# The CMB polarization at large scales: Planck 2015 and future prospects

B-modes from space
IPMU 10th-16th December 2015

**Anna Mangilli**
Institut d'Astrophysique Spatiale

ON BEHALF OF THE PLANCK COLLABORATION

+ **Matthieu Tristram**
+ work in progress: J. Aumont, J. Grain, F. Boulanger

# OUTLINE

- **The CMB polarization at large angular scales**
- **The Planck 2015 release**

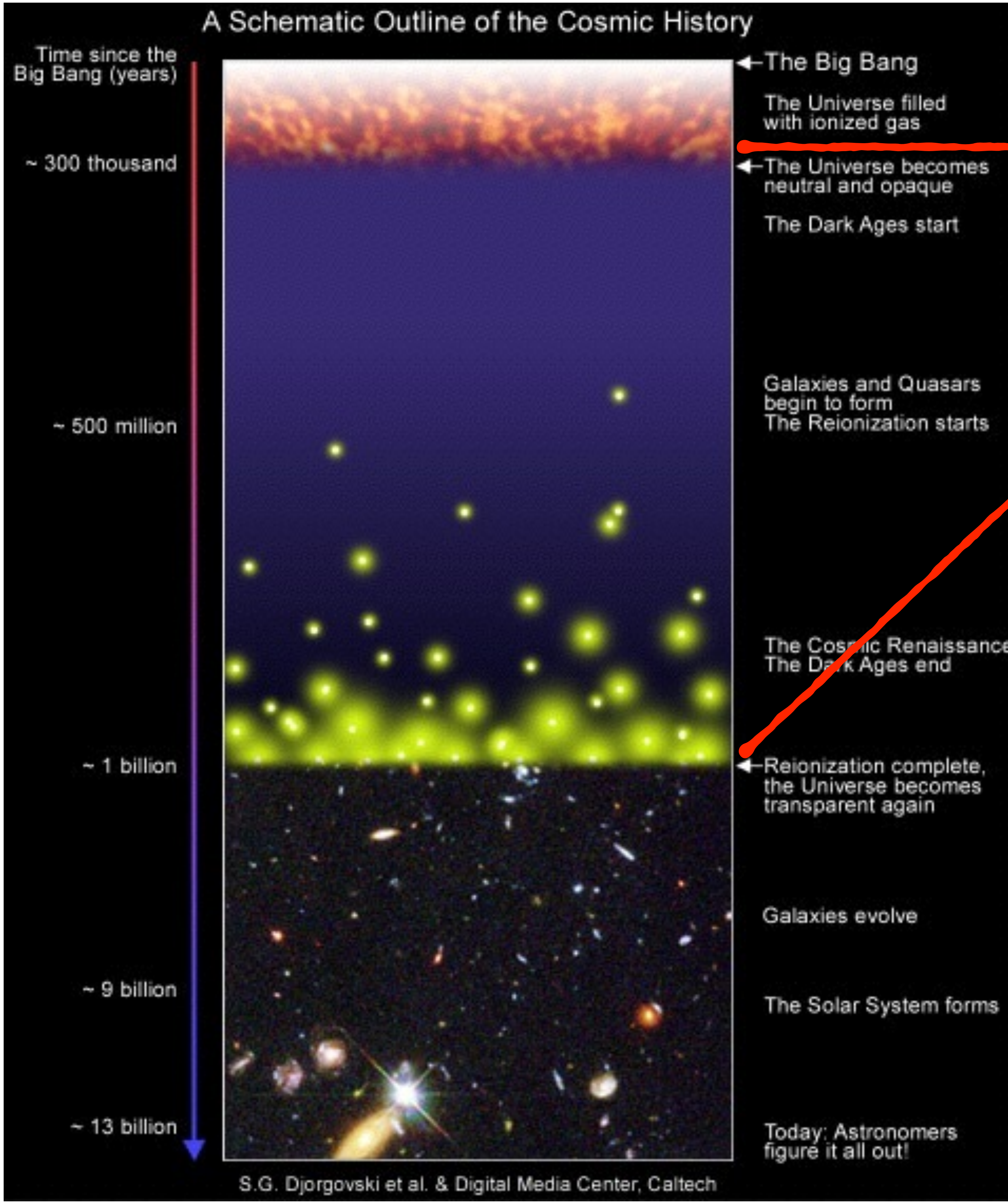
  Current status of the constraints on $\tau$ and r from large scales

- **The challenge**

  Statistical methods [Mangilli, Plaszczynski, Tristram. MNRAS 2015]
  Preliminary Planck HFI results

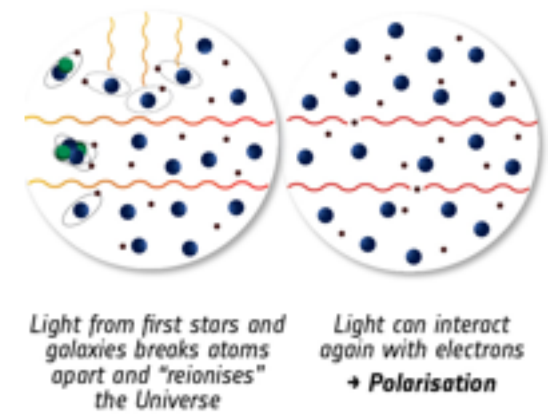
- **Future prospects & conclusions**

# The CMB polarization at large scales




DECOUPLING

REIONIZATION

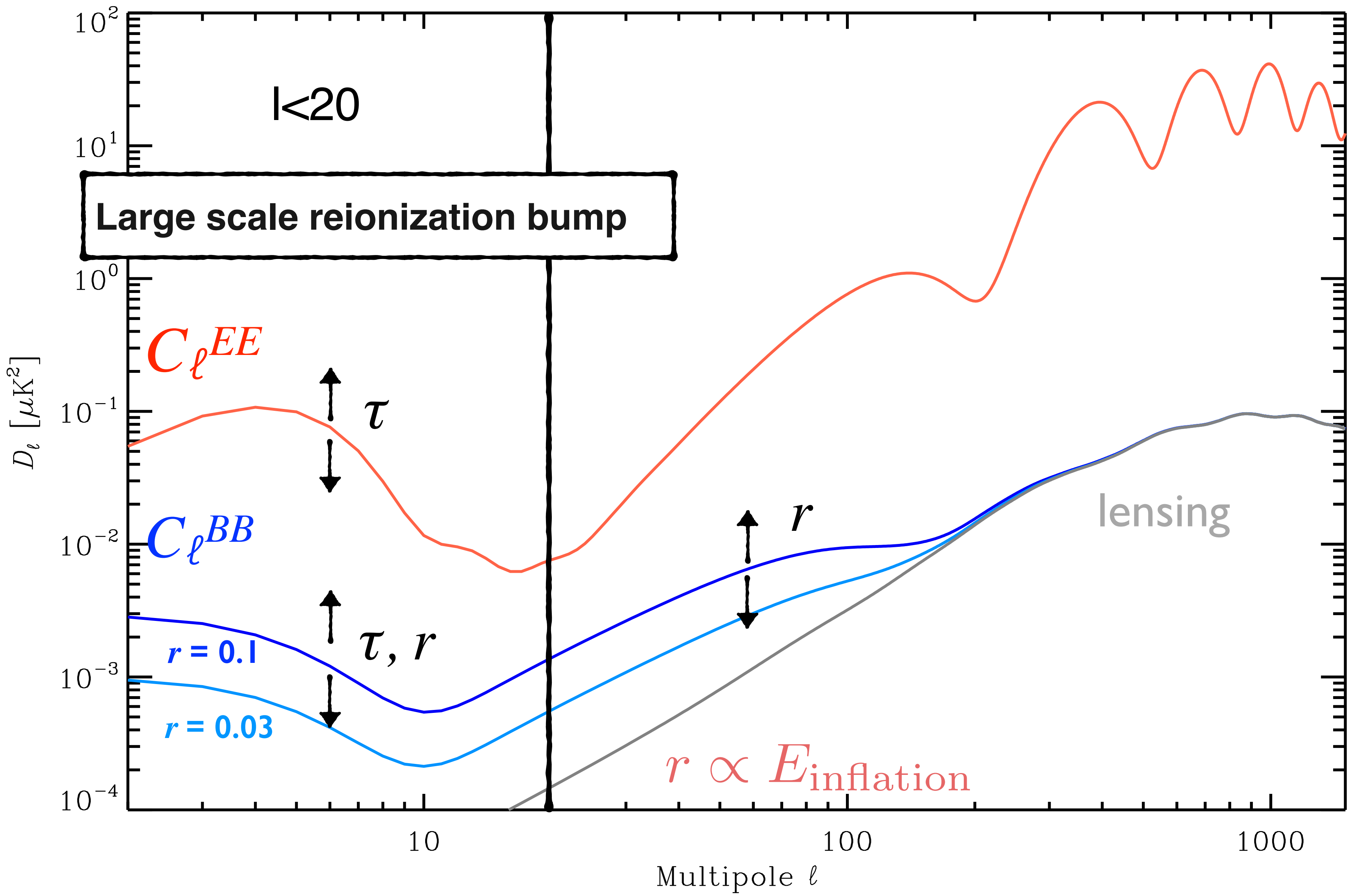



Thomson scattering optical depth:

$$\tau = \int_0^{z\_reio} a n_e \sigma_T \, d\eta$$

**Enhancement** of the E&B modes at large angular scales: REIONIZATION BUMP

# The CMB polarization at large scales




## The major challenges

1) **Polarized diffuse emission from our Galaxy**: dust, synchrotron …

2) **Instrumental** systematics projecting on the sky (any instability of the detectors during the observations)

