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

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The Universe's history

Inflation Accelerated expansion of the Universe

Formation of light and matter

Light and matter are coupled Dark matter evolves independently: it starts clumping and forming a web of structures

Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages Atoms start feeling the gravity of the cosmic web of dark matter

First stars The first stars and galaxies form in the densest knots of the cosmic web

Galaxy evolution

The present Universe

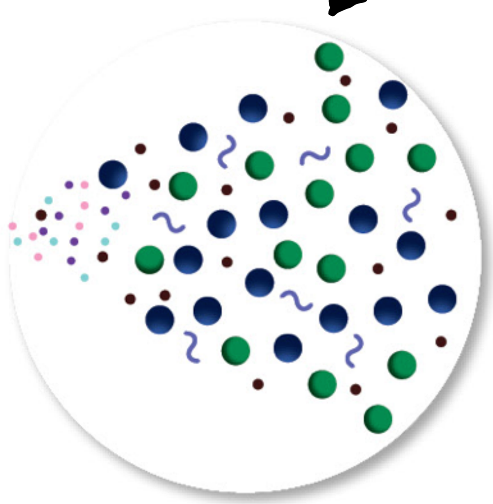
- *Tiny fluctuations: the seeds of future structures*
- *Gravitational waves?*

Inflation generates the primordial perturbations (scalar & tensor)

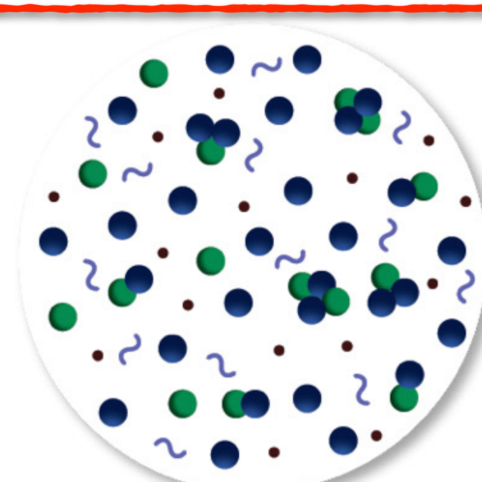
The Hot Big-bang inflationary model

The Universe's history

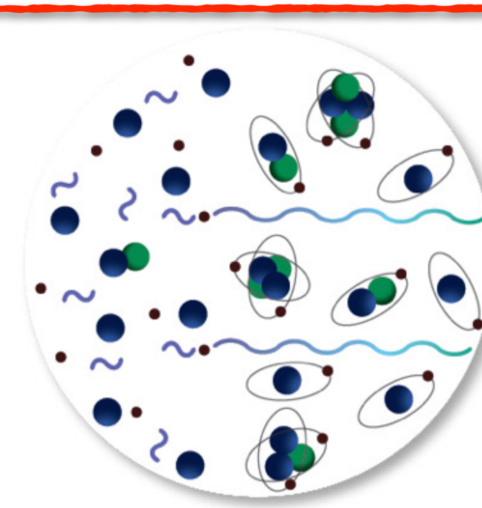
The Cosmic Microwave Background (CMB)



