Constraining the reionization era and inflation with the CMB polarization at large angular scales

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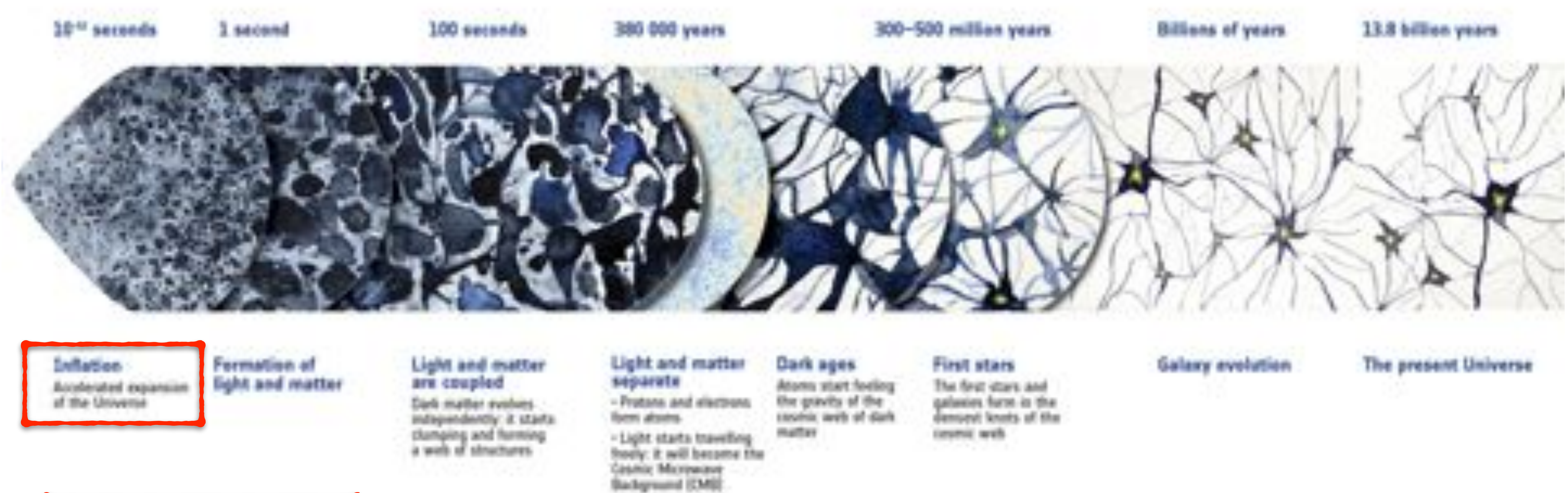
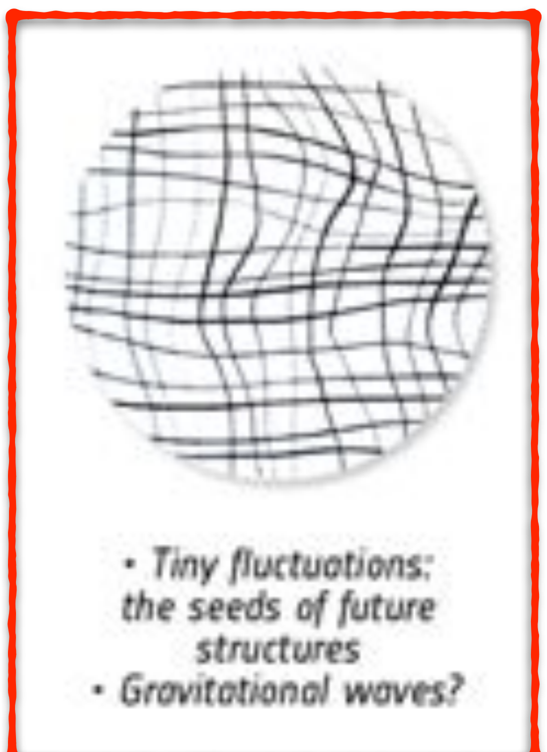
Orsay, Paris Sud

LPSC Grenoble - January 26th 2016

The Universe's history

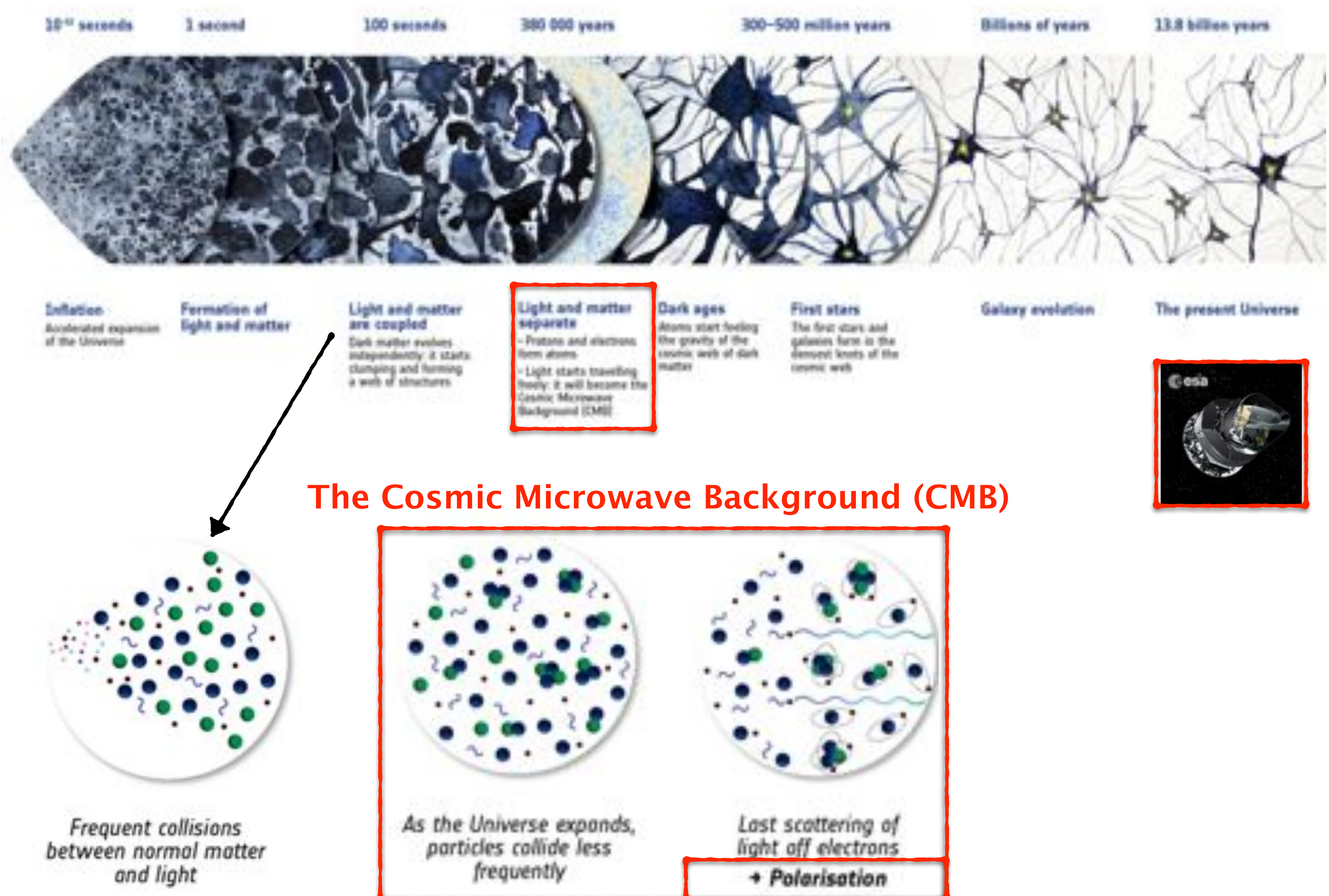




Inflation generates the primordial perturbations (scalar & tensor)

The Hot Big-bang inflationary model

The Universe's history



The Universe's history

The **Epoch of Reionization (EoR)** describes the period during which the cosmic gas went from neutral to ionized because of the first emitting sources.

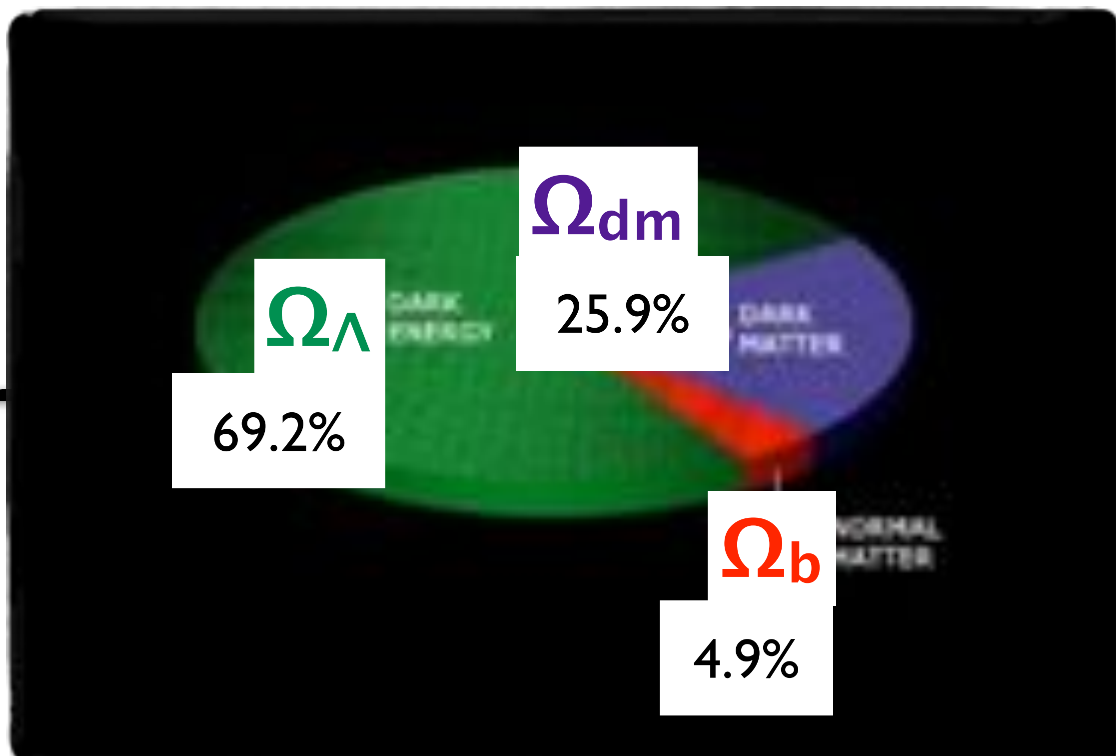
Non-standard energy injections (e.g. Dark Matter annihilation) can also contribute

The concordance ΛCDM model

The Cosmic Microwave Background (CMB)

Quasar, 21-cm, Lymanα

Galaxy clusters
Supernovae

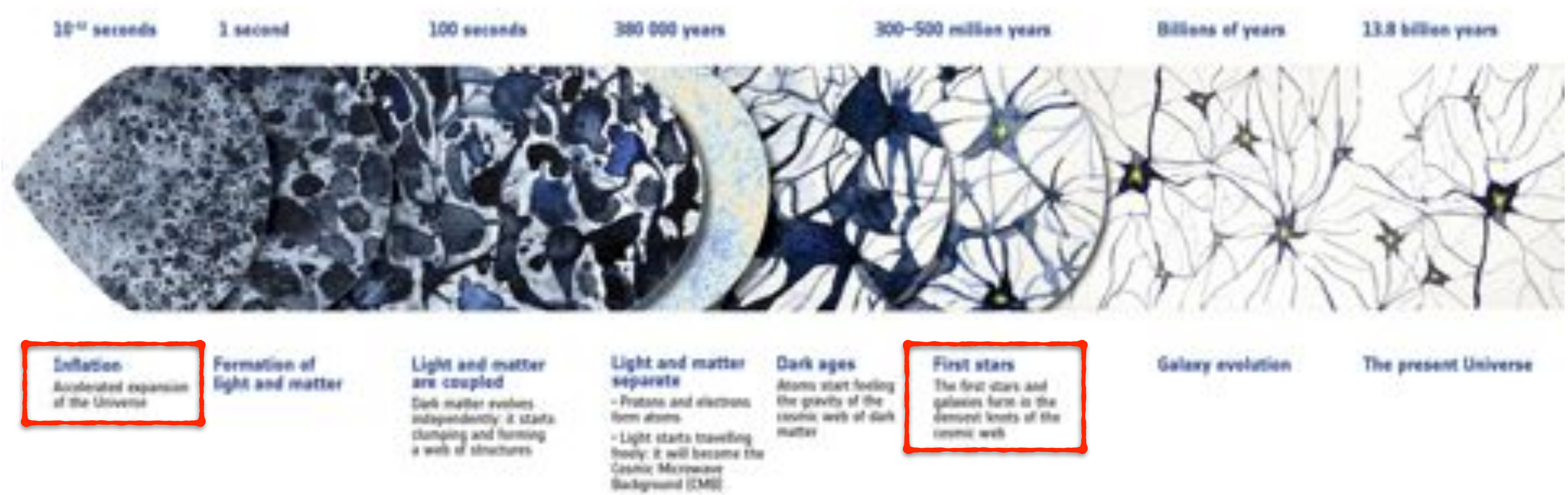


what is inflation?

what is the nature of dark matter?

what is the nature of dark energy?

how did the structure form?



