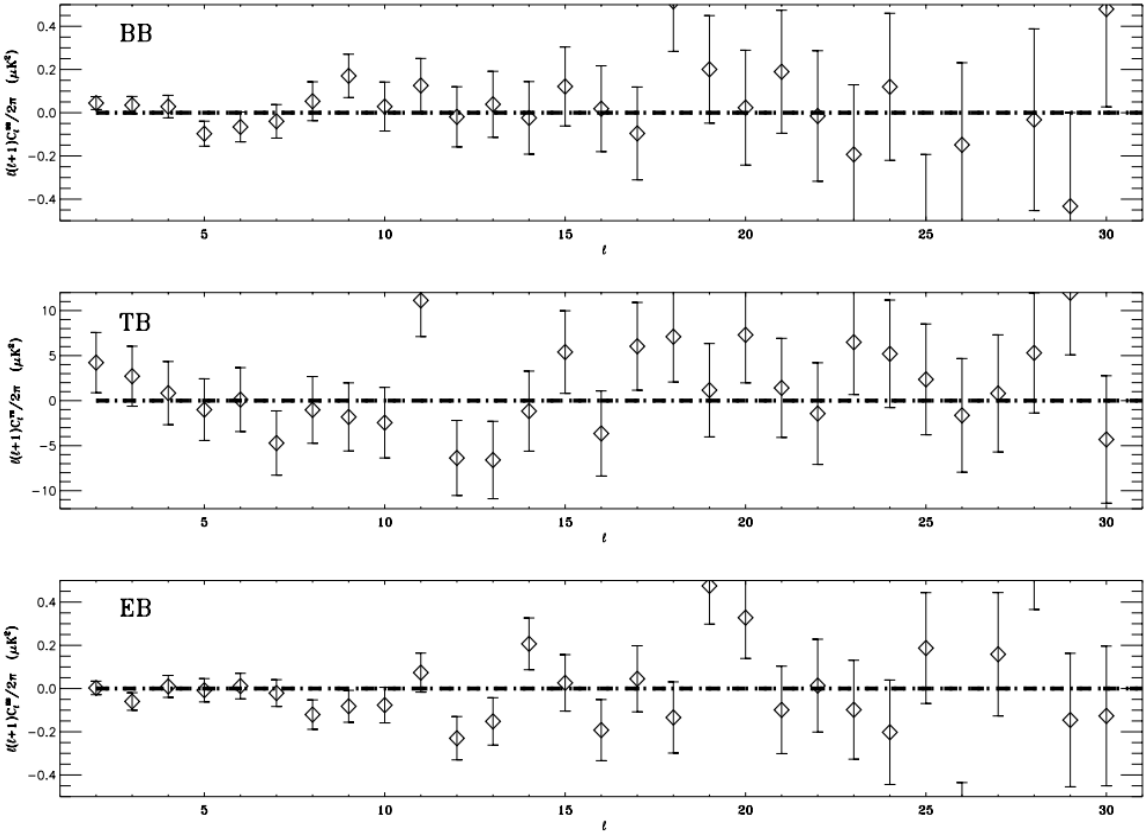


.... Planck 2013

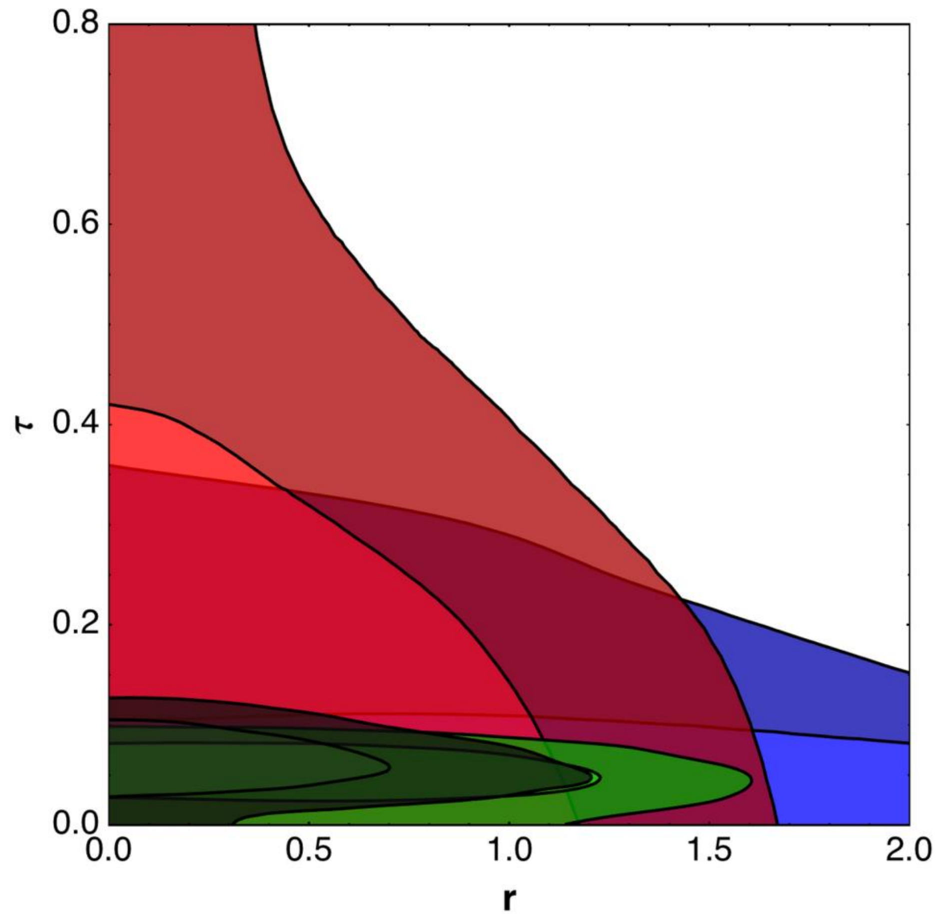
– – – – τ = 0.065

Preliminary

Low ell power spectra 2/2



Preliminary



X, Ferrara, Dec 2014