Frequent collisions between normal matter and light



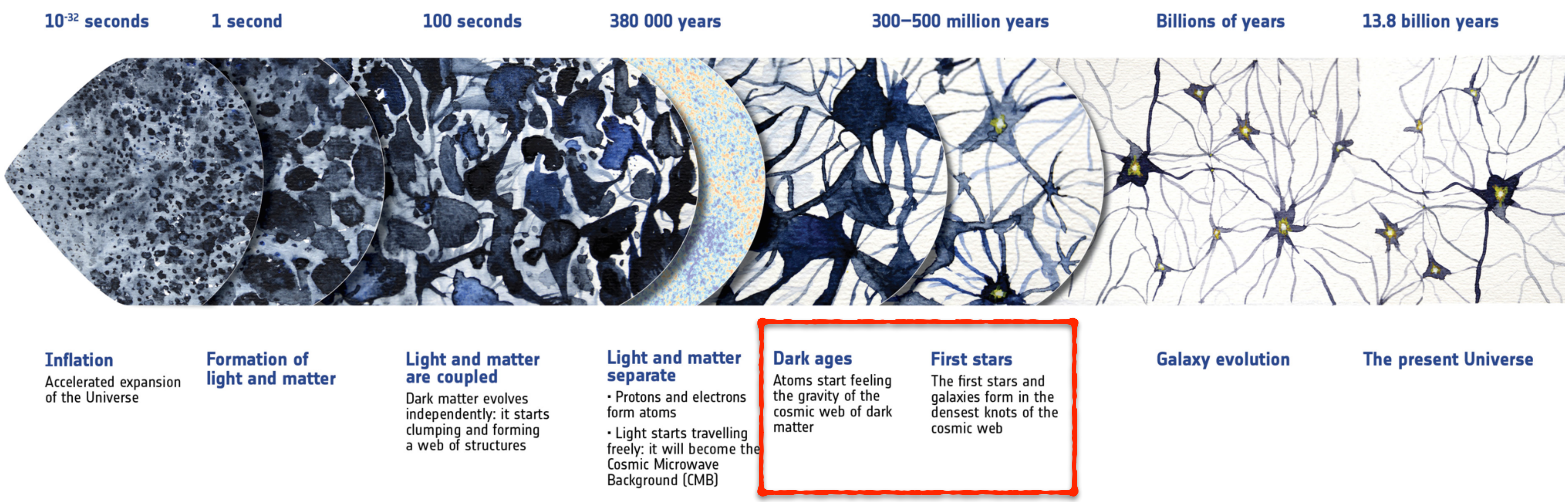
As the Universe expands, particles collide less frequently