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# Polarization at large angular scales status

- Planck detectors are sensitive to one polarization direction
- Polarization reconstruction: detector combinations
- Mismatch between detectors will create spurious polarization signal (Calibration mismatch, bandpass mismatch, etc…)

**Major systematics in polarization at large angular scales:**

**Intensity to Polarization leakage**

**2015 release:**

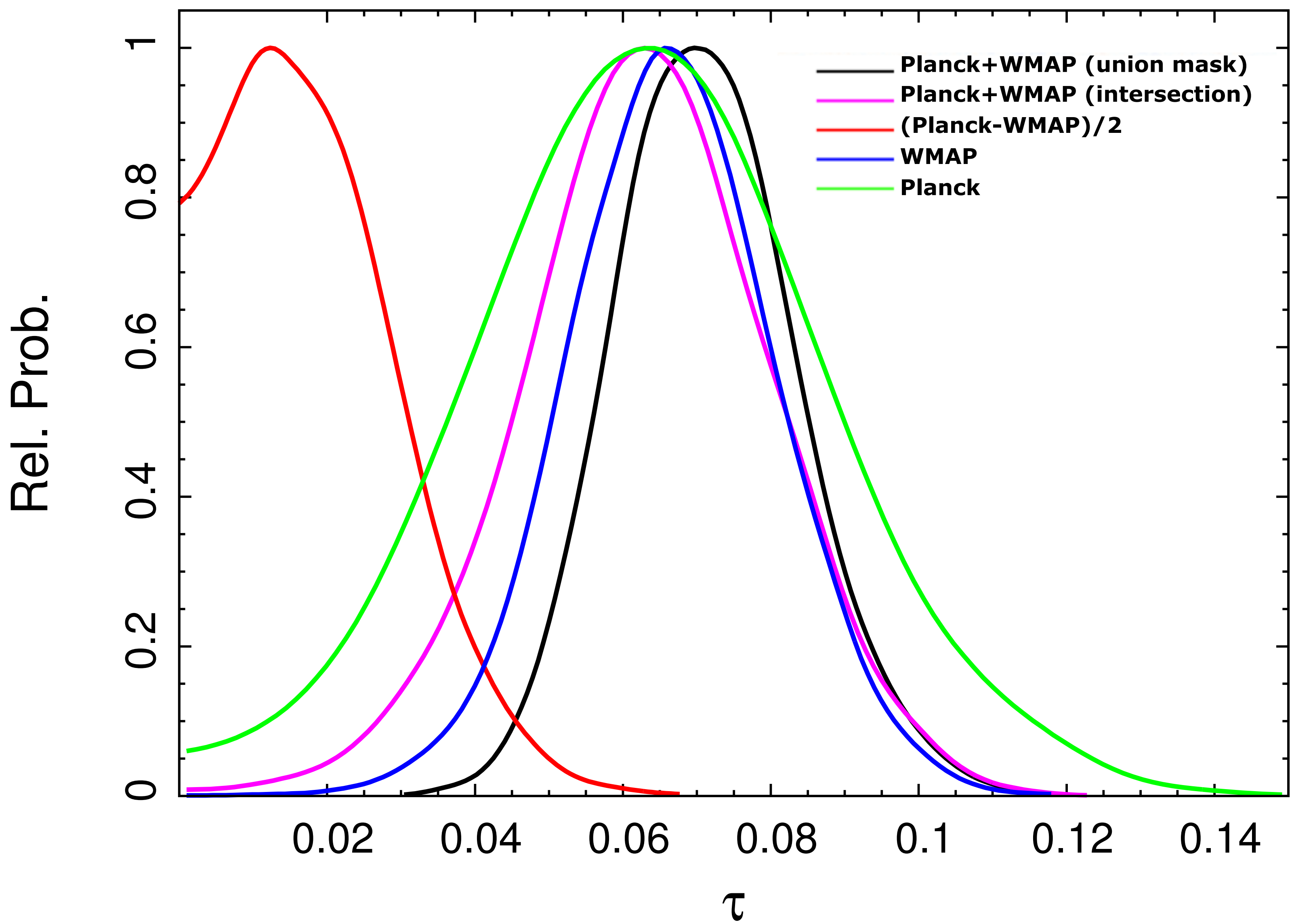
LFI: negligible residuals with respect to noise, **LFI 70GHz released**

HFI has higher sensitivity, lower noise: residuals systematics

**HFI 100GHz, 143GHz, 217GHz NOT used for the 2015 low-l analysis**

↳ **Preliminary results (pre-release 2016)**

# τ from Planck 2015 large scale polarization




The Planck Coll. XI, 2015

- ✓ **WMAP and Planck LFI-70GHz yield consistent estimates**
- ✓ Planck: conservative mask ($f_{sky}$=0.46)
- ✓ **The signal disappears in the null map**

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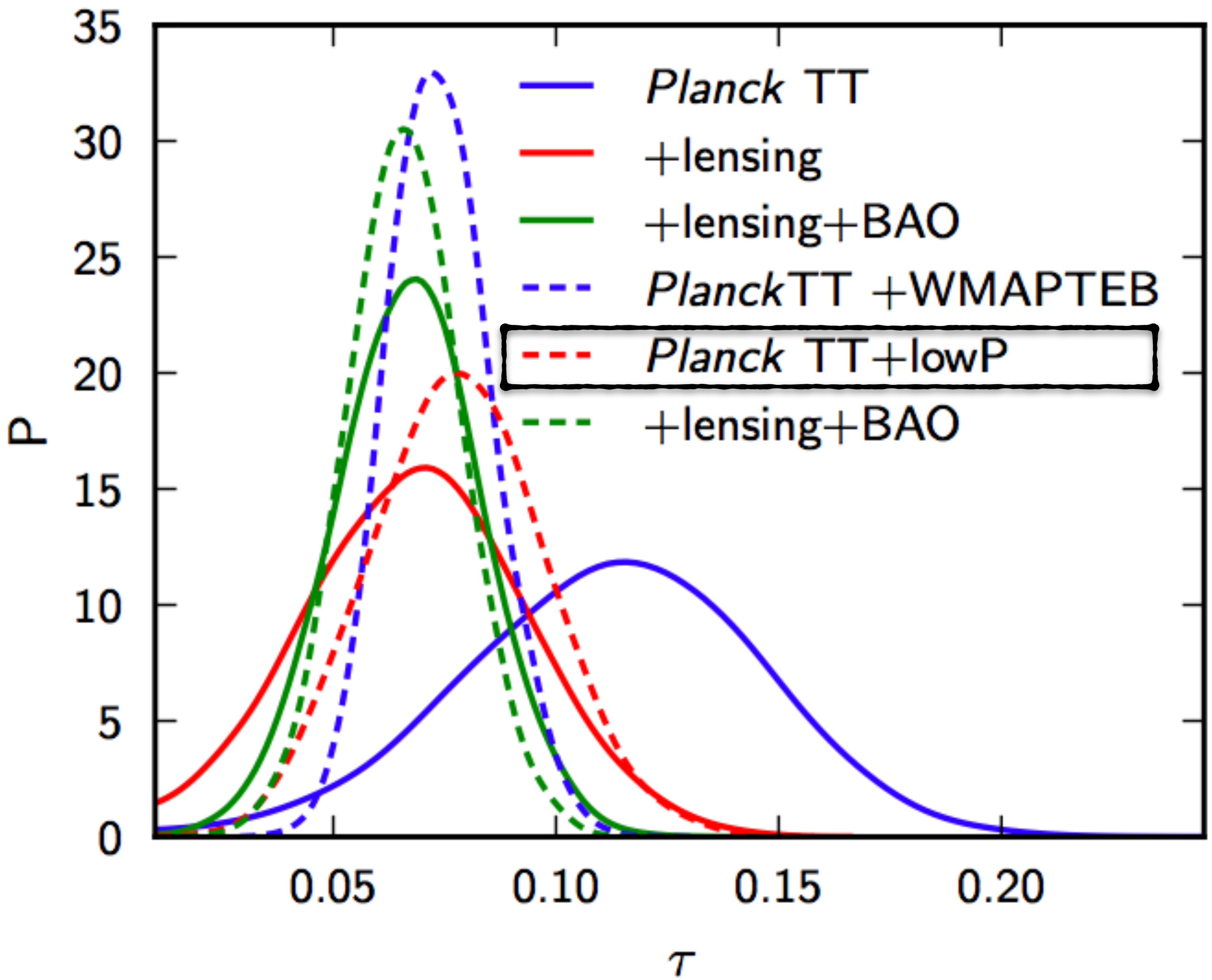
# Planck 2015: reionization optical depth summary