The CMB polarization as a powerful probe of:

- Inflation
- The epoch of reionization/structure formation

OUTLINE

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

  Current status of the constraints on τ and r

- **The challenge**

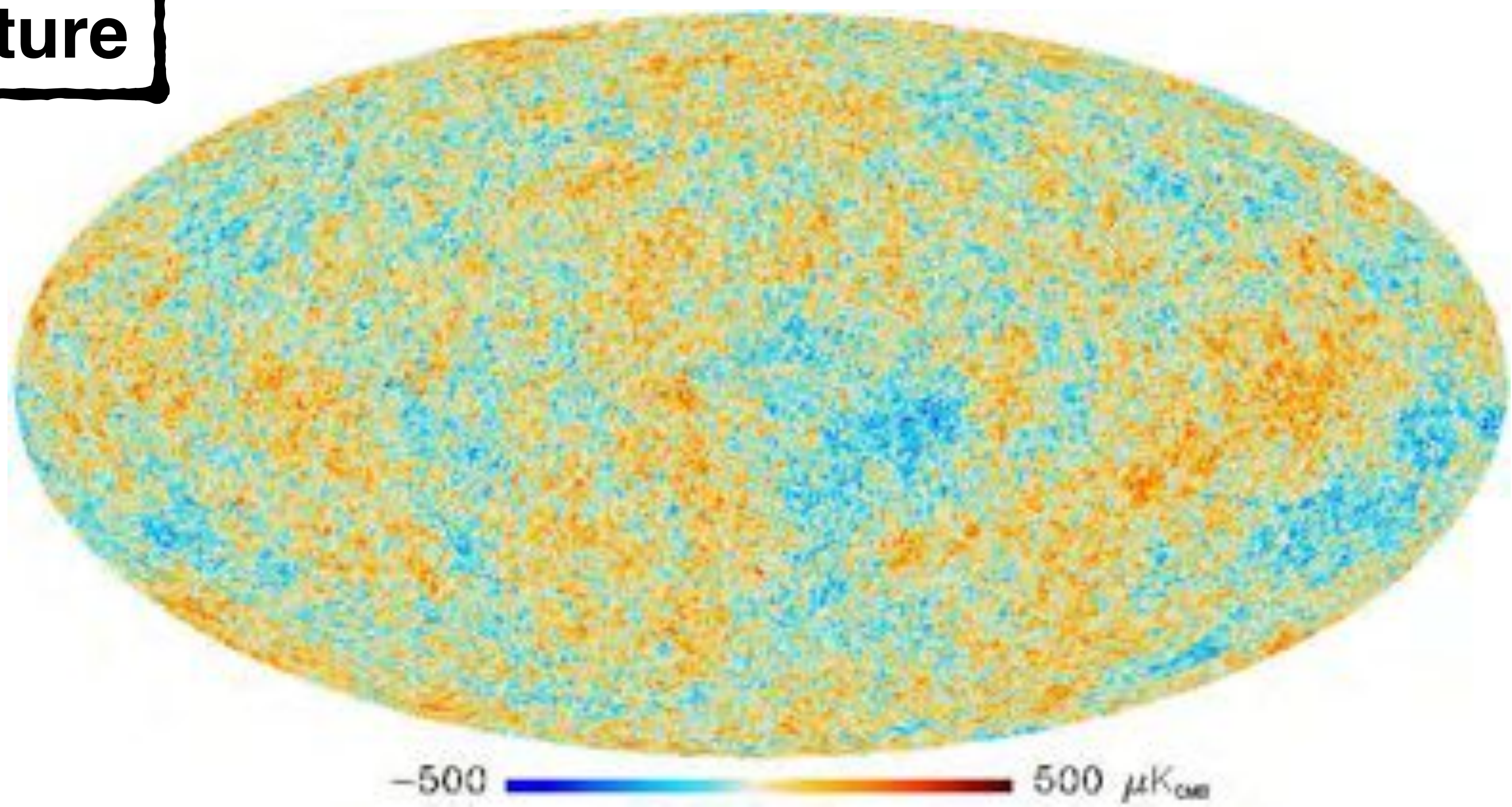
  Data improvements
  Statistical methods (Mangilli et al. MNRAS 2015)

- **Preliminary HFI results**
- **Future prospects & conclusions**

The CMB anisotropies

Temperature

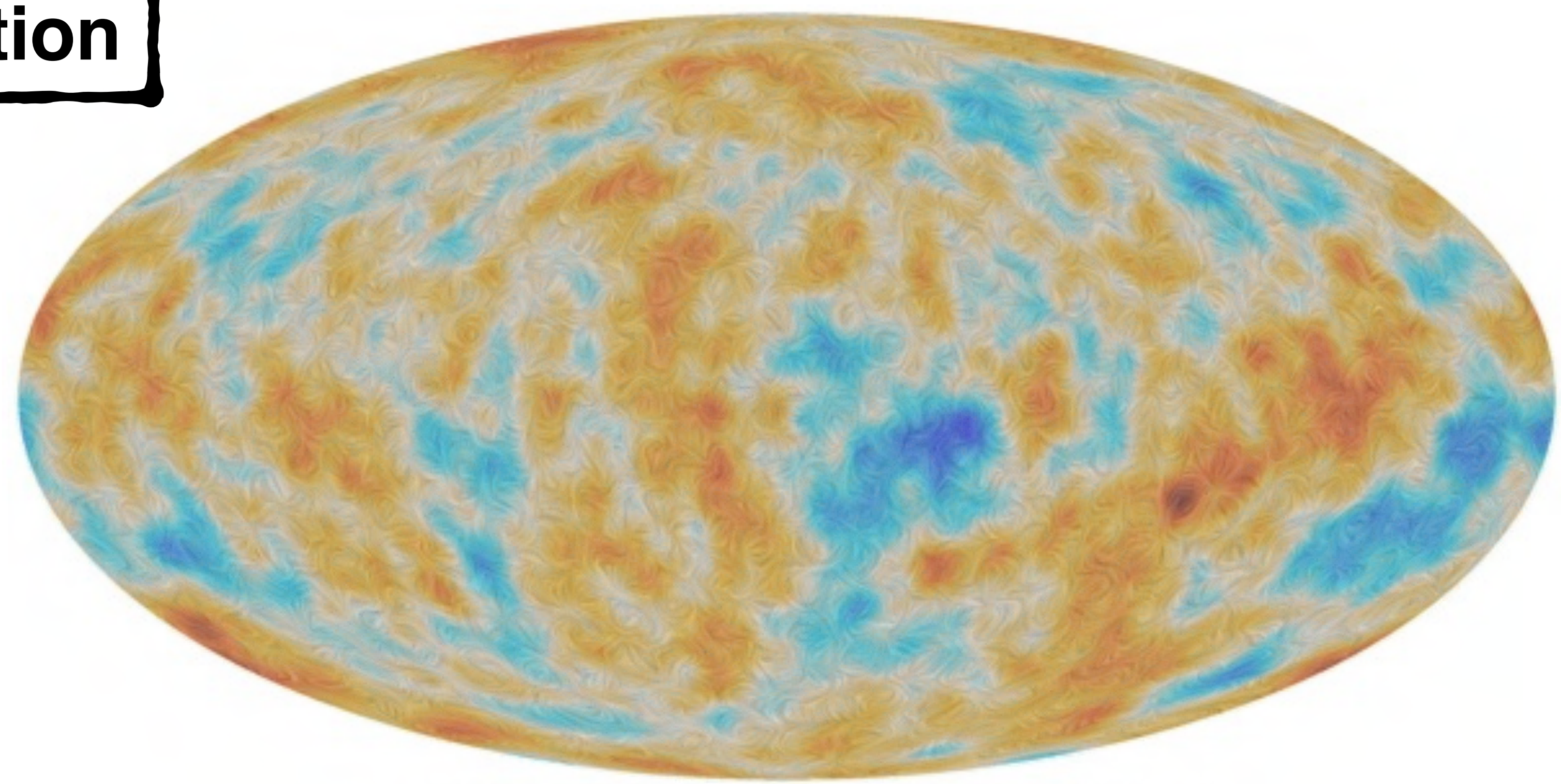
Planck



The CMB polarization

Polarization

Planck



CMB polarization signal: orders of magnitude weaker than temperature

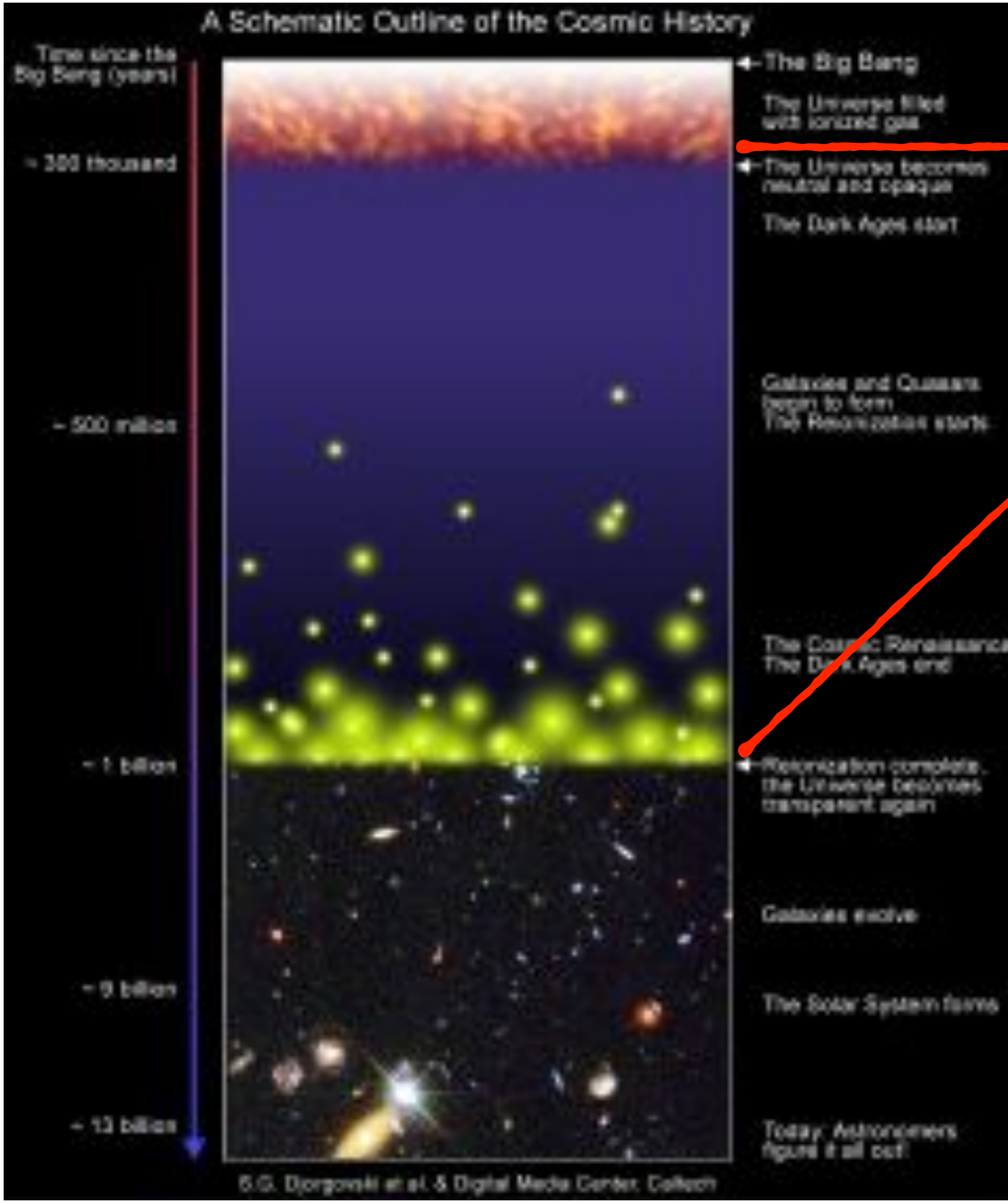
E-modes

- Electric type polarization field.
- Generated by scalar density perturbations.