Last scattering of light off electrons

→ ***Polarisation***

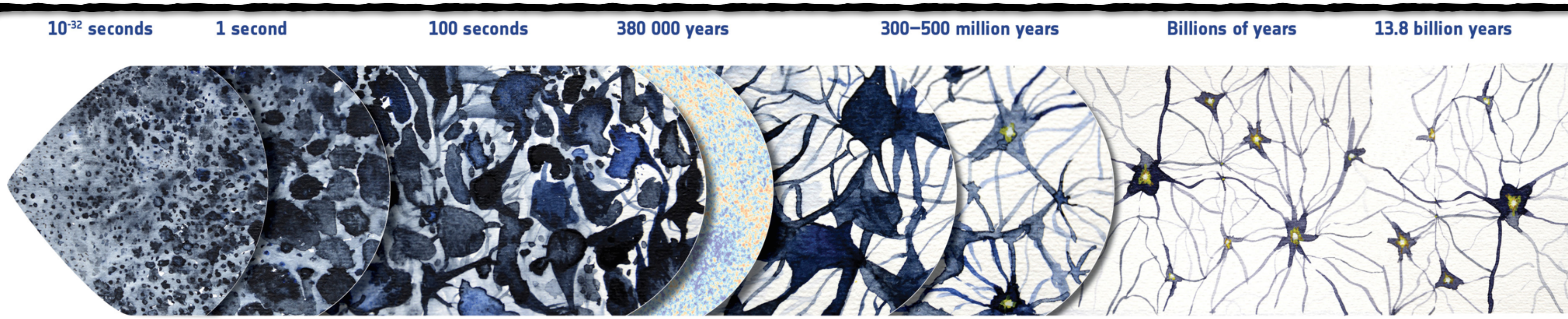
The Universe's history



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

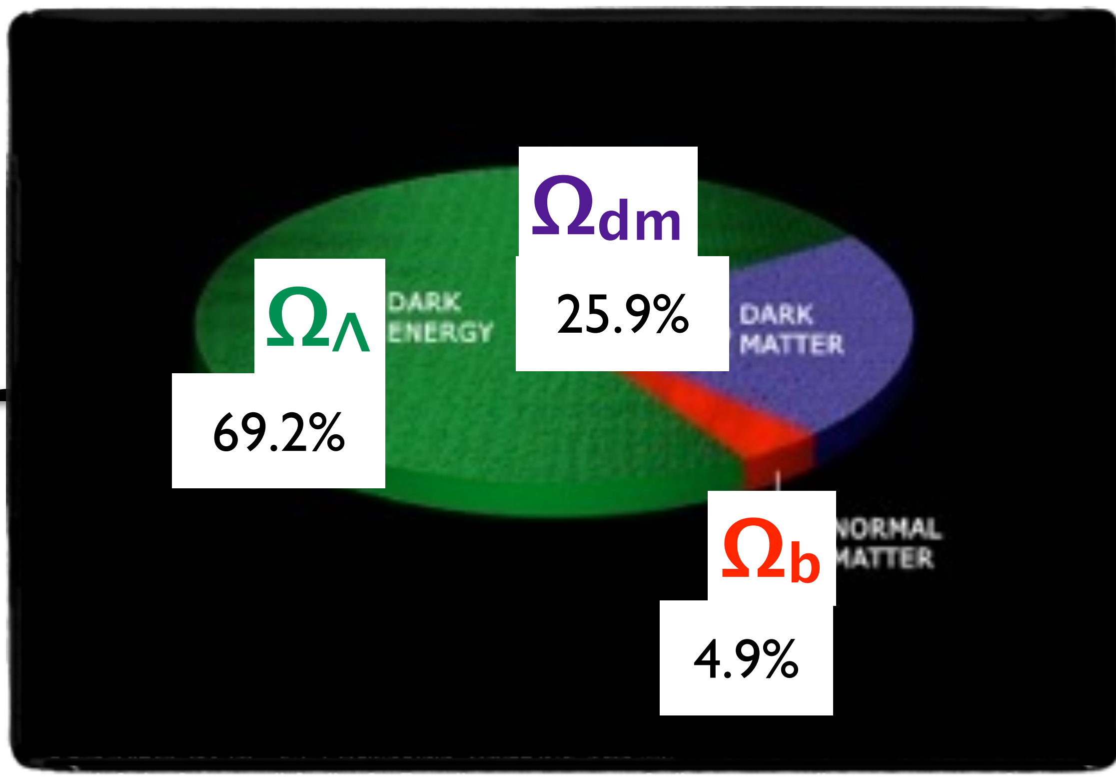
The concordance ΛCDM model



The Cosmic Microwave Background (CMB)

Quasar, 21-cm, Lymanα

Galaxy clusters
Supernovae

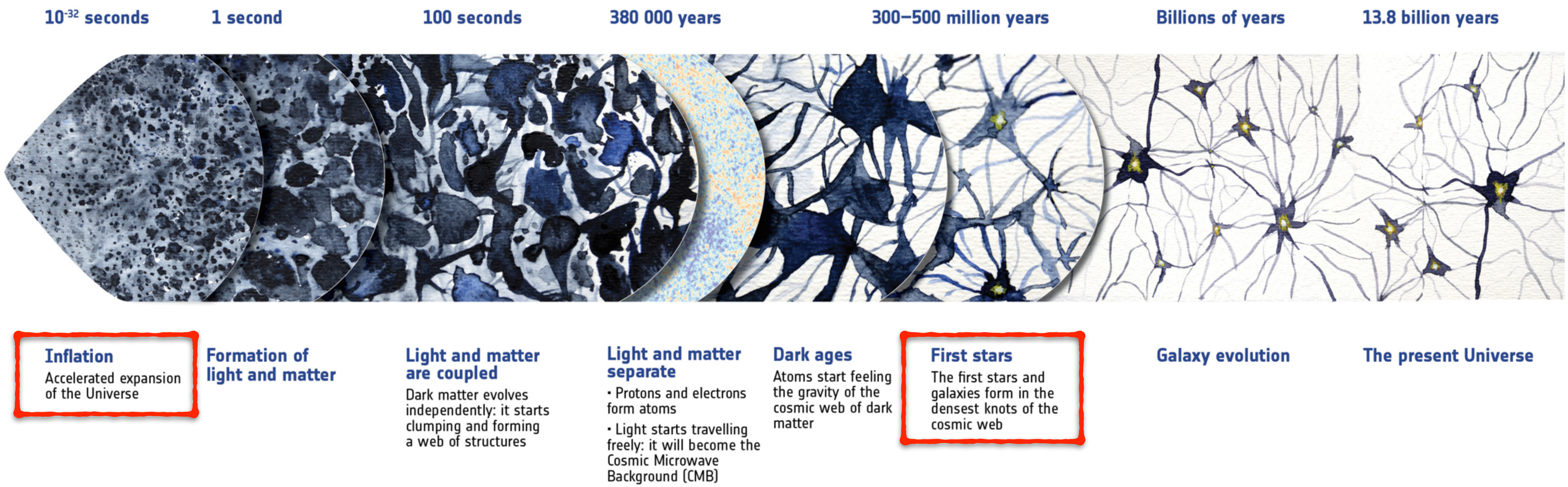


what is inflation?