The Planck Coll. XIII, 2015

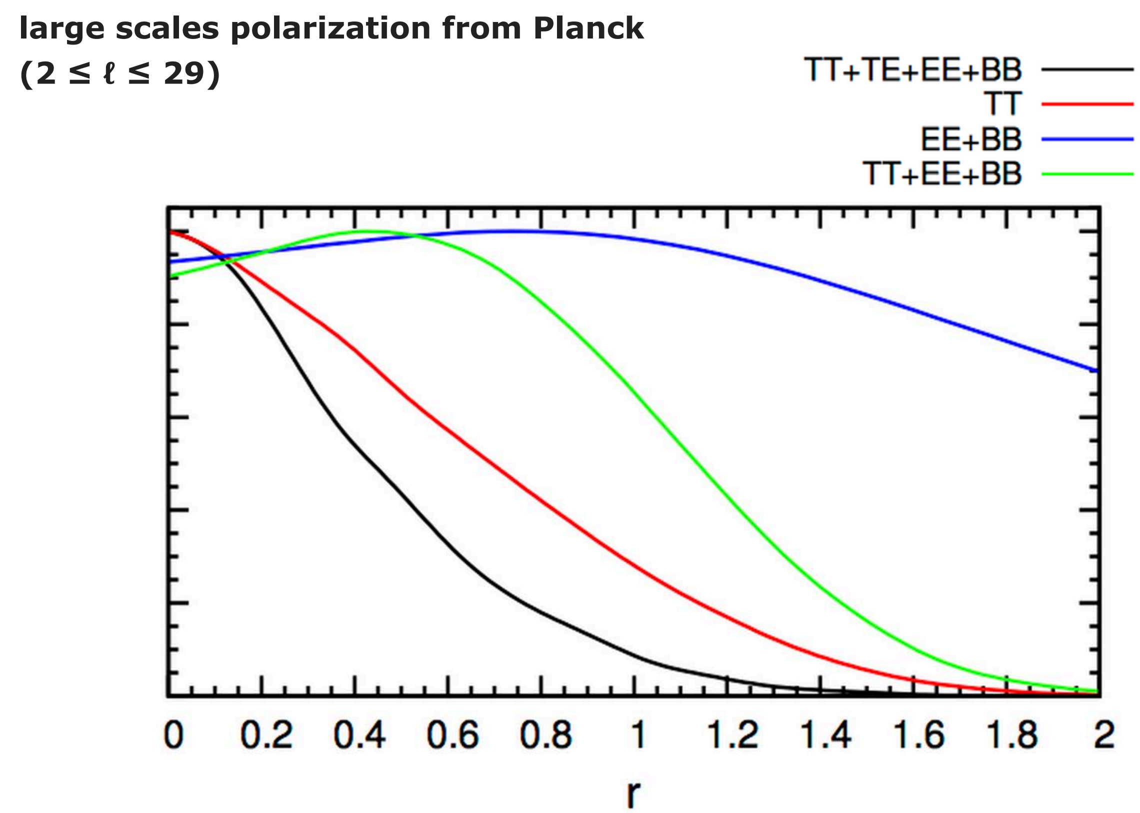
**… Planck results seems to point to lower τ.**

This has an implication also for the large scales B-modes detection

# Planck 2015: Tensor-to-scalar ratio

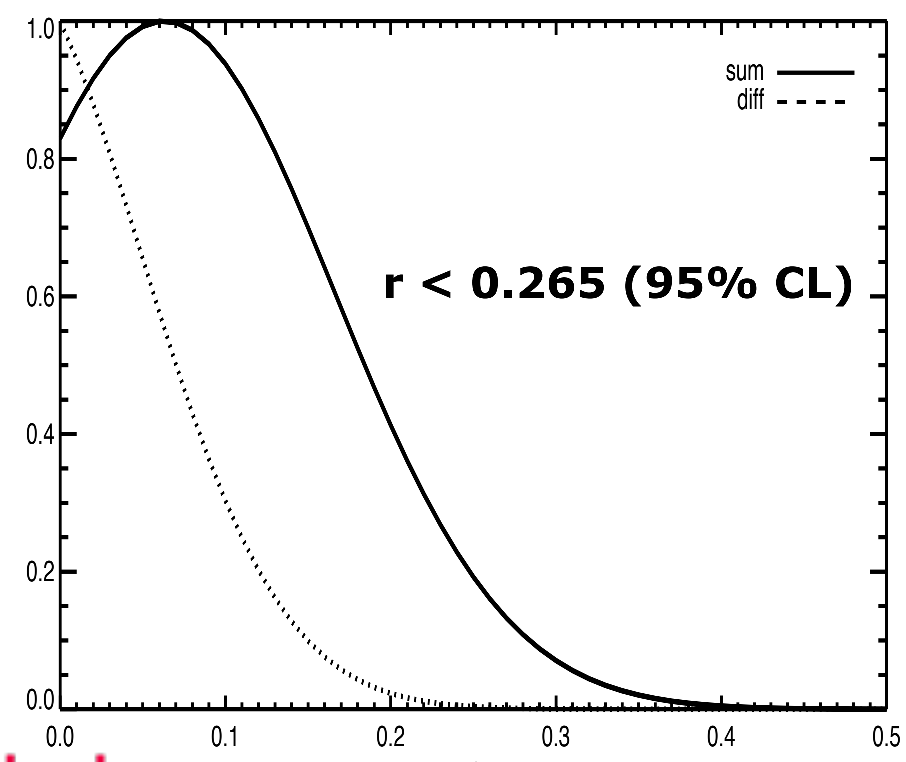
From large scales: still far.
But significant improvement on the way for 2016

The Planck Coll. XI 2015



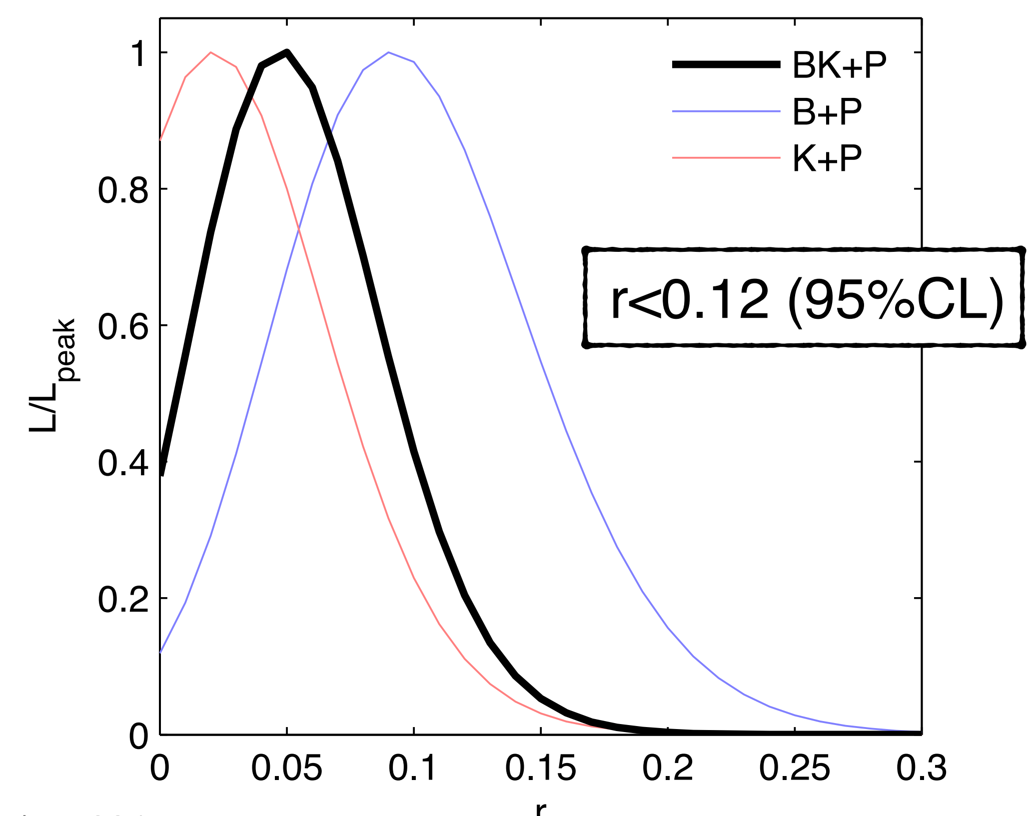

From intermediate scales:

**Planck 100GHz&143GHz**




**Planck + Bicep/Keck**

PRL 114 2015



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# The challenge

➡ **Data quality**

Control of systematics, in particular HFI 100GHz,143GHz,217GHz
(See Matthieu's talk)
Accurate foreground subtraction/modelling