B-modes

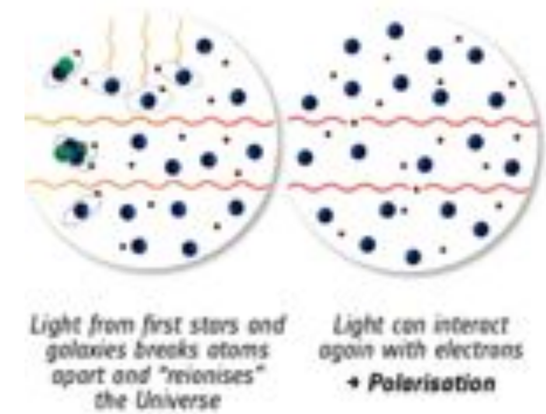
- Magnetic type polarization field.
- Can be generated only by primordial tensor modes i.e. **primordial gravitational waves**
- Contribution from lensing

Generation of the CMB polarization



DECOUPLING

REIONIZATION



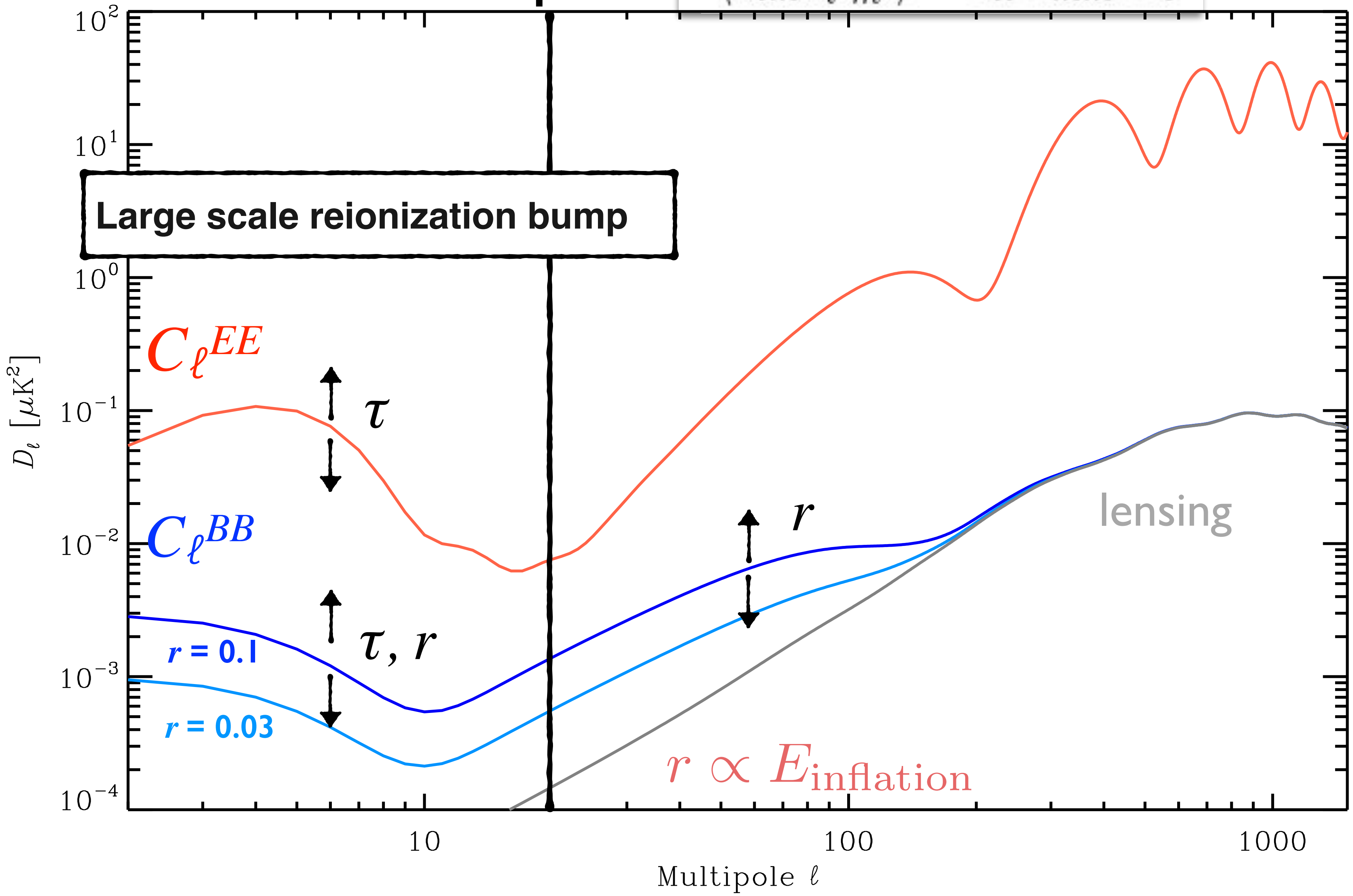
Thomson scattering optical depth:

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

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

The CMB E & B angular power spectra

CMB anisotropies: $\langle a_{lm} a^*_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_\ell$

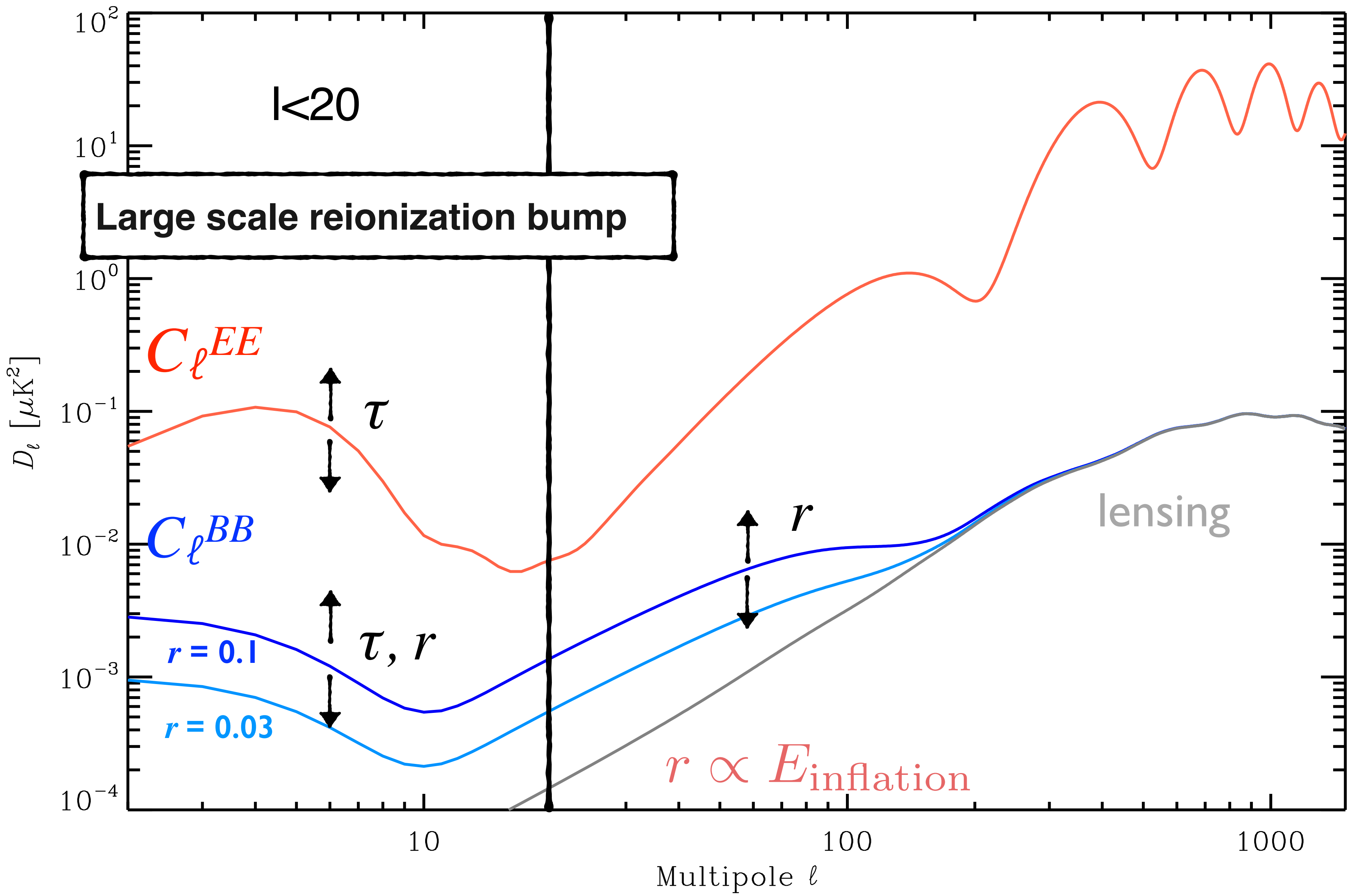


Scientific goals

Reionization history: C_ℓ^{EE} at large angular scales to constrain τ

Inflation: C_ℓ^{BB} at large and intermediate scales to constrain r

The polarization at large angular scales



The major challenges

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

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

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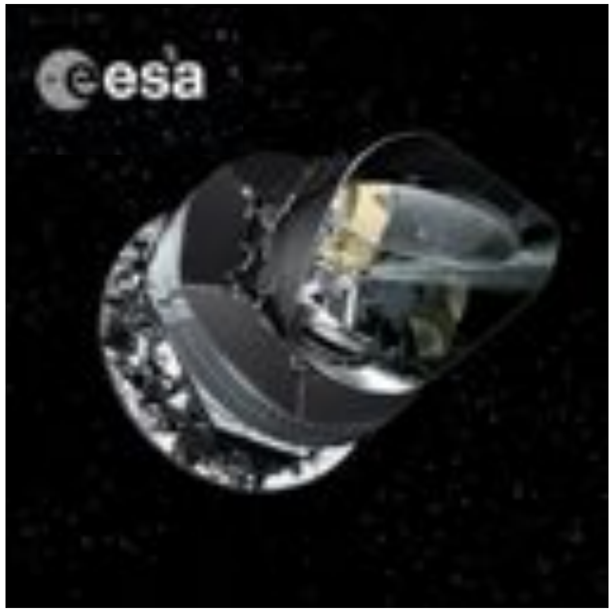
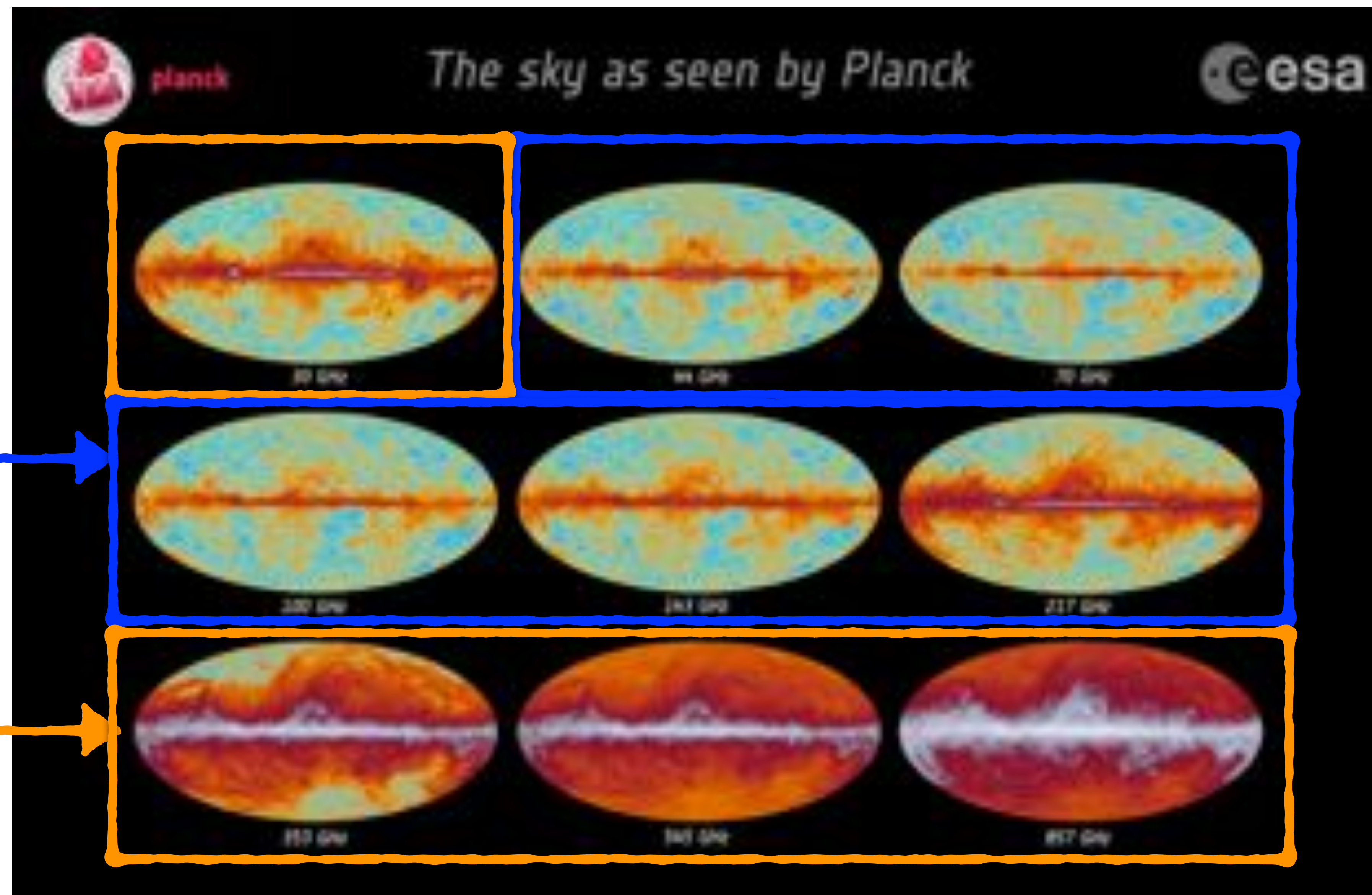
The Planck satellite



- ➡ 9 frequency bands
- ➡ Two instruments:

LFI: 30GHz, 44GHz, 70GHz
HFI: **100GHz, 143GHz, 217GHz**
353GHz, 545GHz, 857GHz



Channels for CMB characterisation

Foregrounds characterisation

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

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

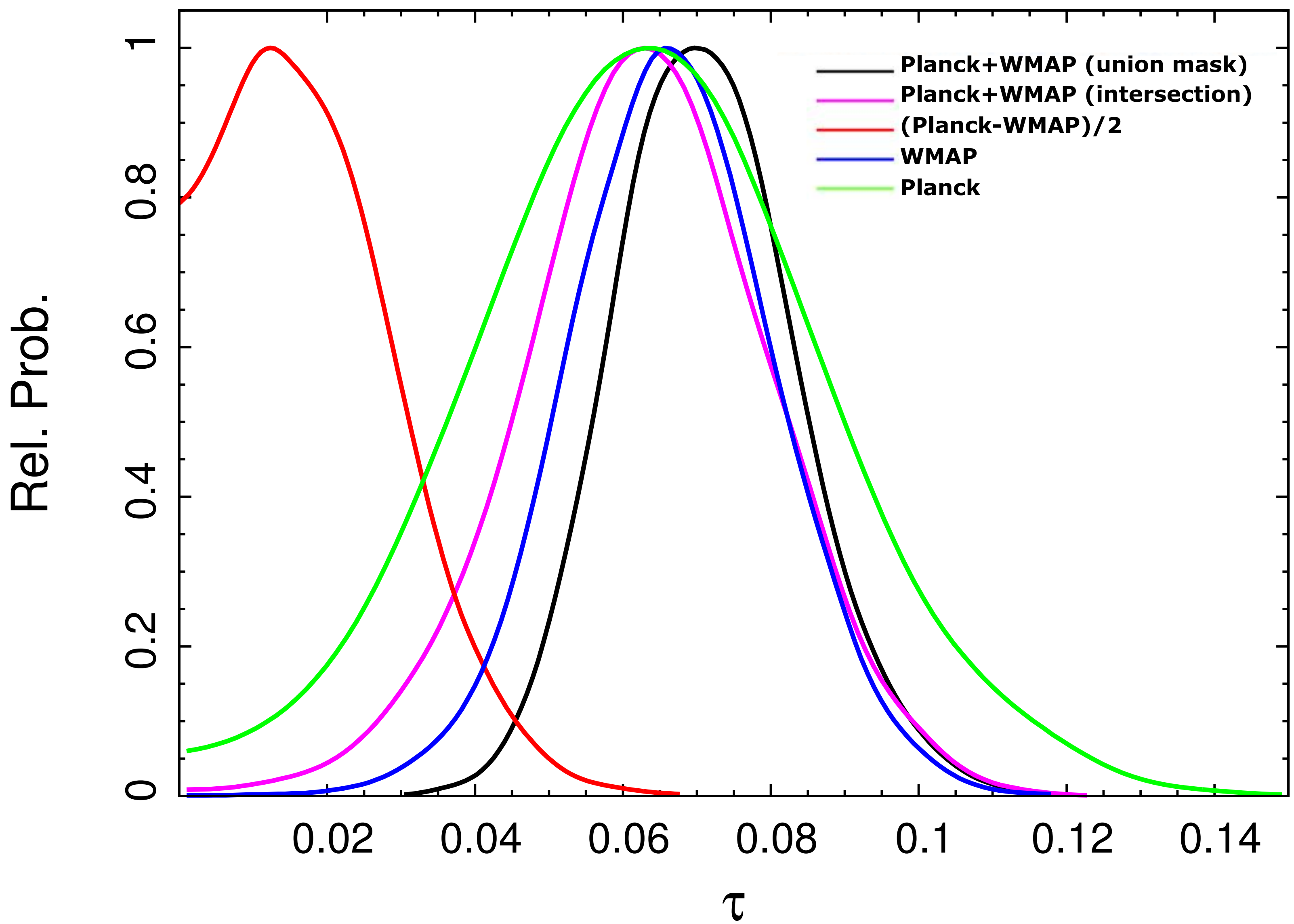
HFI has higher sensitivity, lower noise: residuals systematics

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

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

planck

Reionization optical depth from large scale polarization

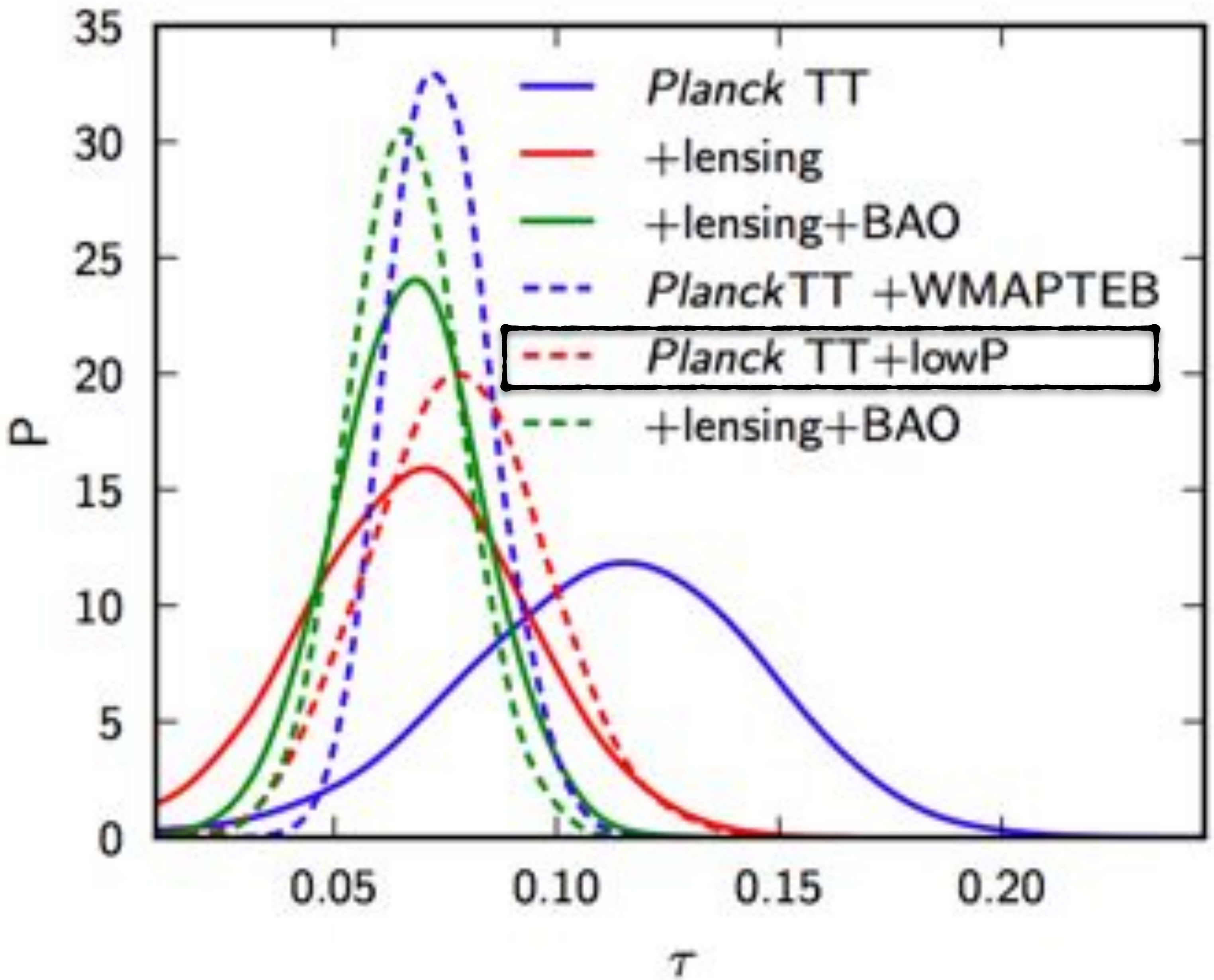


The Planck Coll. XI, 2015

✓ **WMAP and Planck LFI-70GHz yield consistent estimates**

✓ **The τ signal disappears in the null map**

Planck 2015: reionization optical depth summary



The Planck Coll. XIII, 2015

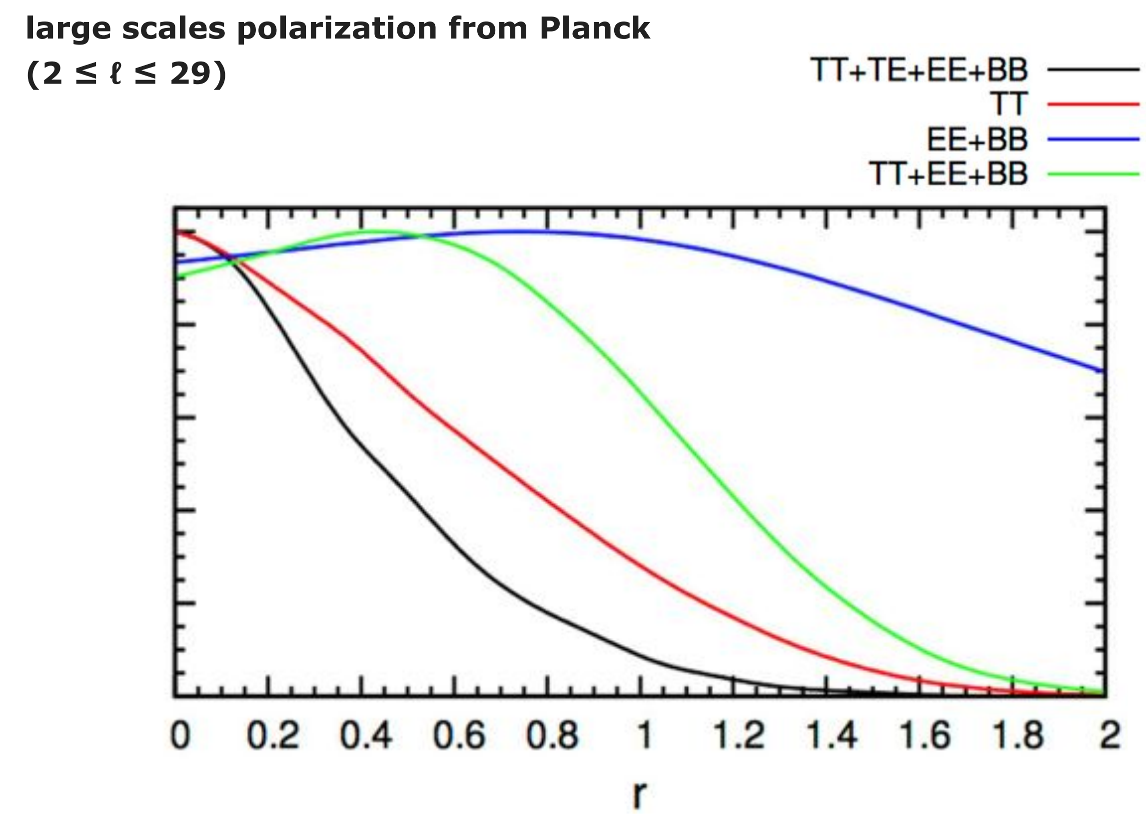
… Planck results seems to point to lower τ.

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

Planck 2015: Tensor-to-scalar ratio

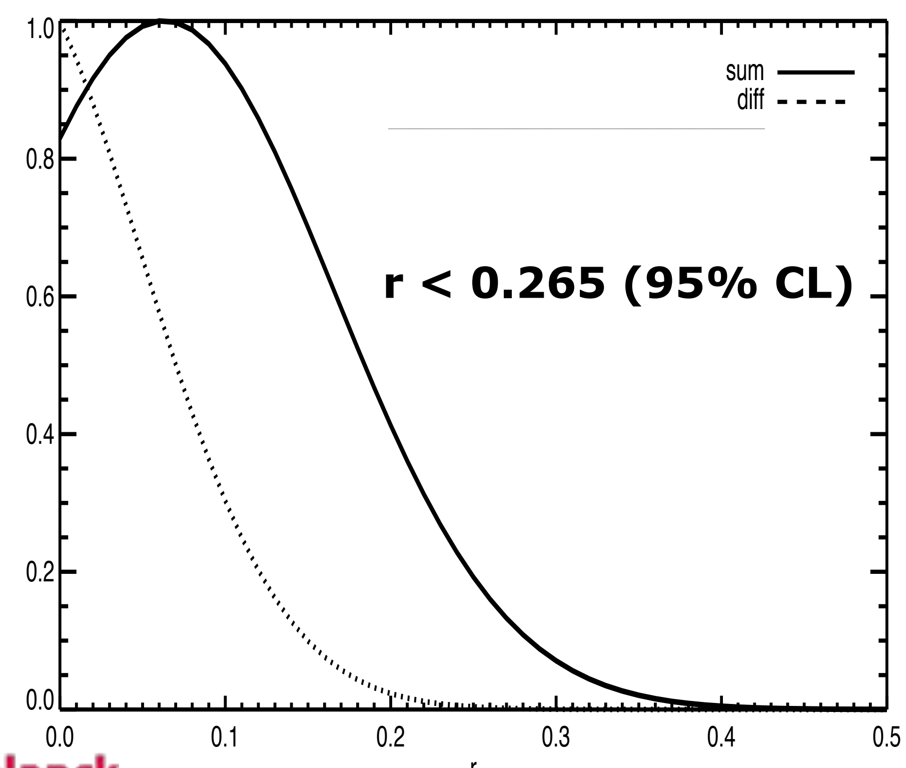
From large scales: still far.
But significant improvement on the way for 2016