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**

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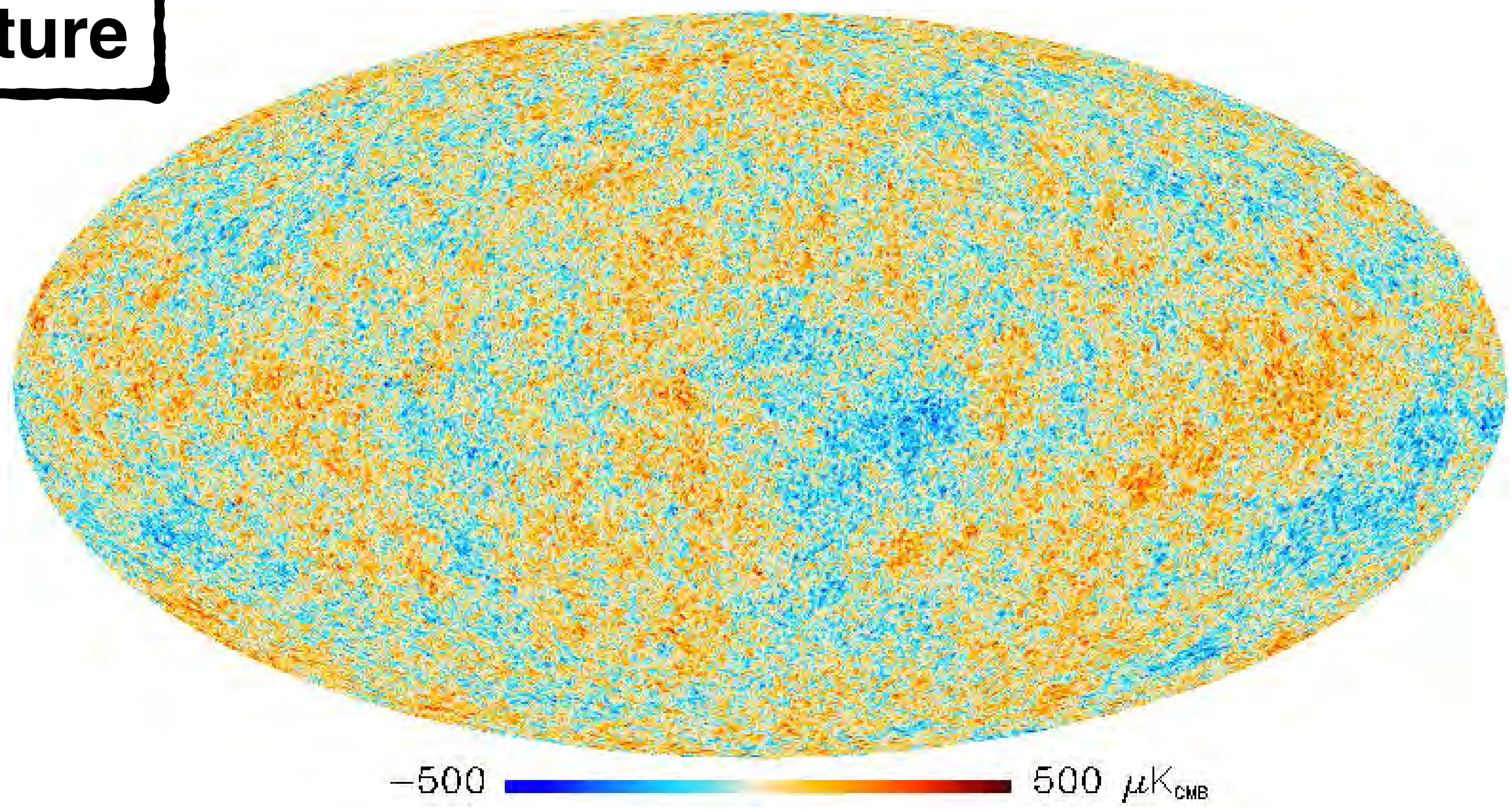
  Statistical methods (Mangilli et al. MNRAS 2015)