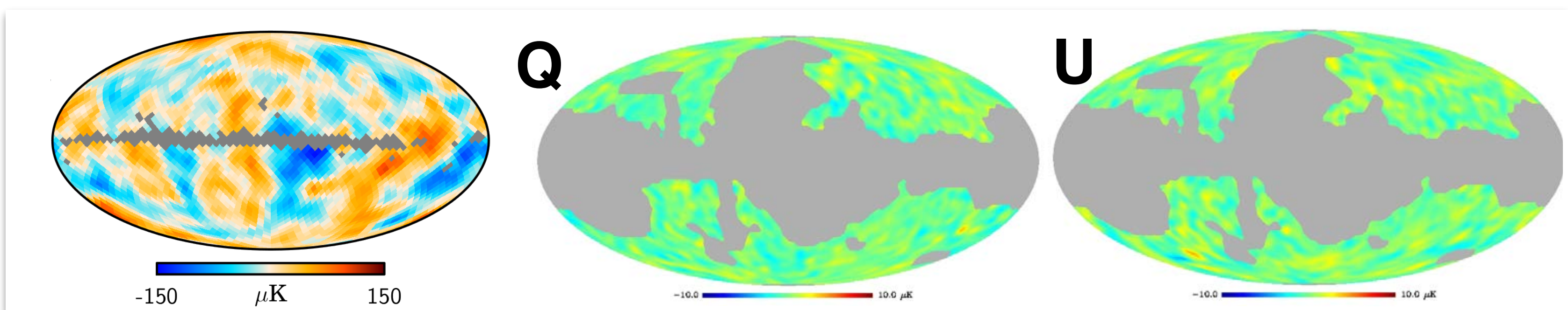
➡ **Data analysis**

Statistical method(s) optimized to CMB analysis @ large angular scales

So far (WMAP, Planck 2013, 2015): Gaussian likelihood in **map space**

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

**M= CMB signal+noise covariance matrix**




Problem: noise covariance matrix reconstruction accuracy

- Can compromise parameter reconstruction in particular for the high sensitivity of HFI channels
- Difficult handling of noise bias/residual systematics

# Cross-spectra likelihood at large scales

[Mangilli, Plaszczynski, Tristram (MNRAS 2015)]

**Use cross-spectra likelihood at large scales**

Noise bias removed. Exploit cross dataset informations
Better handling of residual systematics/foregrounds

**Two solutions** to solve for the non-Gaussianity of the estimator distributions at low multipoles

1. Analytic approximation of the estimators: works for single-field and small mask

2. **Modified Hamimeche&Lewis (2008) likelihood for cross-spectra (oHL)**

Full temperature and polarization analysis

# Cross-spectra likelihood at large scales

[Mangilli, Plaszczynski, Tristram (MNRAS 2015)]

## 2. Modified likelihood for cross-spectra (oHL)

$$-2ln\mathscr{L}(C_\ell|\hat{C}_\ell^{A\times B}) = \sum_{\ell\ell'}[OX_g]_\ell^T [M_f^{-1}]_{\ell\ell'} [OX_g]_{\ell'}$$

- "Gaussianization"

$$g(x) = sign(x-1)\sqrt{(2(x-ln(x)-1))}, \qquad [X_g]_\ell = \mathrm{vecp}\left(\mathbf{C}_{fid}^{1/2}\mathbf{U}(\mathbf{g}[\mathbf{D}(\mathbf{P})])\mathbf{U}^\mathbf{T}\mathbf{C}_{fid}^{1/2}\right)$$

$$\mathbf{P} = \mathbf{C}_{mod}^{-1/2}\hat{\mathbf{C}}_{data}\mathbf{C}_{mod}^{-1/2}$$

"Offset" terms: $\propto$ $N_{eff}$

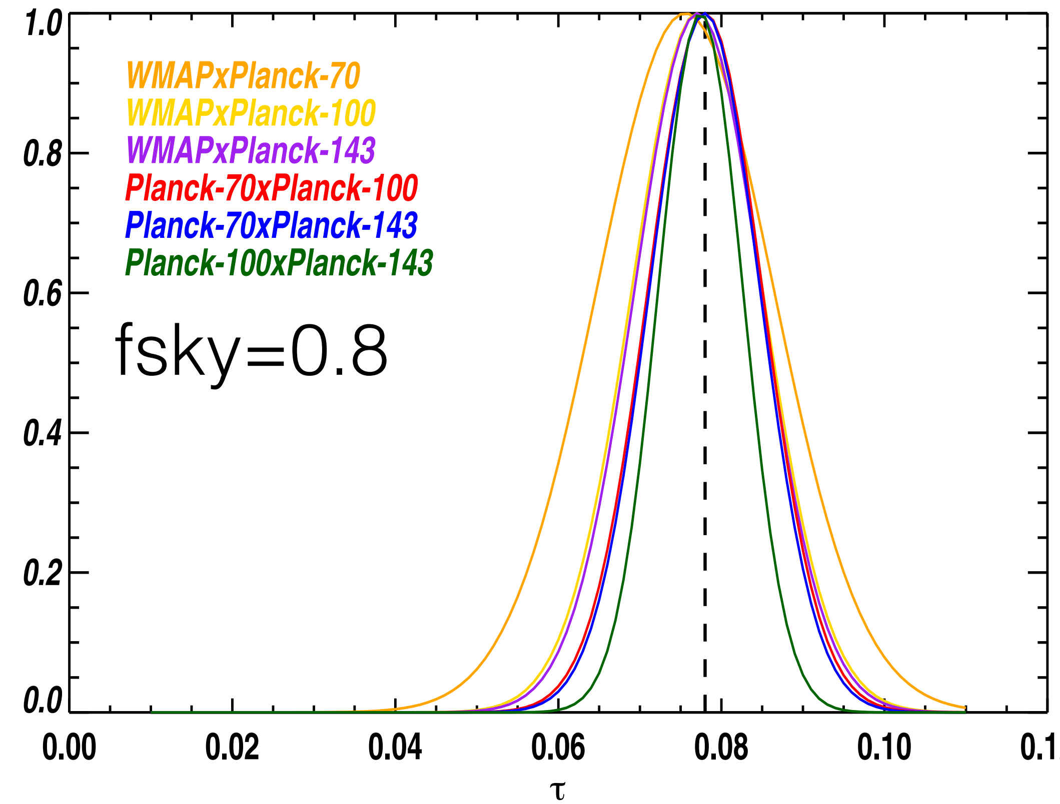
$$\mathbf{C}_\ell^{A\times B} \rightarrow O(\mathbf{C}_\ell^{A\times B}) = \begin{pmatrix} C_\ell^{TT} + o_\ell^{TT} & C_\ell^{TE} & C_\ell^{TB} \\ C_\ell^{TE} & C_\ell^{EE} + o_\ell^{EE} & C_\ell^{EB} \\ C_\ell^{TB} & C_\ell^{EB} & C_\ell^{BB} + o_\ell^{BB} \end{pmatrix}$$

Full temperature and polarization analysis

# Cross-spectra oHL: τ estimation

[Mangilli, Plaszczynski, Tristram (MNRAS 2015)]

τ posterior from realistic MC simulations, different noise levels, l=[2,20]