The Planck Coll. XI 2015



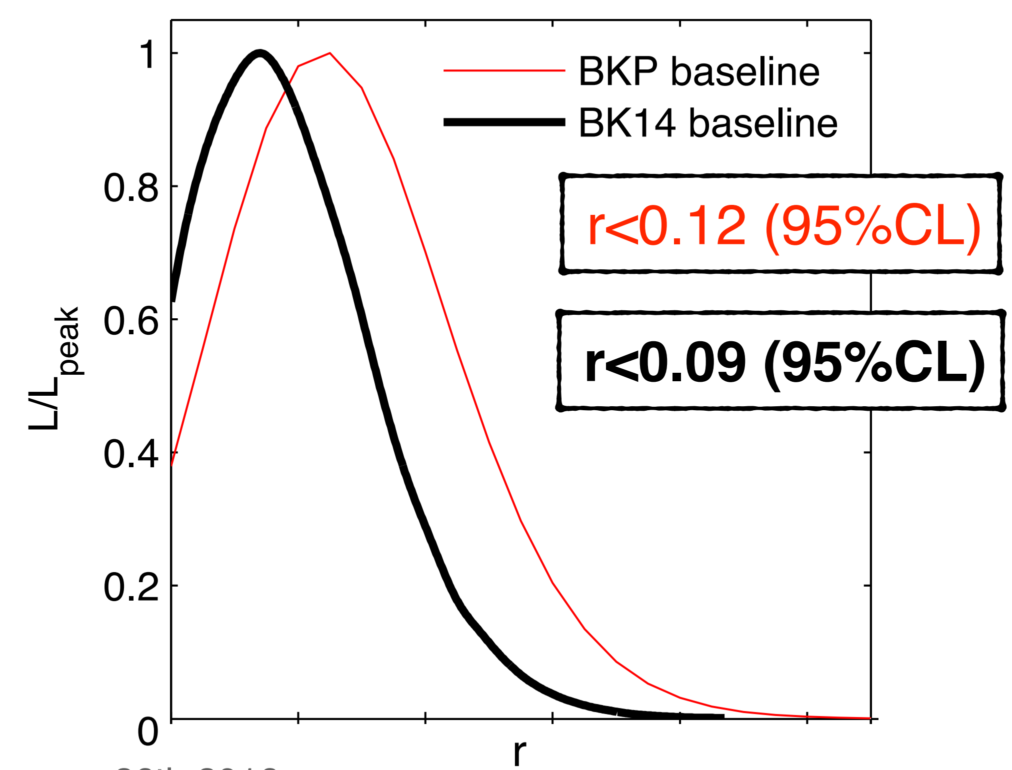
From intermediate scales:

Planck 100GHz&143GHz



Planck 353GHz + Bicep2&Keck

PRL 114 2015 & arXiv1510.09217



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The challenge

➡ **Data quality**

Control of systematics, in particular HFI 100GHz,143GHz,217GHz
Accurate foreground subtraction/modeling

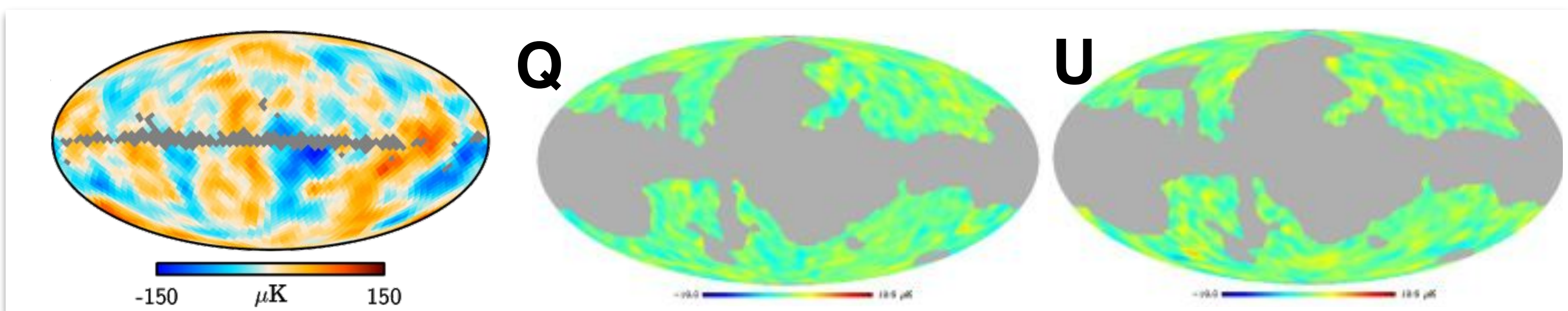
➡ **Data analysis**

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: ∝ 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

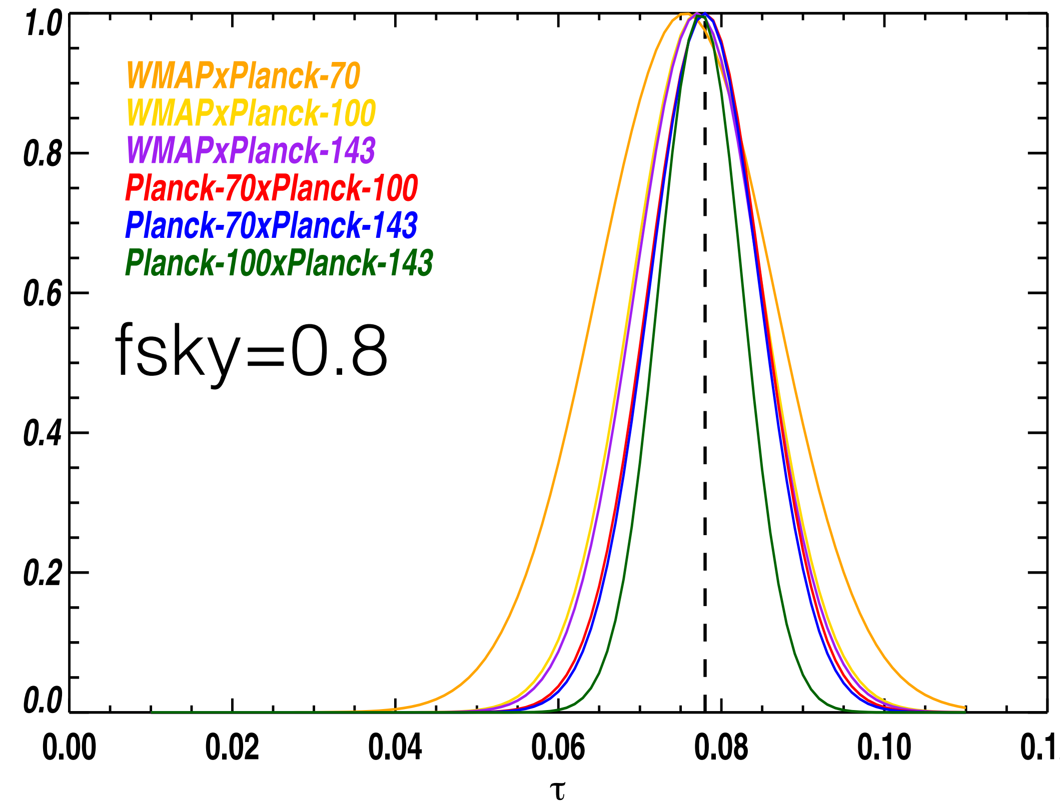
Cross-spectra oHL: τ estimation

[**Mangilli**, Plaszczynski, Tristram (MNRAS 2015)]

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

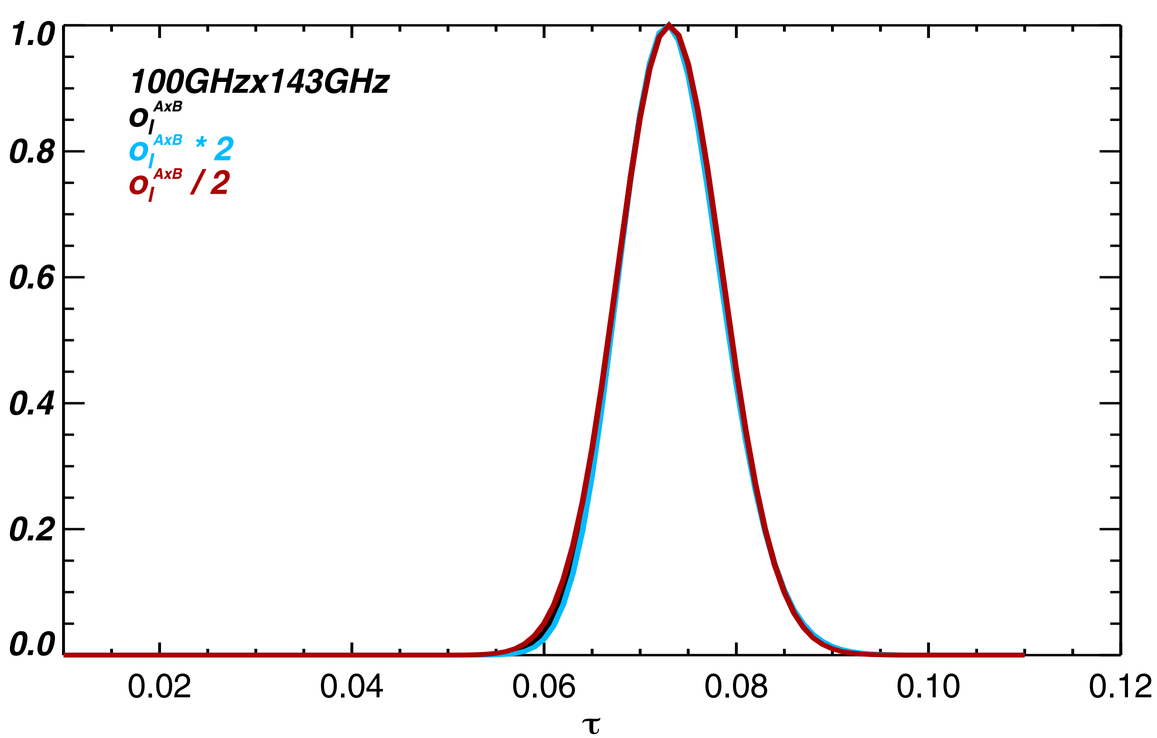
Unbiasedness

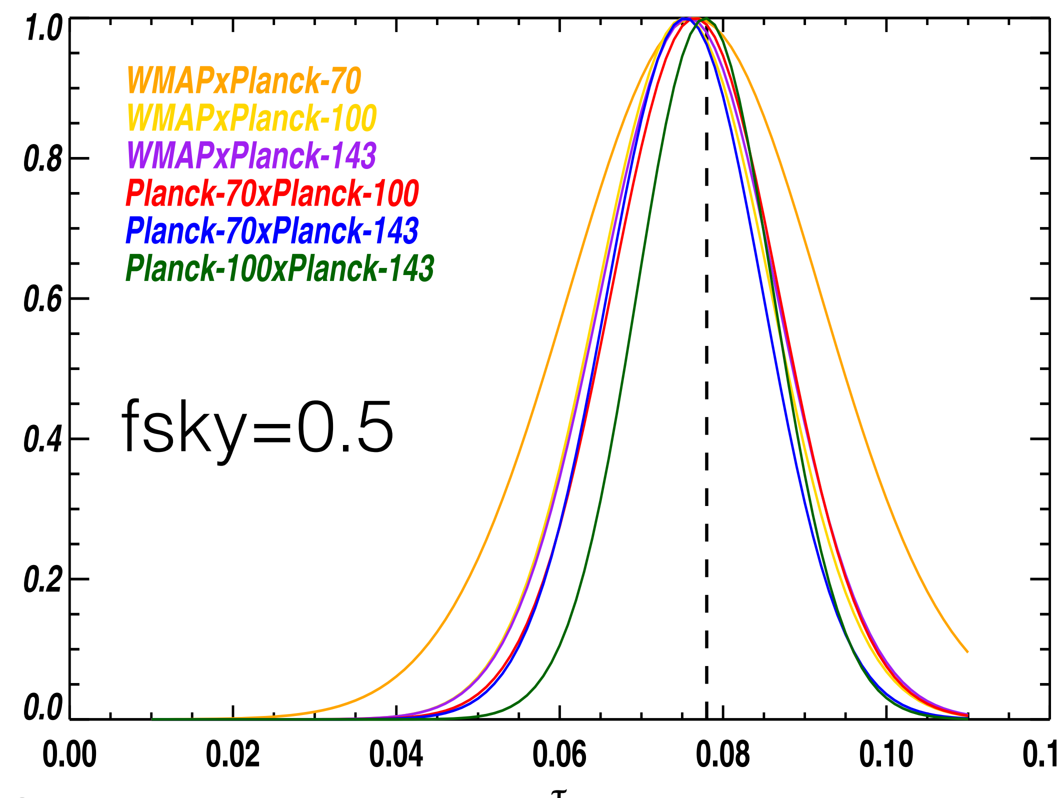
Best constraints expected from HFI 100GHzx143GHz