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

The CMB anisotropies

Temperature

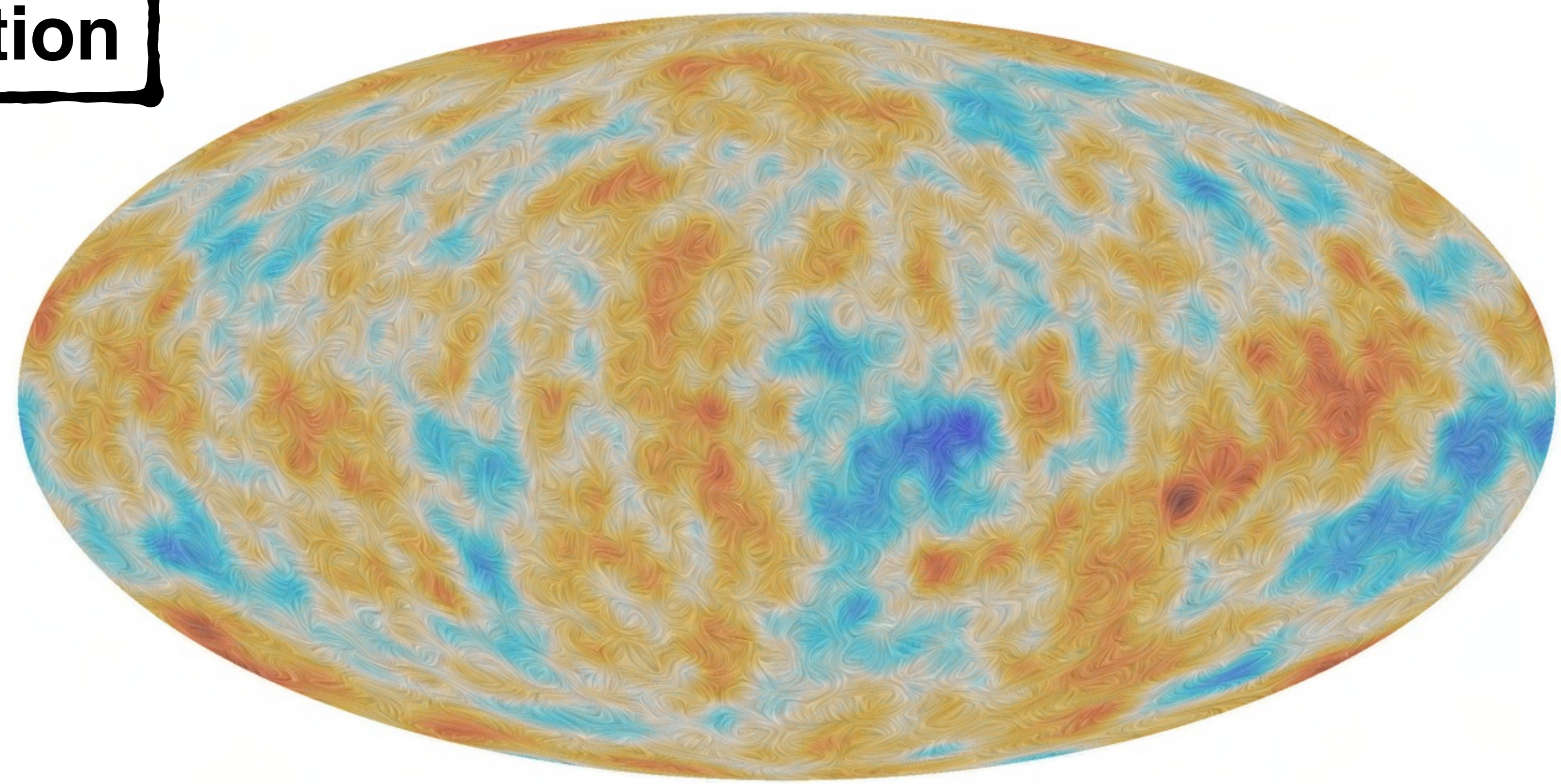
Planck



The CMB polarization

Polarization

Planck



CMB polarization signal: orders of magnitude weaker than temperature

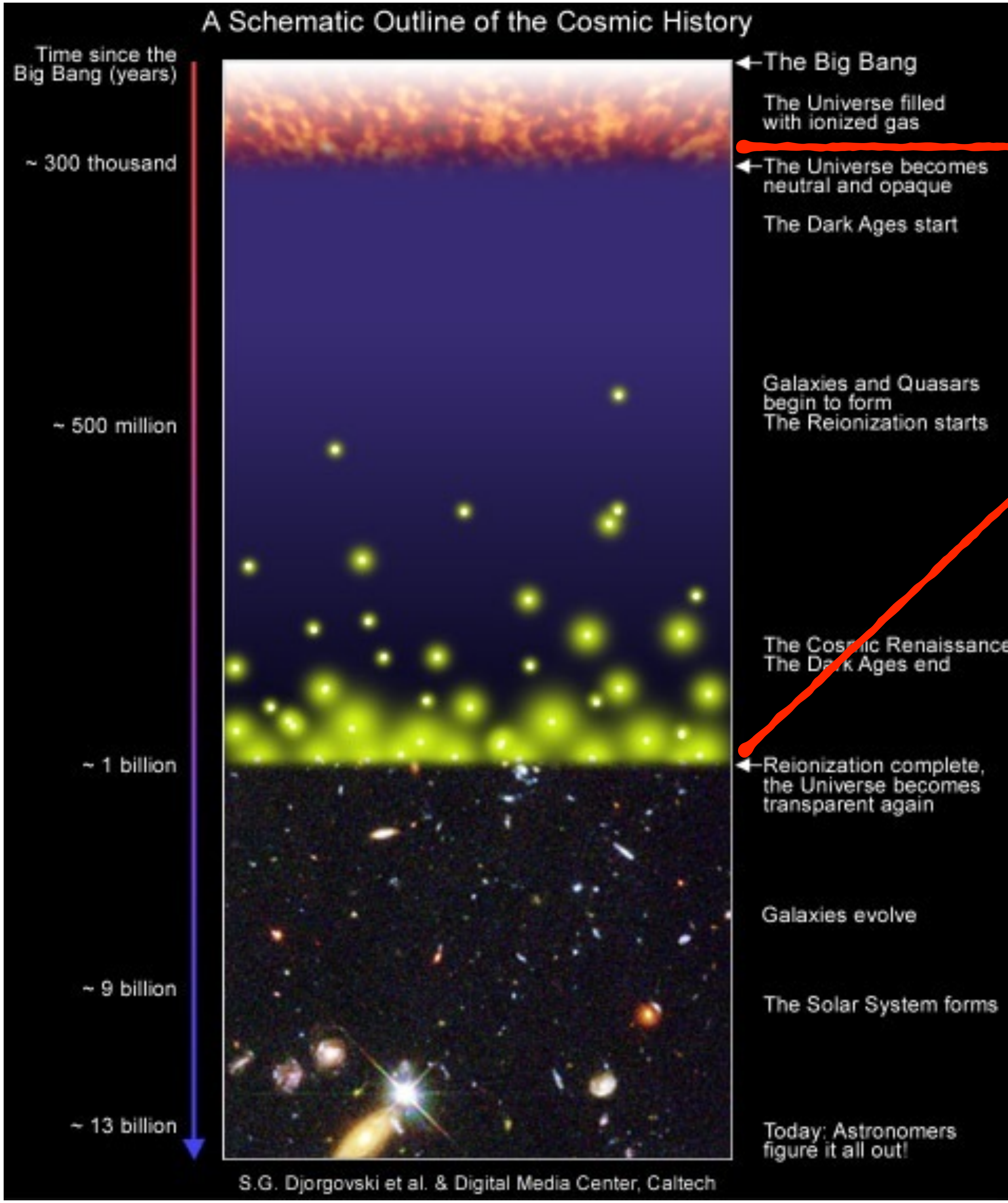
E-modes

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

B-modes

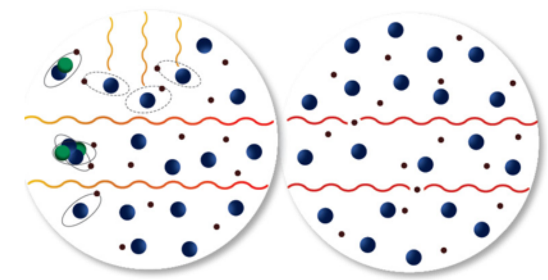
- Magnetic type polarization field.
- Can be generated only by primordial tensor modes i.e. **primordial gravitational waves**
- Contribution from lensing