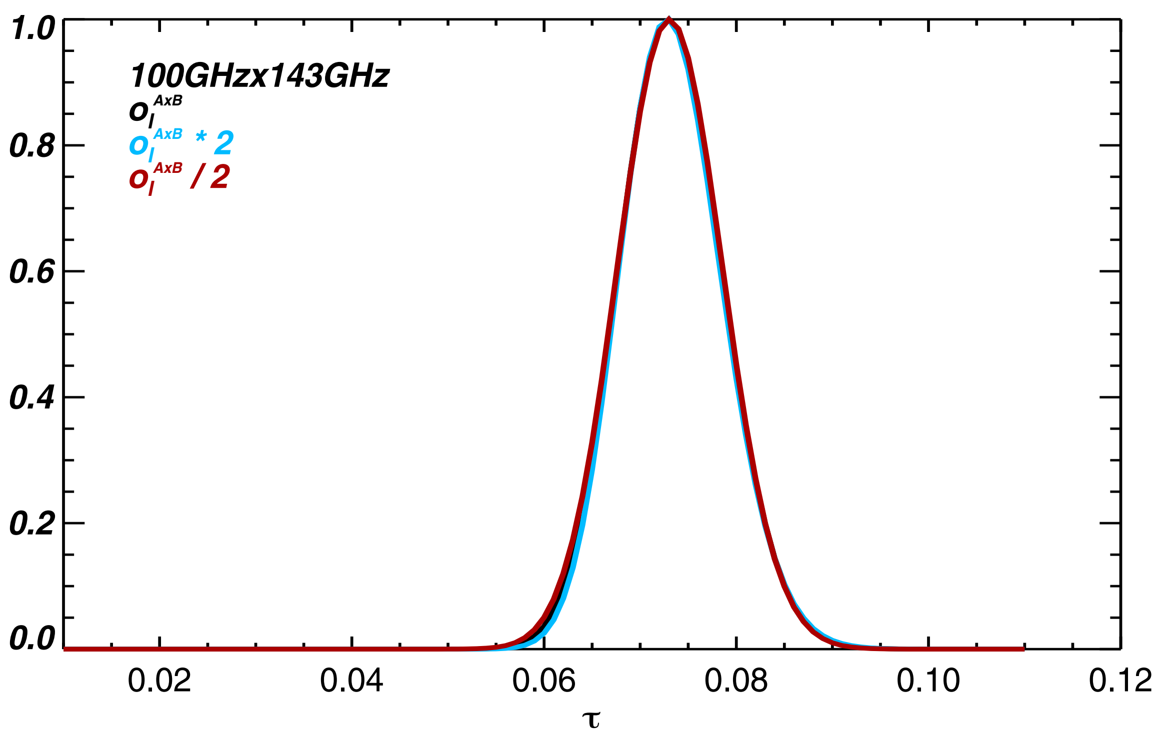


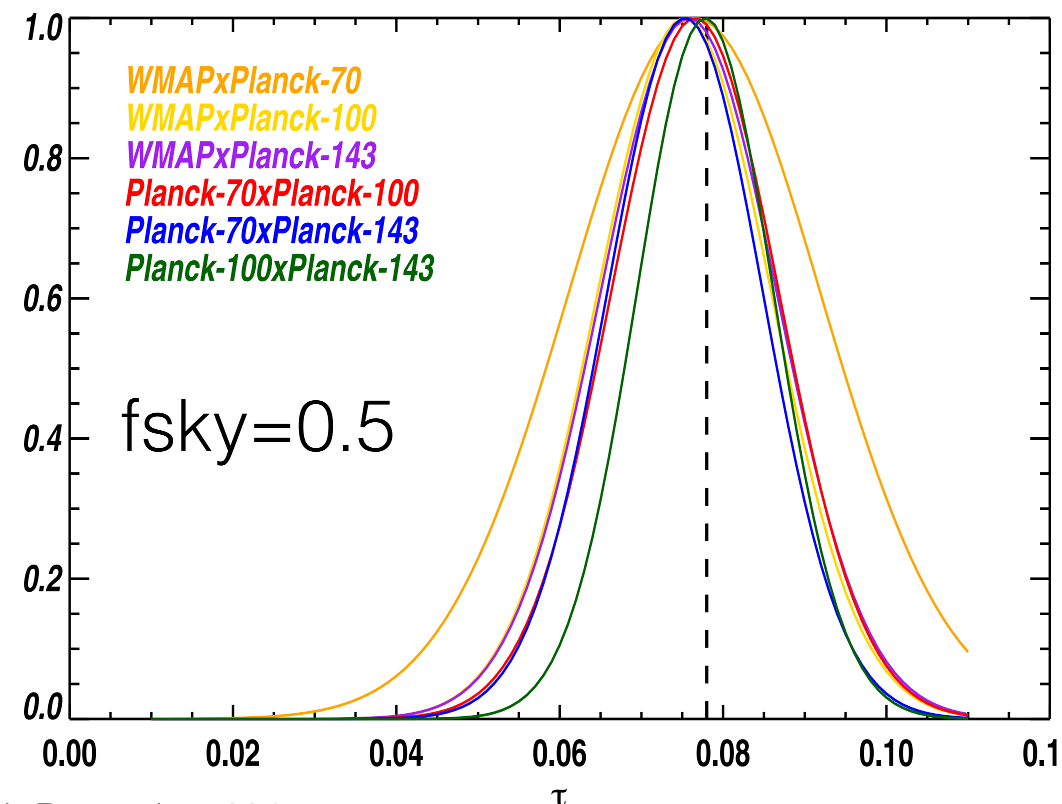

## Unbiasedness

Best constraints expected from HFI 100x143GHz

## Robustness

Offset change



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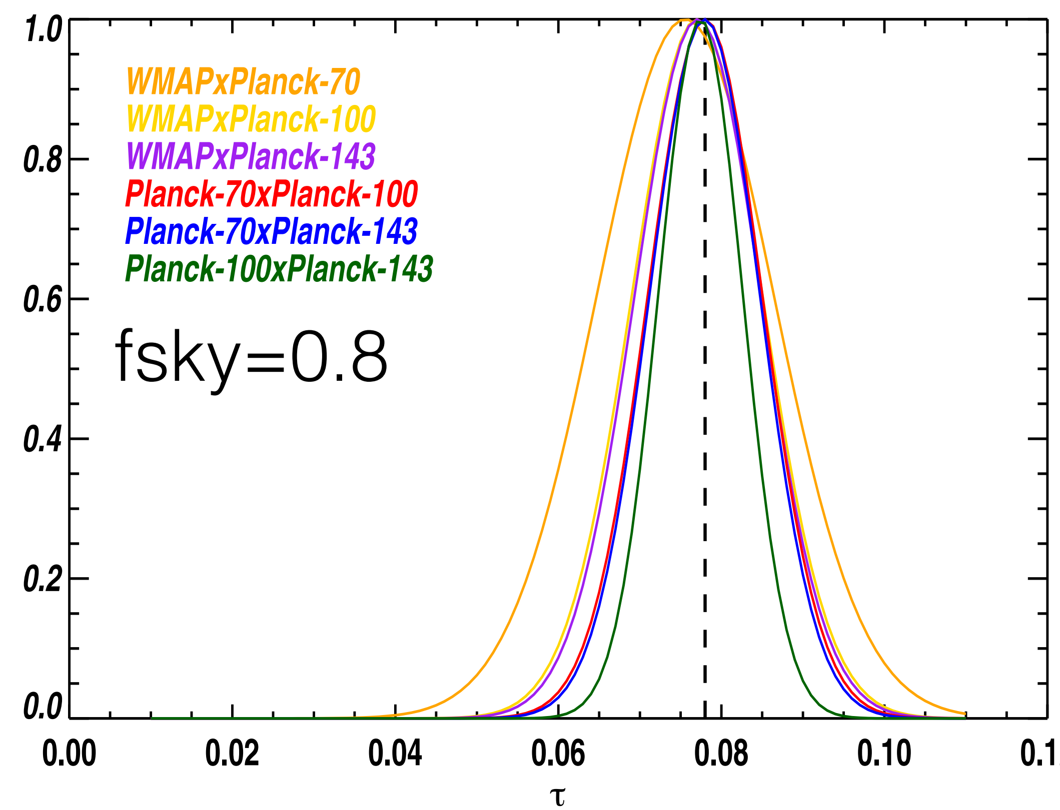
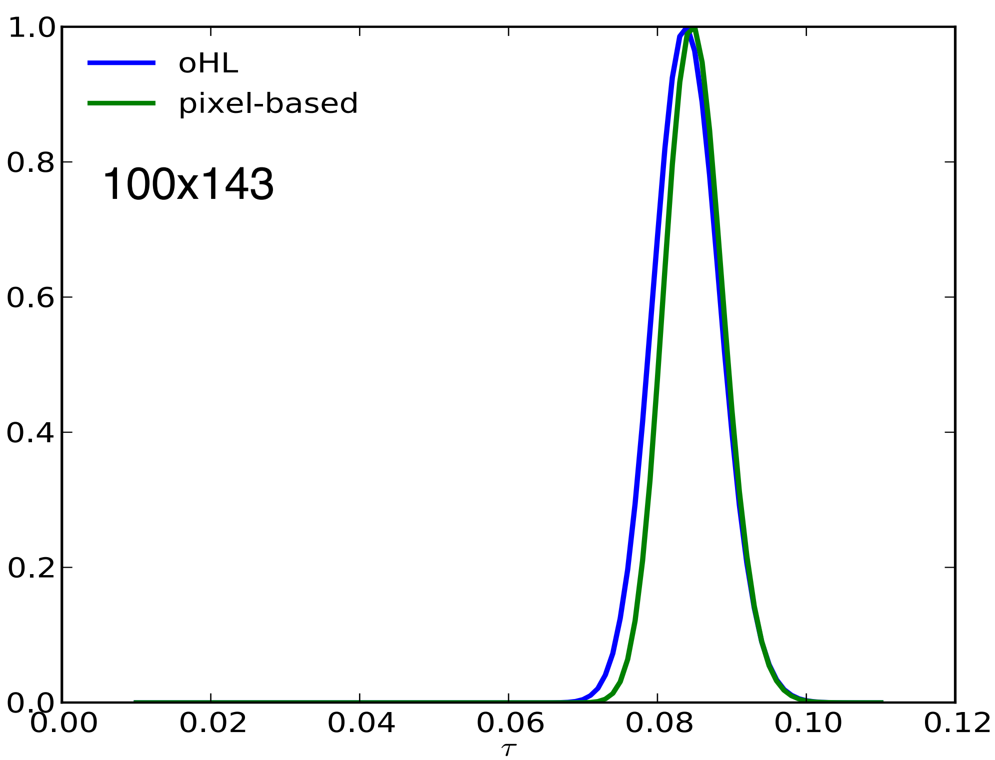