Robustness

Offset change





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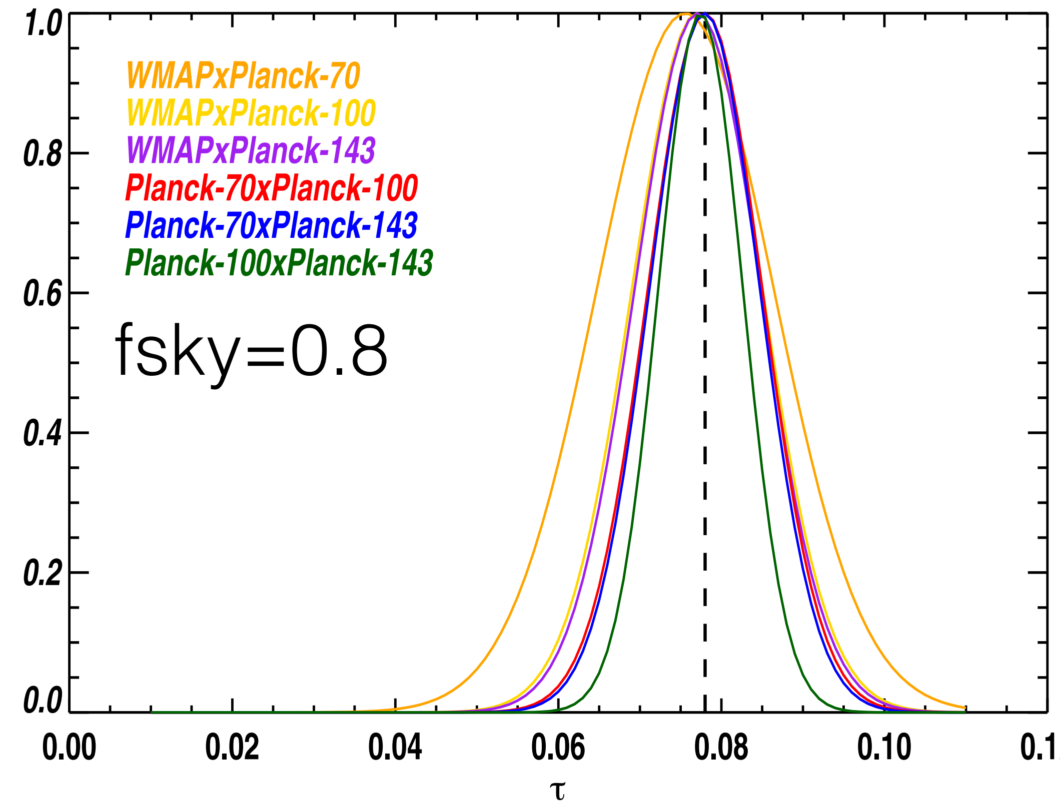
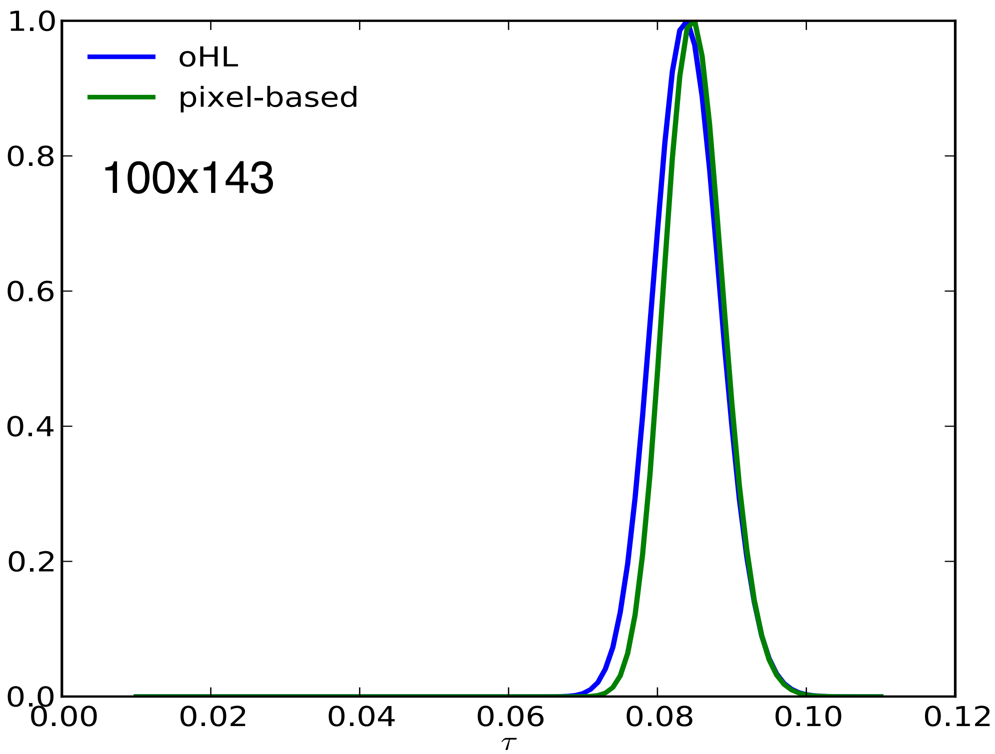


Best constraints expected from HFI 100GHzx143GHz

Optimality

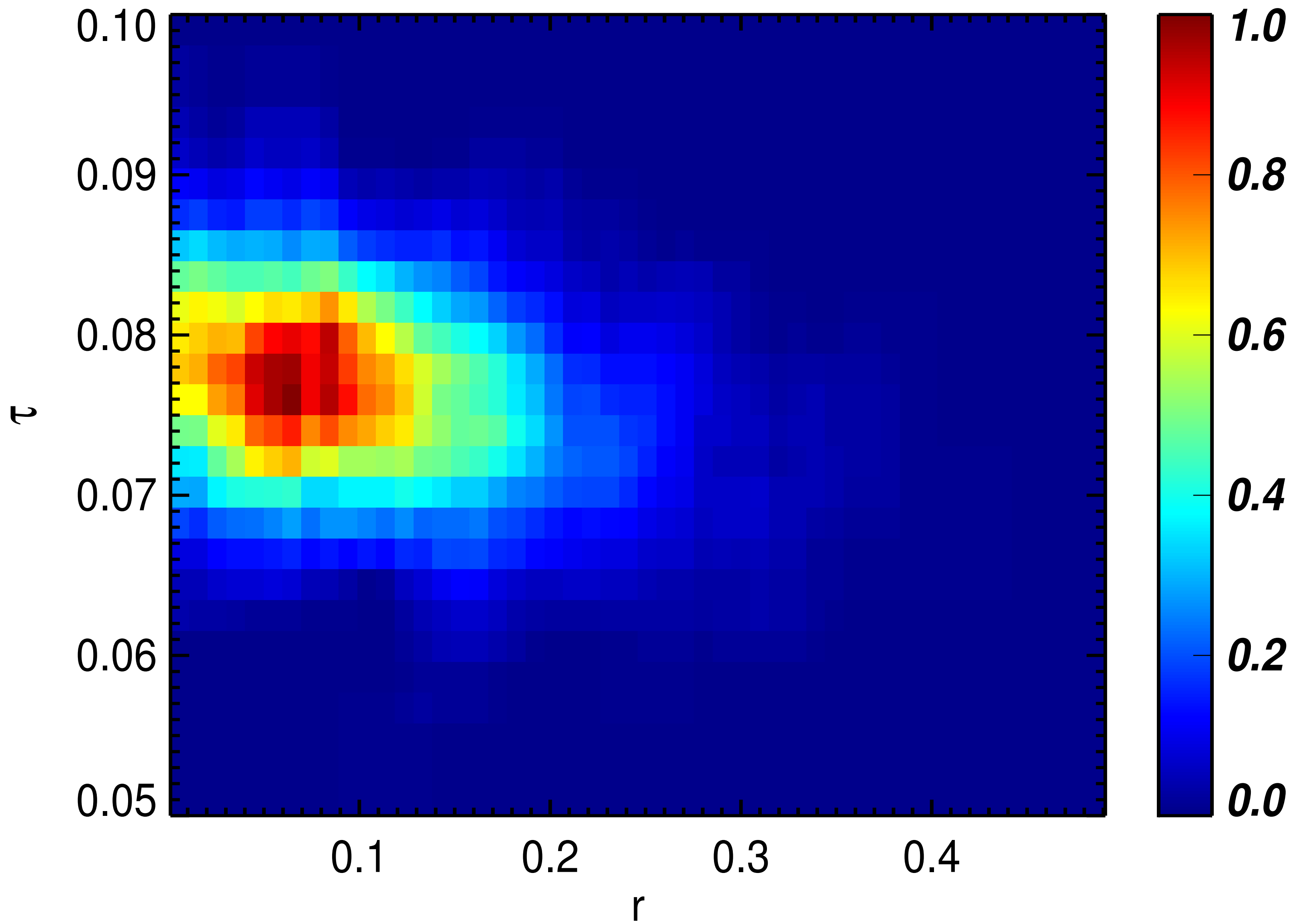


Comparison with the pixel-based approach: compatible error bars estimation at better than 10%

Cross-spectra oHL: τ-r 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

- All dominant sources of residual systematics for HFI low-l data now identified
- Biggest systematic: ADC-Non-Linearity. Now reduced by a factor almost 10
- Results on E2E Monte-Carlo simulations including systematic residuals: error bars increased due to systematics uncertainties
- Further data improvement ongoing at map-making level for end 2016

PRELIMINARY

New preliminary Planck-HFI results

- Large scale Polarization l=[4,20]
- E-modes, B-modes 100GHzx143GHz cross spectra
- Sky fraction: 50%
- Polarization foreground cleaning

  Planck frequencies corrected for polarization leakage:

  - 30GHz for polarized synchrotron
  - 353GHz for polarized dust

- Cross-spectra based likelihood analysis oHL (Mangilli et al. MNRAS 2015)

New preliminary Planck–HFI results

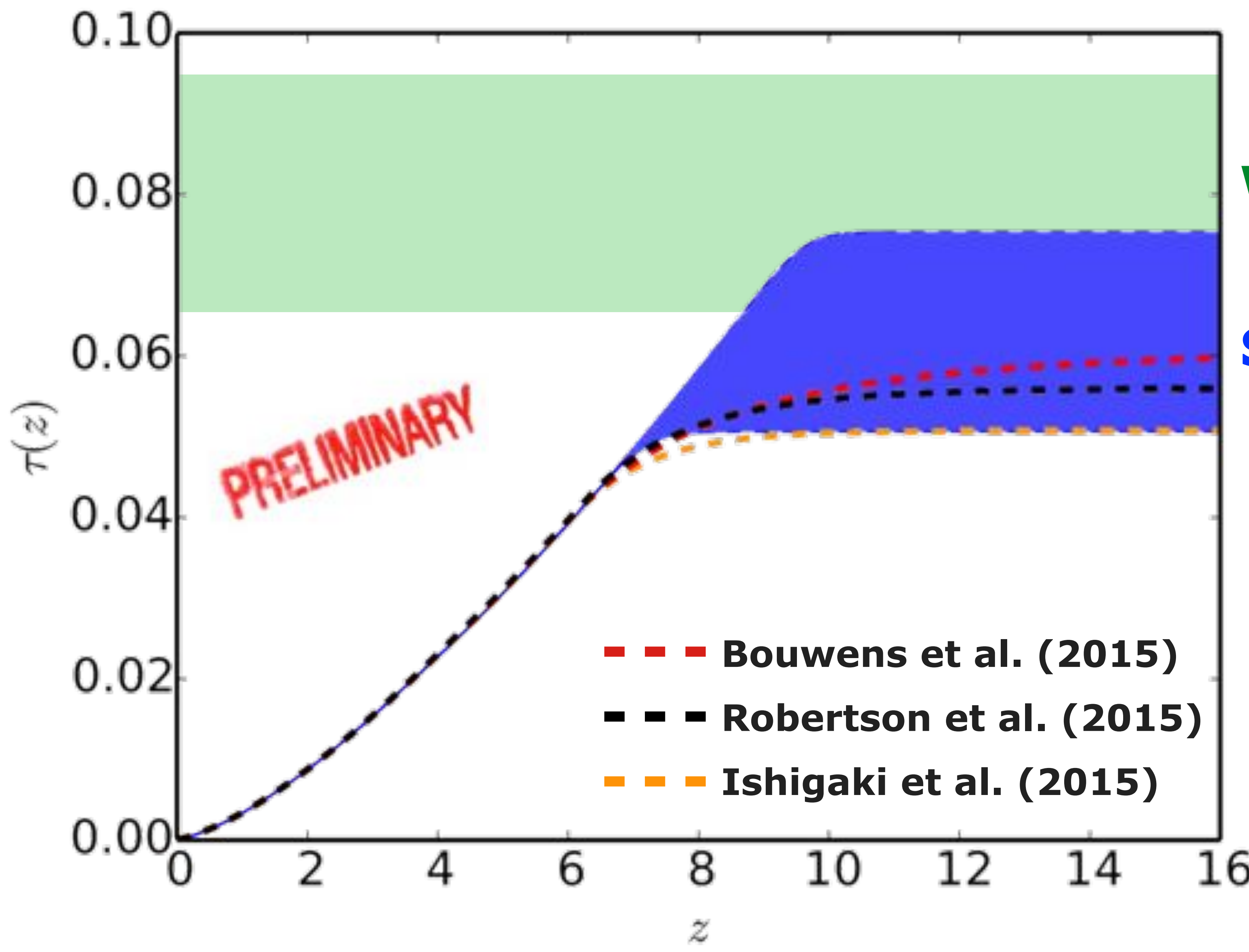
Preliminary Planck 100GHzx143GHz E-modes at low-l:

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

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

PRELIMINARY

Better agreement with astrophysical data



WMAP

smaller value

Improved and lower τ: impact on parameters

PRELIMINARY

+ improvement on total neutrino mass from CMB only

Planck low-ell polarization take away message

- A **significantly lower value for the reionization optical depth** as suggested by preliminary Planck HFI results would:
  - be consistent with a fully reionized Universe at $z \sim 6$
  - be in better **agreement with recent astrophysical constraints**
  - **disfavor** high-z reionization tail and complicated reionization histories in general (e.g. 2 steps, asymmetric …)
  - make the **quest of B-modes at low-l more challenging**
- **Improved τ constraint:** tighter constraints on cosmological parameters A_s, n_s, σ_8, Σm_ν

The Planck collaboration incl. A. Mangilli: "Improved large angular scale polarization data and the reionization optical depth", in prep A&A 2016