## Optimality

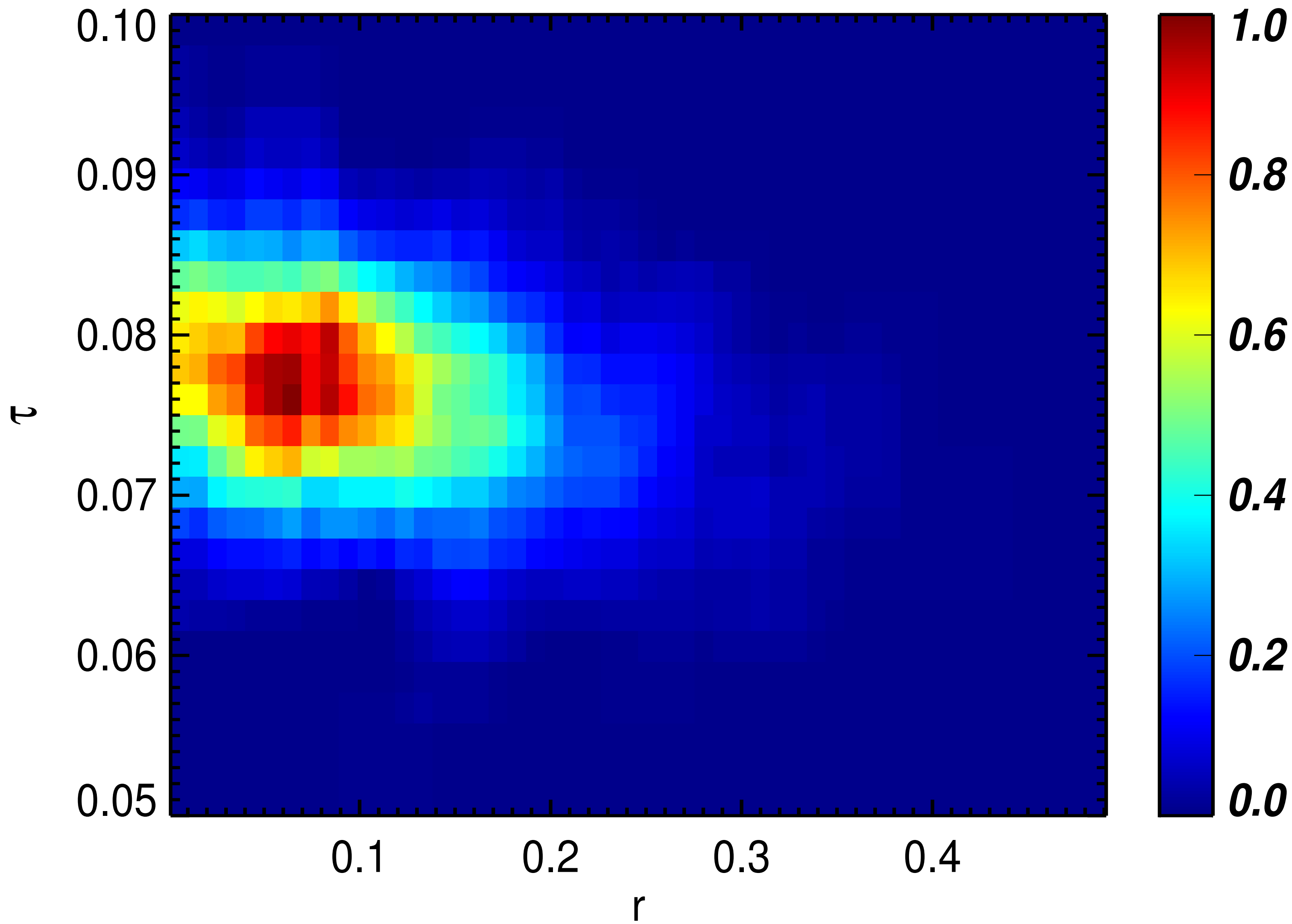



Comparison with the pixel-based approach: compatible error bars estimation at better than 10%

# Cross-spectra oHL: τ estimation

[Mangilli, Plaszczynski, Tristram (MNRAS 2015)]

l=[2,20], full temperature and polarization oHL likelihood
MC simulations Planck 100x143 with correlated noise



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# Planck preliminary HFI results

**Preliminary Planck 100GHzx143GHz E-modes at low-l:**

+ Example of results from combination of low-l with:

1. **+Planck TT** CMB spectrum (2015)
2. **+Very High-l** ground-based experiments (ACT & SPT)
3. **+lensing** Planck 2015

See more details in Matthieu's talk

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# Planck at large scales take away message

Preliminary Planck results points to a **significantly lower value for the reionization optical depth.**

**This has important implications:**

- CMB consistent with a **fully reionized Universe at z ~ 6** (more details in Matthieu's talk )
- in better agreement with recent astrophysical constraints
- **More challenging to detect the B-modes at large scales**
- **Improved preliminary Planck measurements of the B-modes at large scales with 100GHzx143GHz**

**The Planck collaboration:** "Improved large angular scale polarization data and the reionization optical depth", to be submitted A&A

**The Planck collaboration:** "Reionization history constraints from Planck", to be submitted A&A

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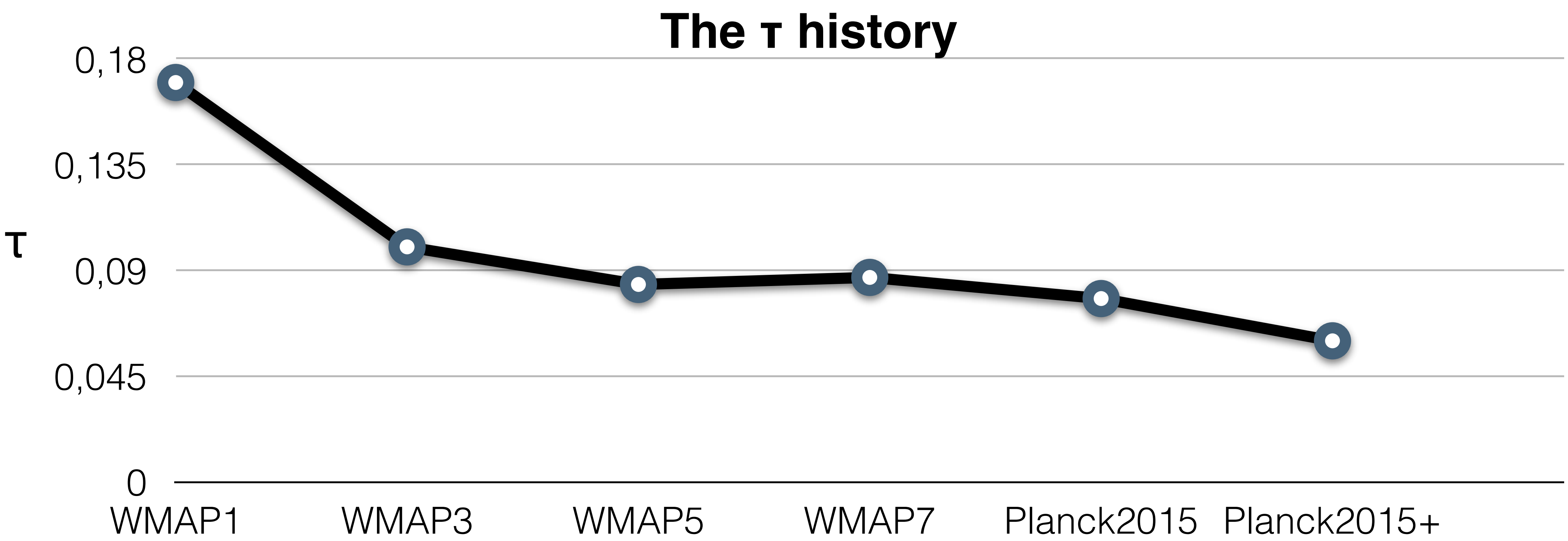
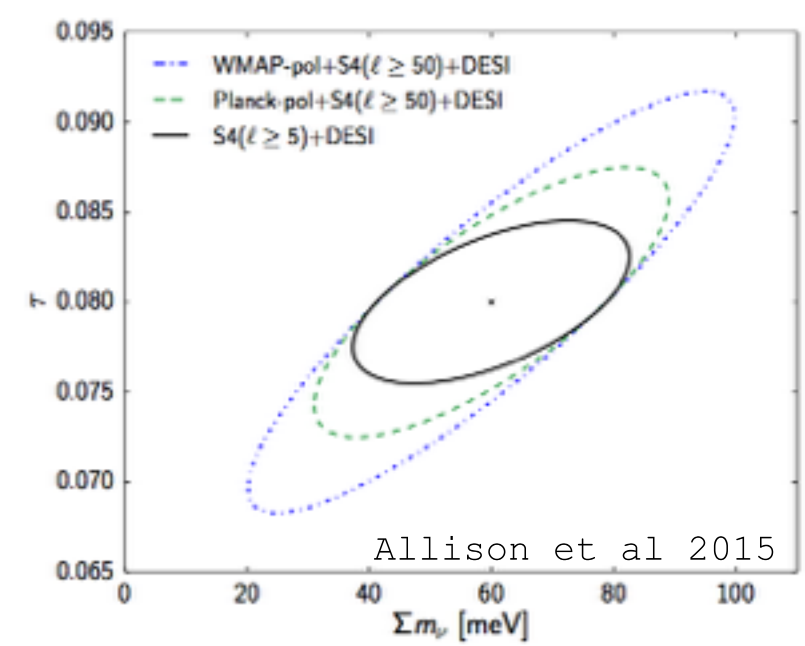
# Future prospects: E-modes



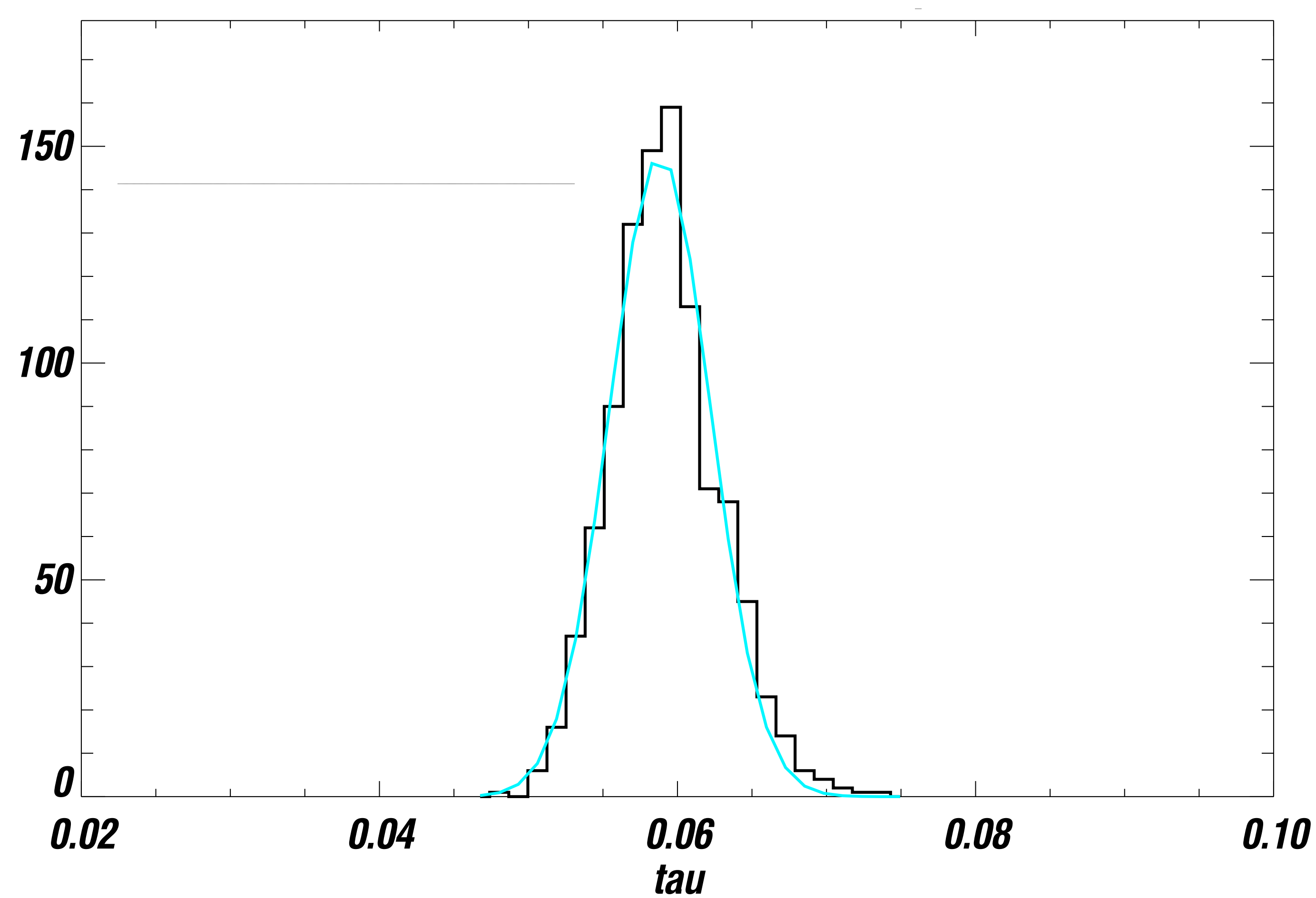

- The lower the τ value, the more difficult also for future experiments to detect features in the E-modes reionization bump to constrain e.g. evolution of reionization/non-standard energy injections
- More precision on τ, improved constraints on cosmological parameters ($A_s$, $\Sigma m_\nu$, …)



# Future prospects: E-modes

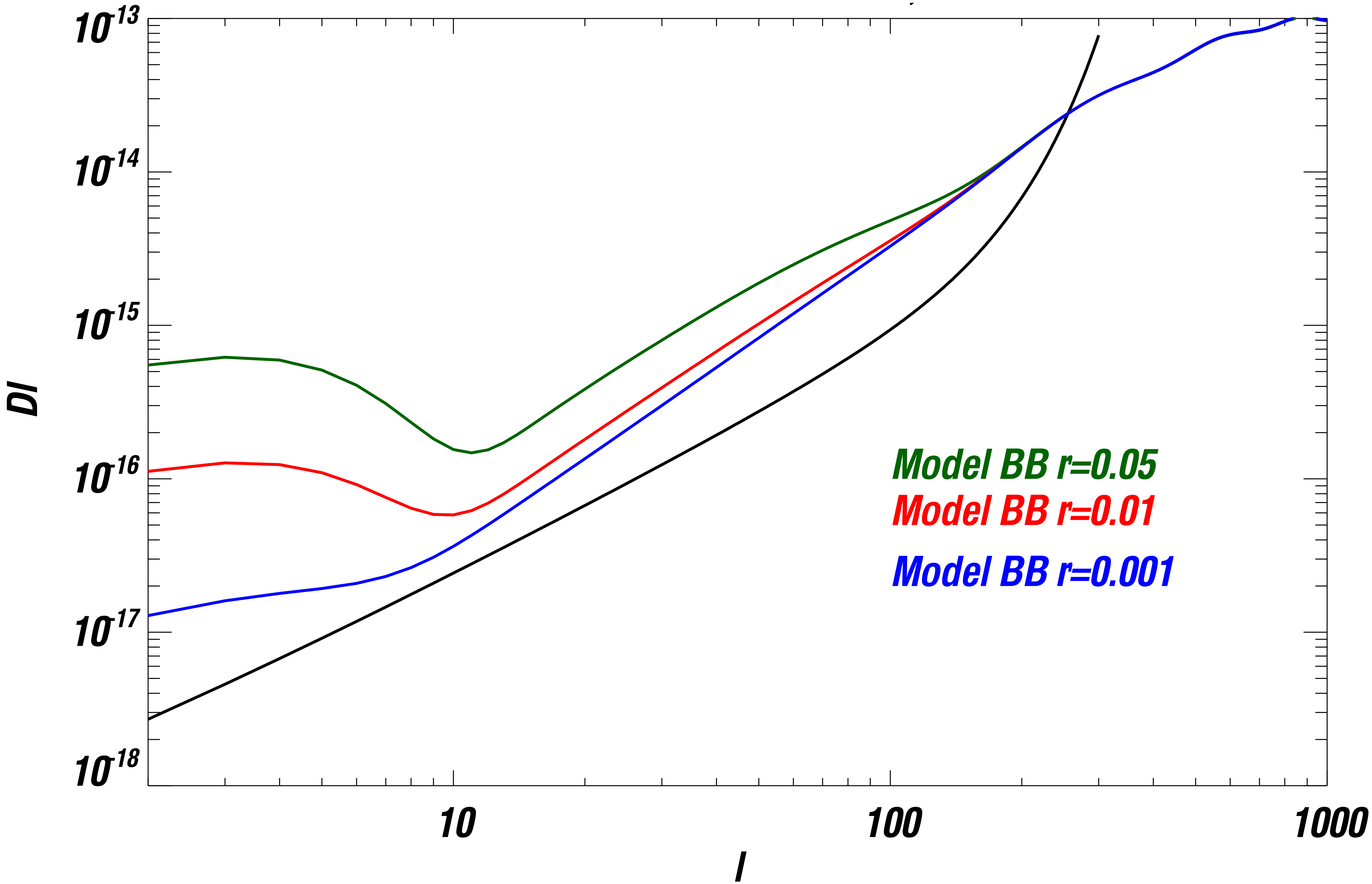
E-modes MC simulations 100x140 LiteBIRD,
80% of the sky, l=[2,20], $\tau_{fid}$=0.06
oHL likelihood `(Mangilli et al. MNRAS 2015)`

| Band GHz | Bandwidth $\Delta\nu/\nu$ | NET $\mu K\sqrt{s}$ | Pixels/wafer | $N_{wf}$ | $N_{bolo}$ | $NET_{arr}$ $\mu K\sqrt{s}$ | Sensitivity with margin $\mu K$·arcmin |
|---|---|---|---|---|---|---|---|
| 60 | 0.23 | 94 | 19 | 8 | 304 | 5.4 | 15.7 |
| 78 | 0.23 | 59 | 19 | 8 | 304 | 3.4 | 9.9 |
| 100 | 0.23 | 42 | 19 | 8 | 304 | 2.4 | 7.1 |
| 140 | 0.30 | 37 | 37 | 5 | 370 | 1.9 | 5.6 |
| 195 | 0.30 | 31 | 37 | 5 | 370 | 1.6 | 4.7 |
| 280 | 0.30 | 38 | 37 | 5 | 370 | 2.0 | 5.7 |
| total | | | | | 2022 | | 2.6 |