The Planck collaboration incl. A. Mangilli: "Reionization history constraints from Planck", in prep A&A 2016

planck

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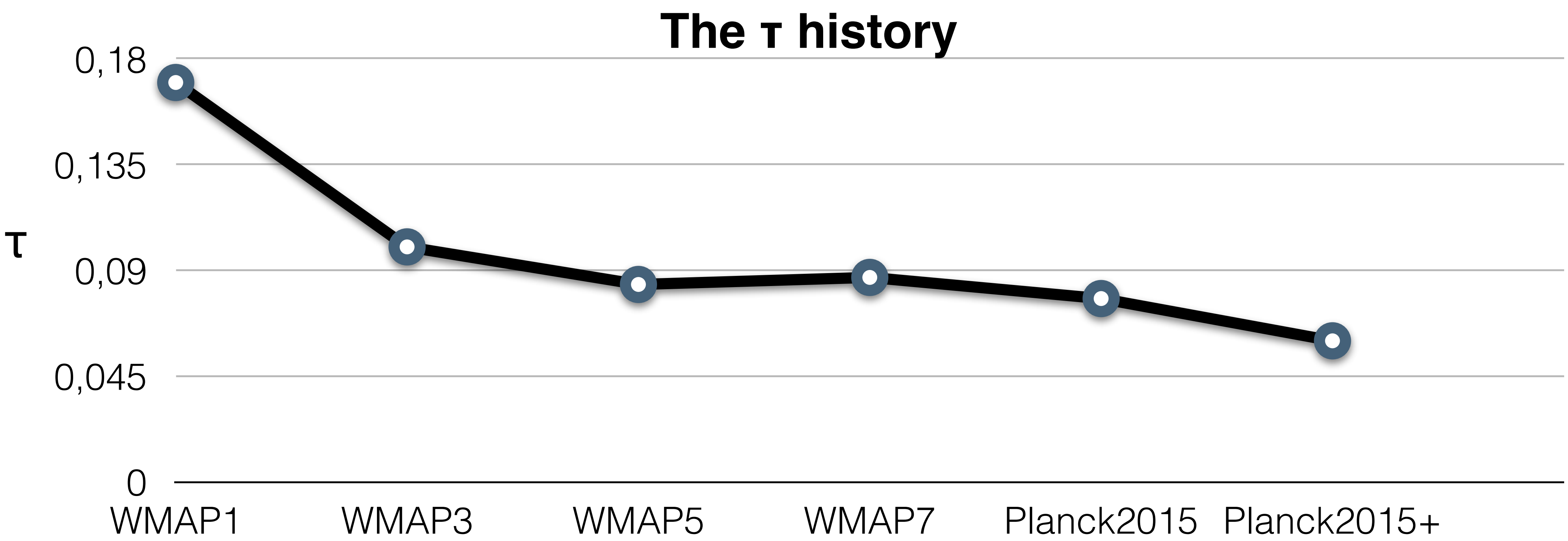
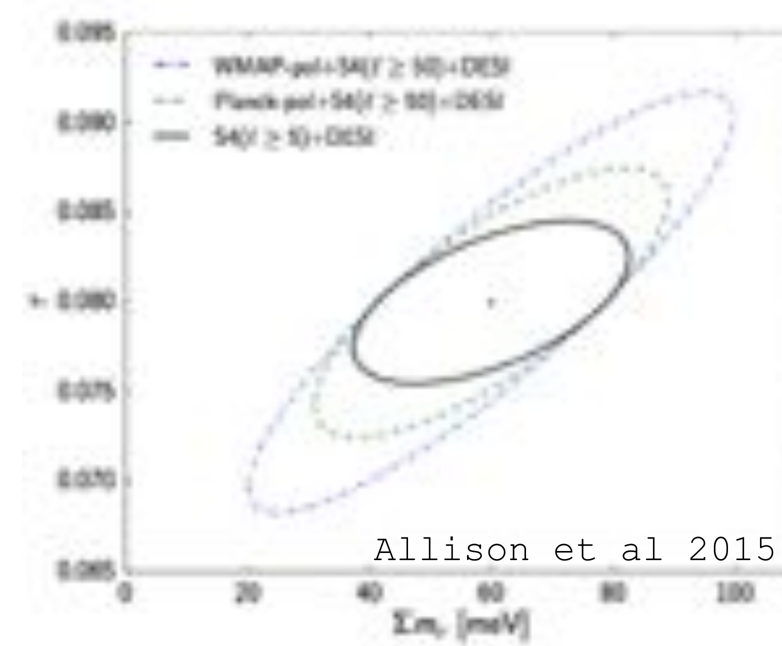
Future prospects: E-modes



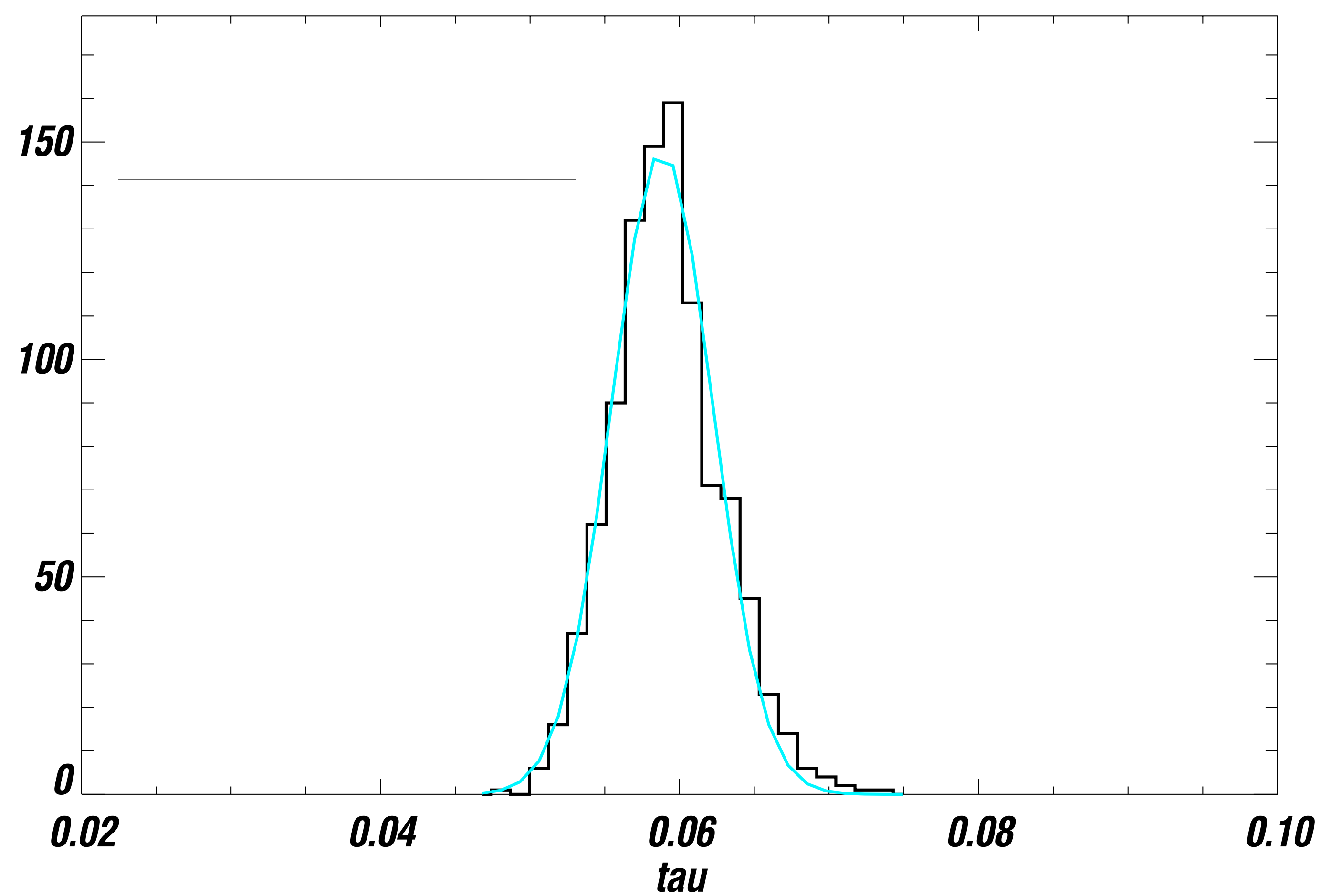
- The lower the τ value, the more difficult also for future experiments to detect features in the E-modes reionization bump to constrain e.g. evolution of reionization/non-standard energy injections
- More precision on τ, improved constraints on cosmological parameters (A_s, Σm_ν, …)



Future prospects: E-modes

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

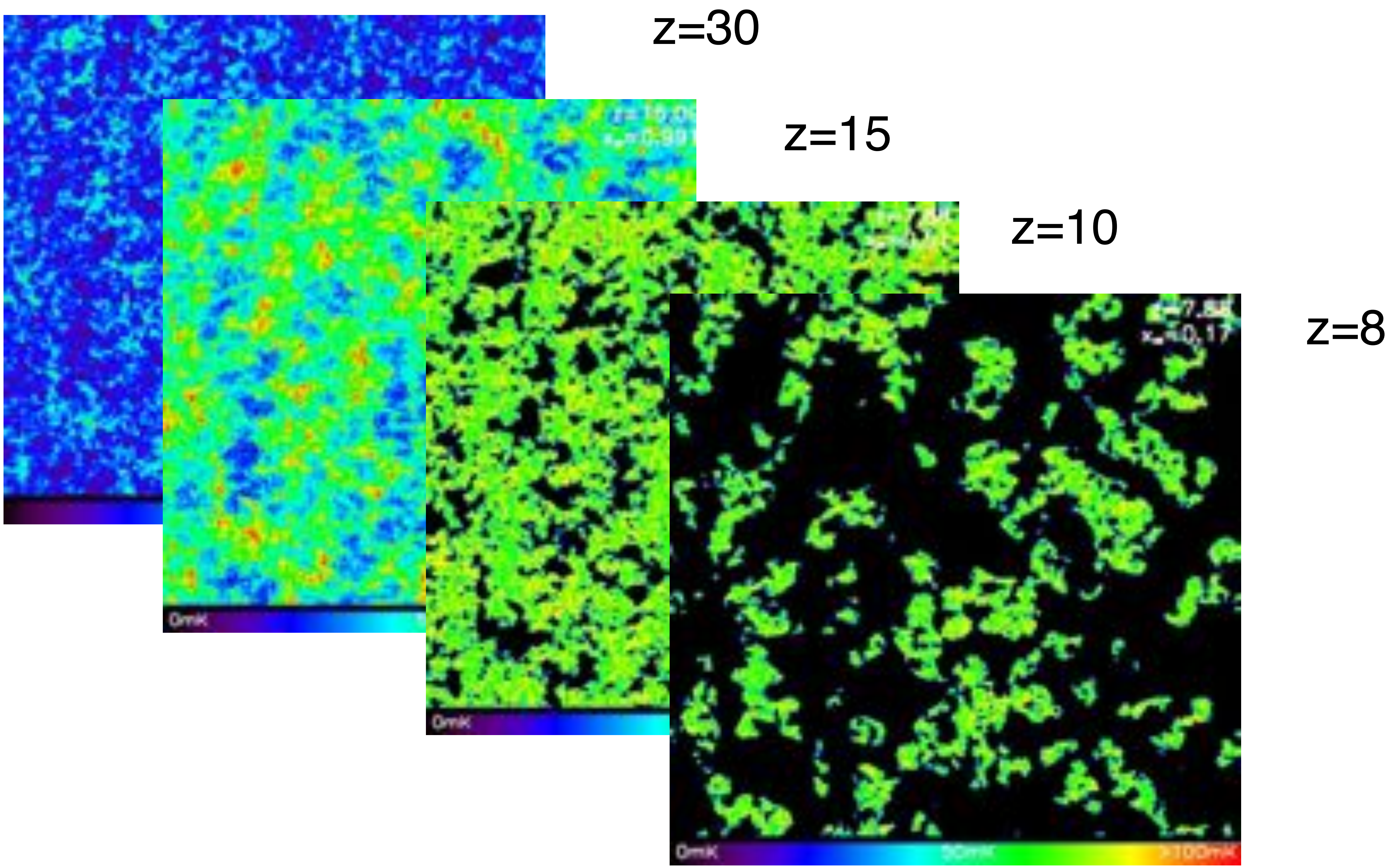
Band GHz	Bandwidth $\Delta\nu/\nu$	NET $\mu K\sqrt{s}$	Pixels/wafer	N_{wf}	N_{bolo}	NET_{arr} $\mu K\sqrt{s}$	Sensitivity with margin μK·arcmin
60	0.23	94	19	8	304	5.4	15.7
78	0.23	59	19	8	304	3.4	9.9
100	0.23	42	19	8	304	2.4	7.1
140	0.30	37	37	5	370	1.9	5.6
195	0.30	31	37	5	370	1.6	4.7
280	0.30	38	37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