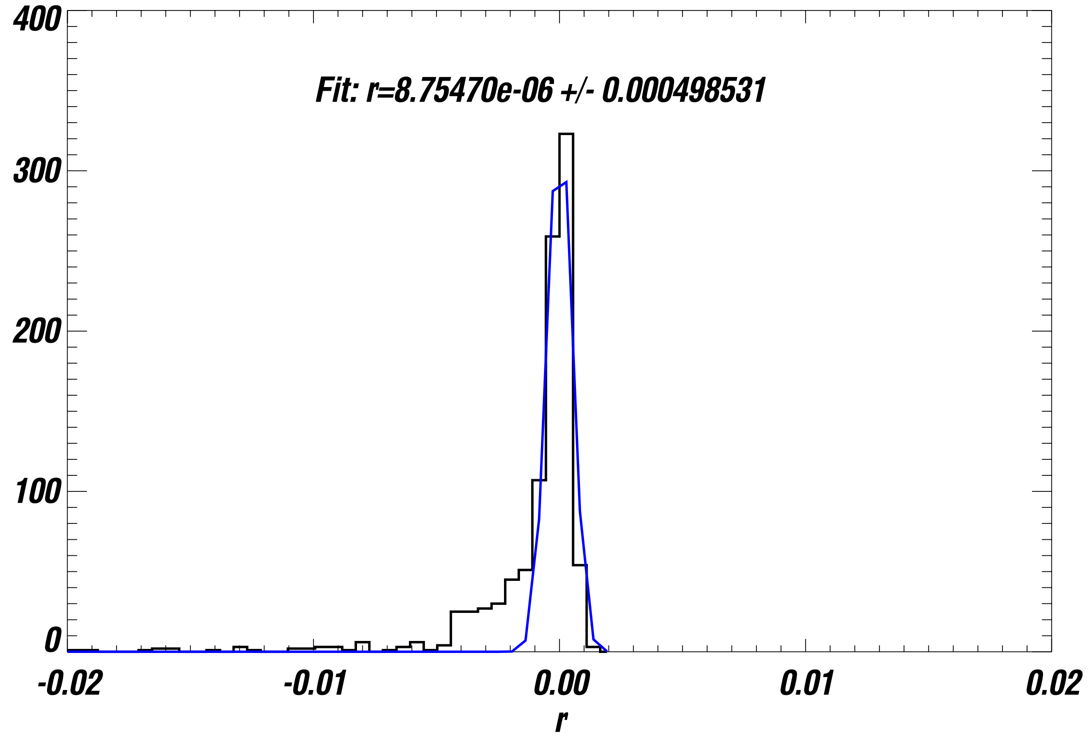

$\sigma(\tau) \sim 0.0035$
Further improvements: combination of different cross-spectra and datasets
Significant improvement with respect to current constraint

# Future prospects: B-modes



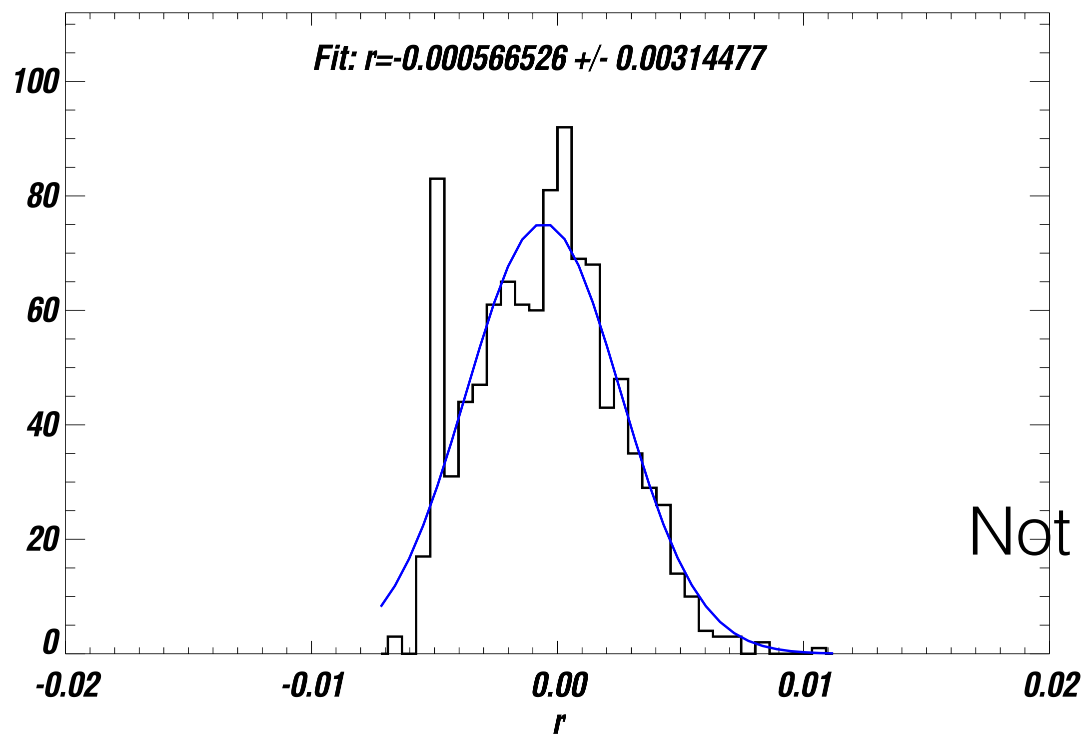

Variance MC sims LiteBIRD, 100GHzx140GHz, r=0, fsky=0.8

l=[2,300]




- B-modes MC sims (r=0)
- LiteBIRD 100x140
- 80% sky
- oHL likelihood (Mangilli et al. MNRAS 2015)

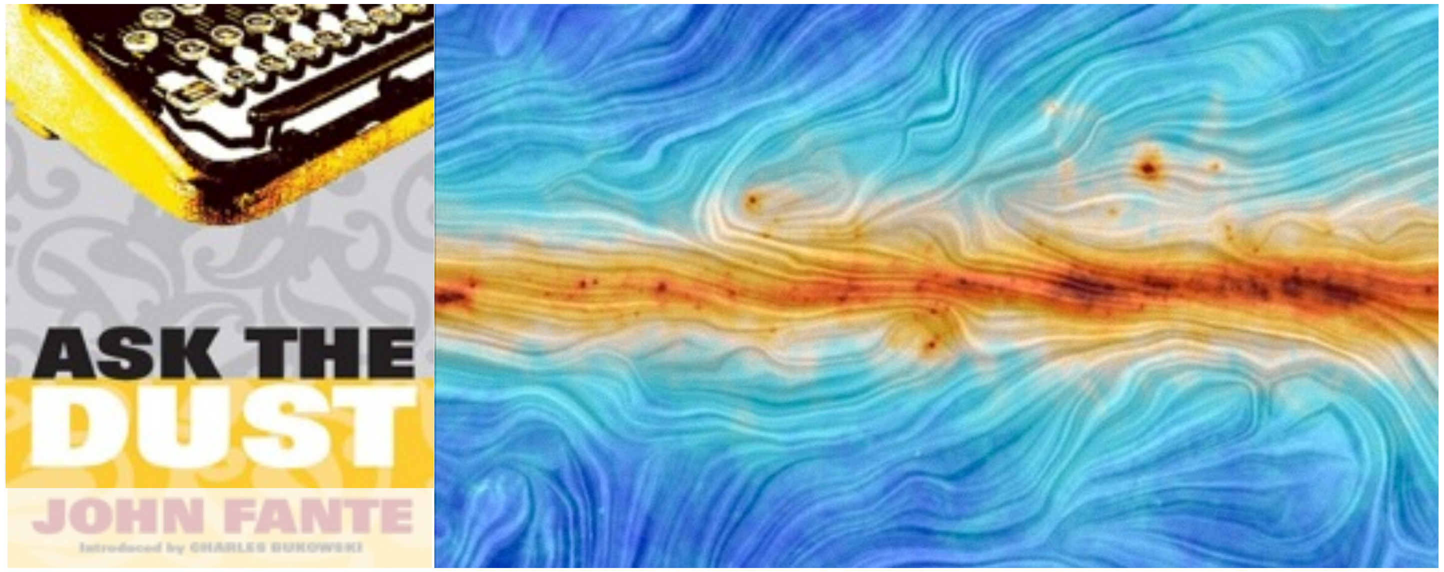
l=[30,300]




Not de-lensed

Including B-modes at large angular scales: better constraints!

## Precise modelling of the foreground is crucial
## Realistic forecasts must include accurate description of the polarized dust contribution




In preparation:

`Montier, Aumont, Boulanger et al. to be submitted 2015`
`Mangilli, Aumont, Tristram, Grain et al., in prep 2016`

- MC simulations with polarized dust (turbulent component included)
- Full likelihood analysis including large scales (oHL likelihood, l=[2,300])
- Cross-spectra based analysis for different combinations of datasets

# Conclusions

## Improved large scales polarization results from Planck out soon!

Cross-spectra based likelihood integrated in Planck analysis

**E-modes & reionization history (τ):**

- New preliminary Planck constraints point to significantly lower value of the reionization optical depth parameter $\tau$
- Better agreement with astrophysical data
- Measurements from B-modes at large angular scales more challenging
- Significant improvement expected from future space missions as LiteBIRD

**B-modes & primordial tensor modes (r):**

- For the moment preliminary HFI results: good indications that major systematics are under control
- Including the large scales greatly improve the constraints (not from ground: need the full sky)
- Caveat: correct modelling of the dust polarization must be precisely included to have realistic forecasts and correct interpretation

# Thank you!