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

Future prospects

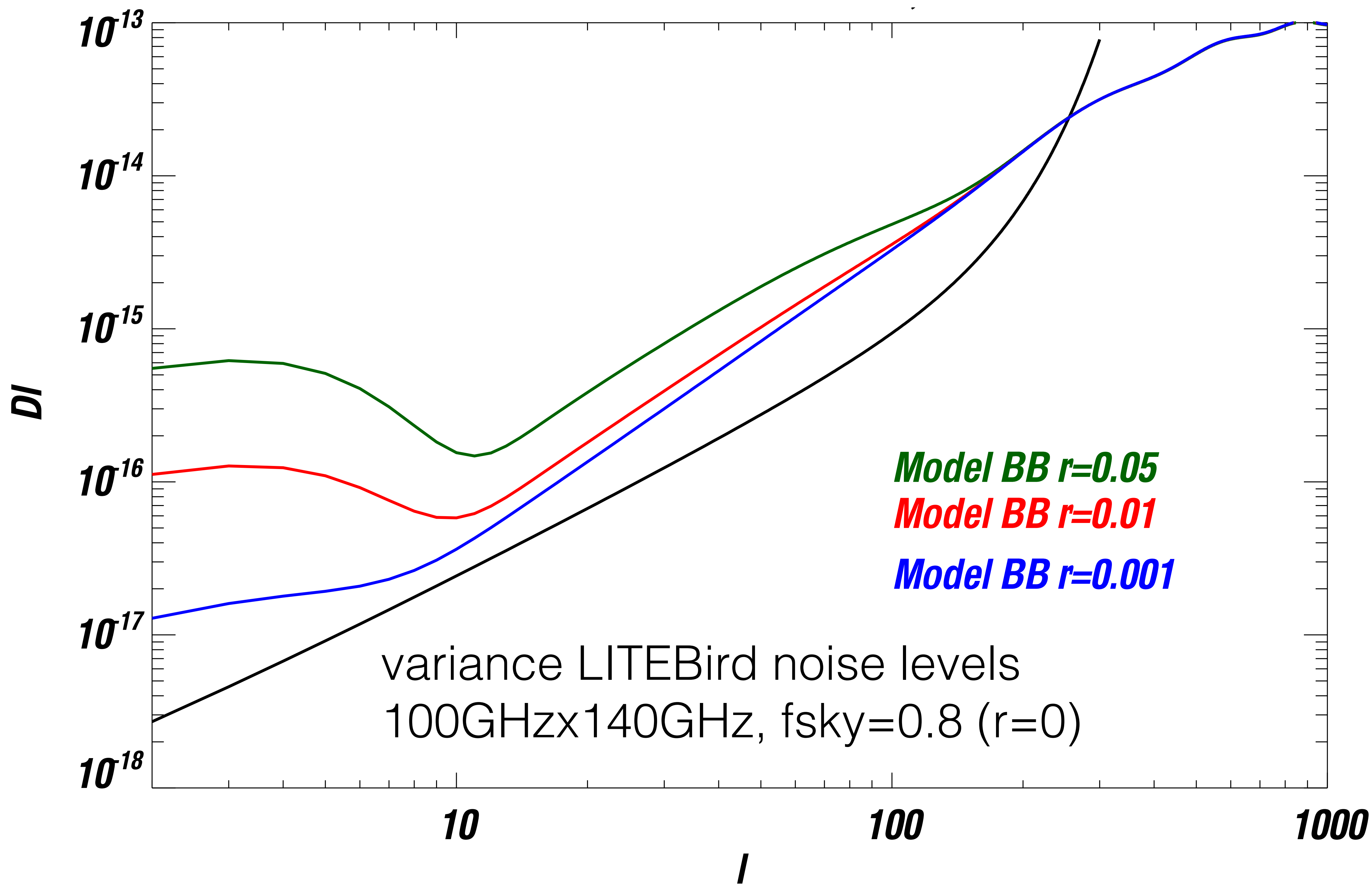
Beyond CMB: **21-cm signal 3-D tomography**



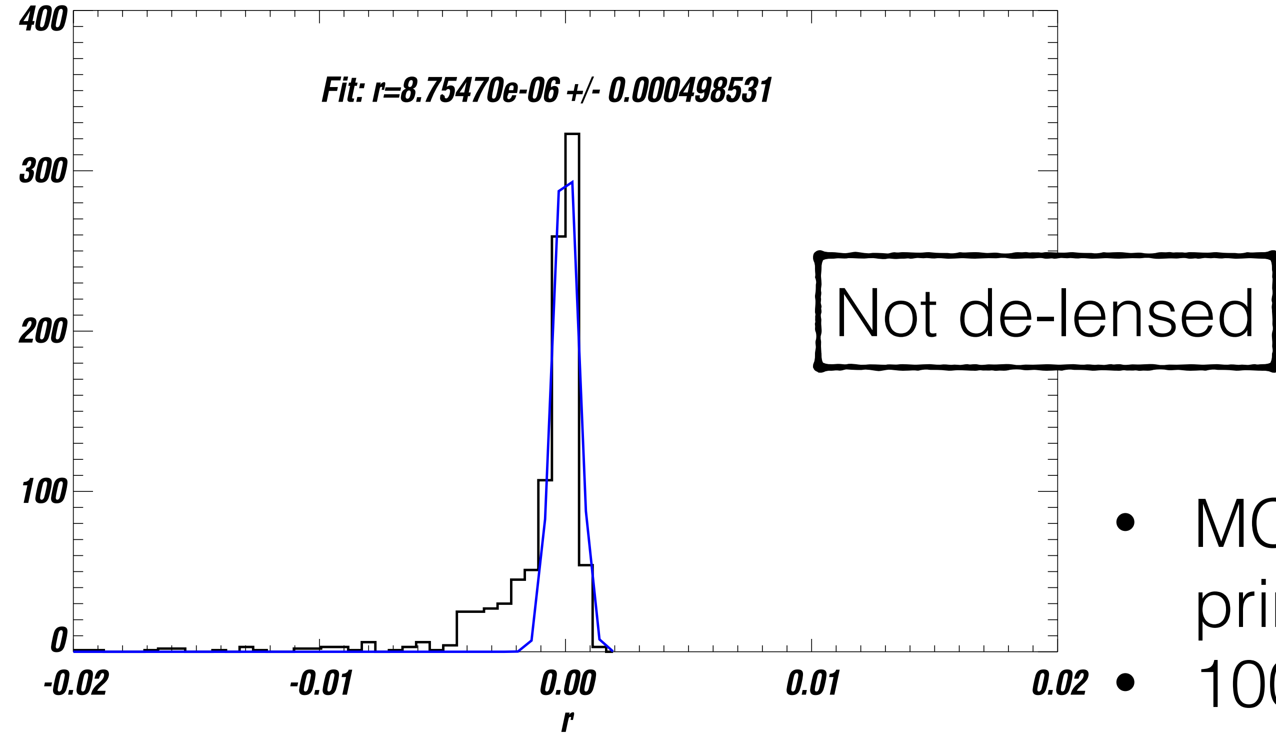
Evolution of the reionization and structure formation process
Powerful probe of dark matter, neutrinos
Accurate astrophysical modeling needed for cosmological predictions

Future prospects: B-modes

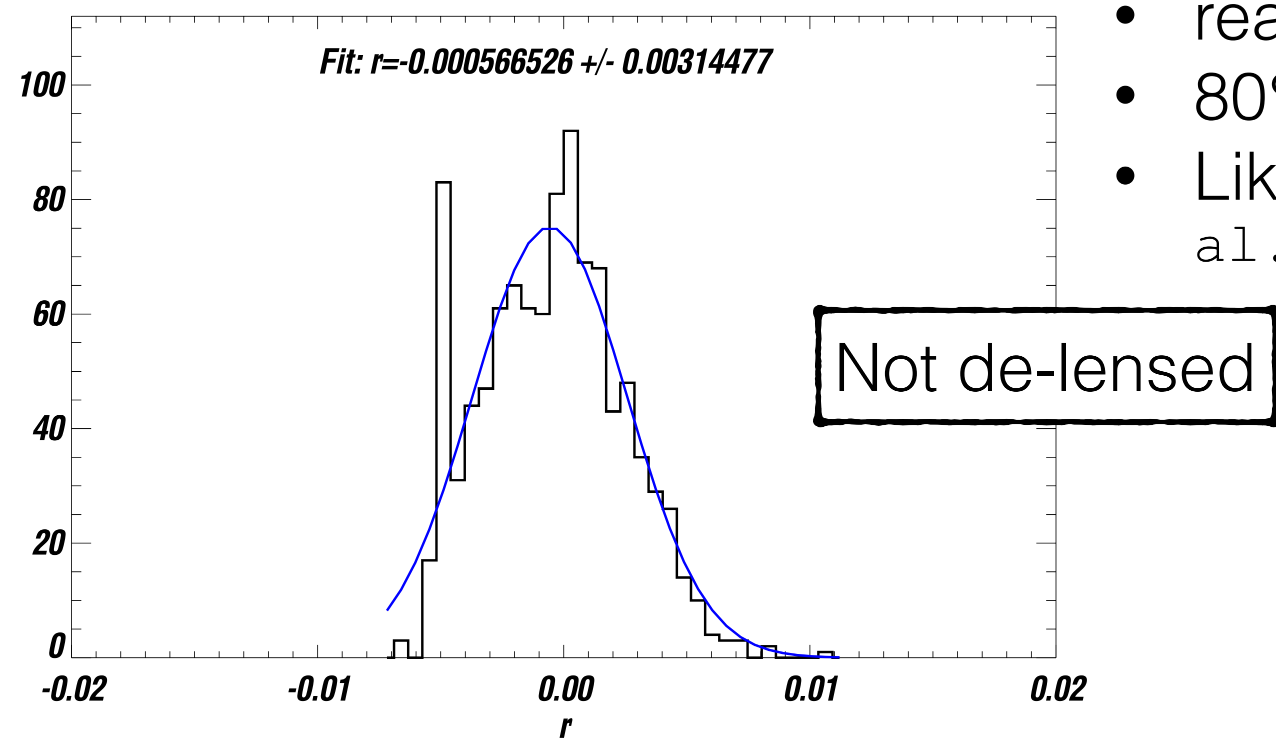
Future proposed CMB experiment as LiteBIRD/Core++



l=[2,300]



l=[30,300]

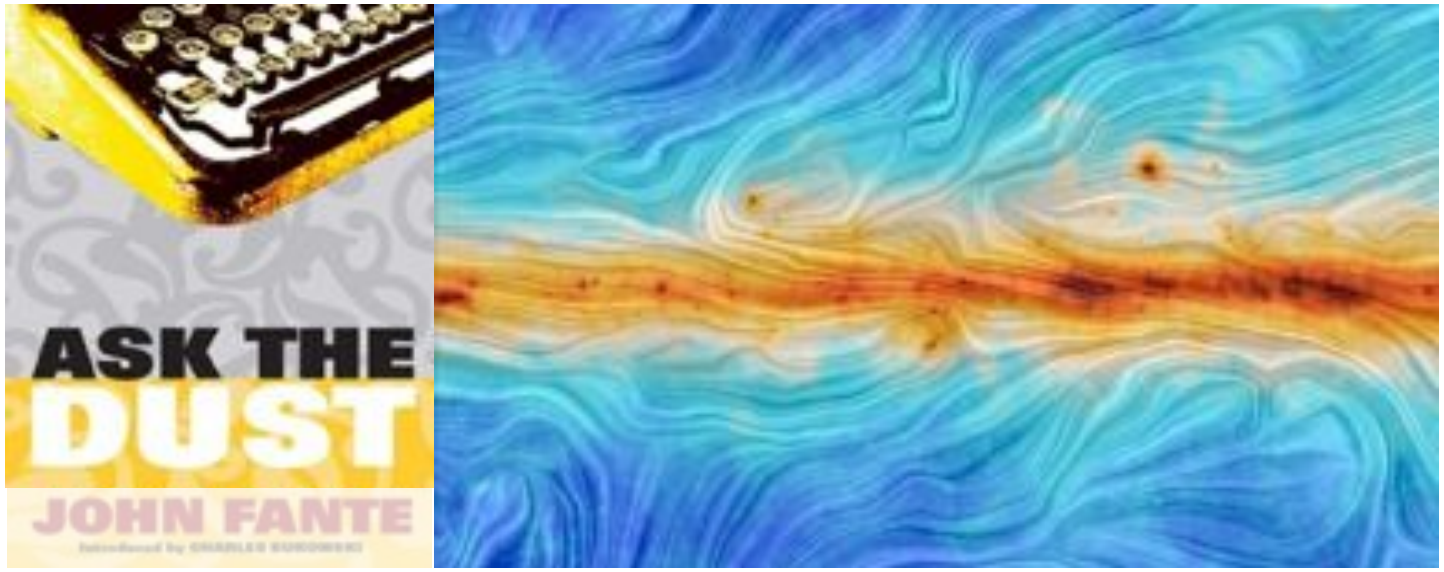


- MC sims without primordial signal (r=0)
- 100GHzx140GHz LiteBIRD cross-spectrum
- realistic noise levels
- 80% sky
- Likelihood `(Mangilli et al. MNRAS 2015)`

Including B-modes at large angular scales: **improved constraints** of the tensor-to-scalar ratio r!

Caveat: correct modelling of the foreground will be crucial

Realistic forecasts must include precise description of the polarised dust contribution



In preparation:
Montier, Aumont, Boulanger, Mangilli et al. 2016 to be submitted A&A (will be Planck paper)
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)
- 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 τ
- Better agreement with astrophysical data
- Measurements from B-modes at large angular scales more challenging
- Significant improvement expected from future space missions

B-modes & primordial tensor modes (r):

- Current best constraints Planck (all data)+Bicep/Keck: $r < 0.07$ 95%CL
- For the moment preliminary HFI results at large scales: 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

What's next

- Future proposed CMB experiments like Core++, LiteBIRD, …(space), and planned AdvACT, CLASS, Bicep3/Keck, QUBIC, SPTPol… (ground) will allow to greatly improve current constraints on τ & r
- Not only primordial B-modes: the lensing signal! Accurate measurement of the total neutrino mass.

Beyond CMB:

- Future galaxy survey as LSST & Euclid: mapping of the Universe at low redshift in combination of CMB (high redshift) to trace evolution of structures
- 3-D mapping 21-cm signal to trace the structure formation process, Dark Matter properties, neutrinos etc (future radio telescope e.g. SKA)