Generation of the CMB polarization



DECOUPLING

REIONIZATION



Light from first stars and galaxies breaks atoms apart and "reionises" the Universe

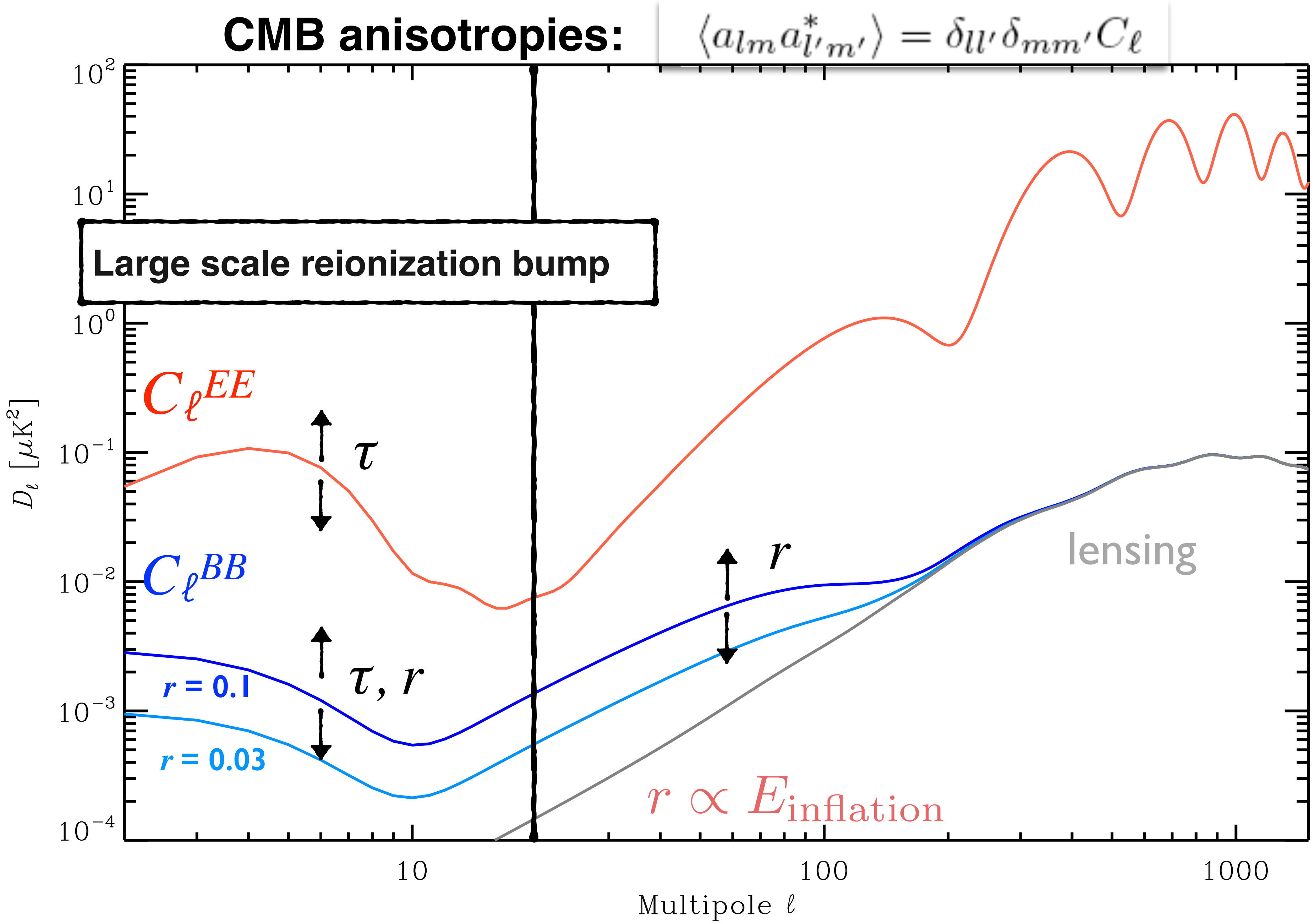
Light can interact again with electrons → ***Polarisation***

Thomson scattering optical depth:

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

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

The CMB E & B angular power spectra

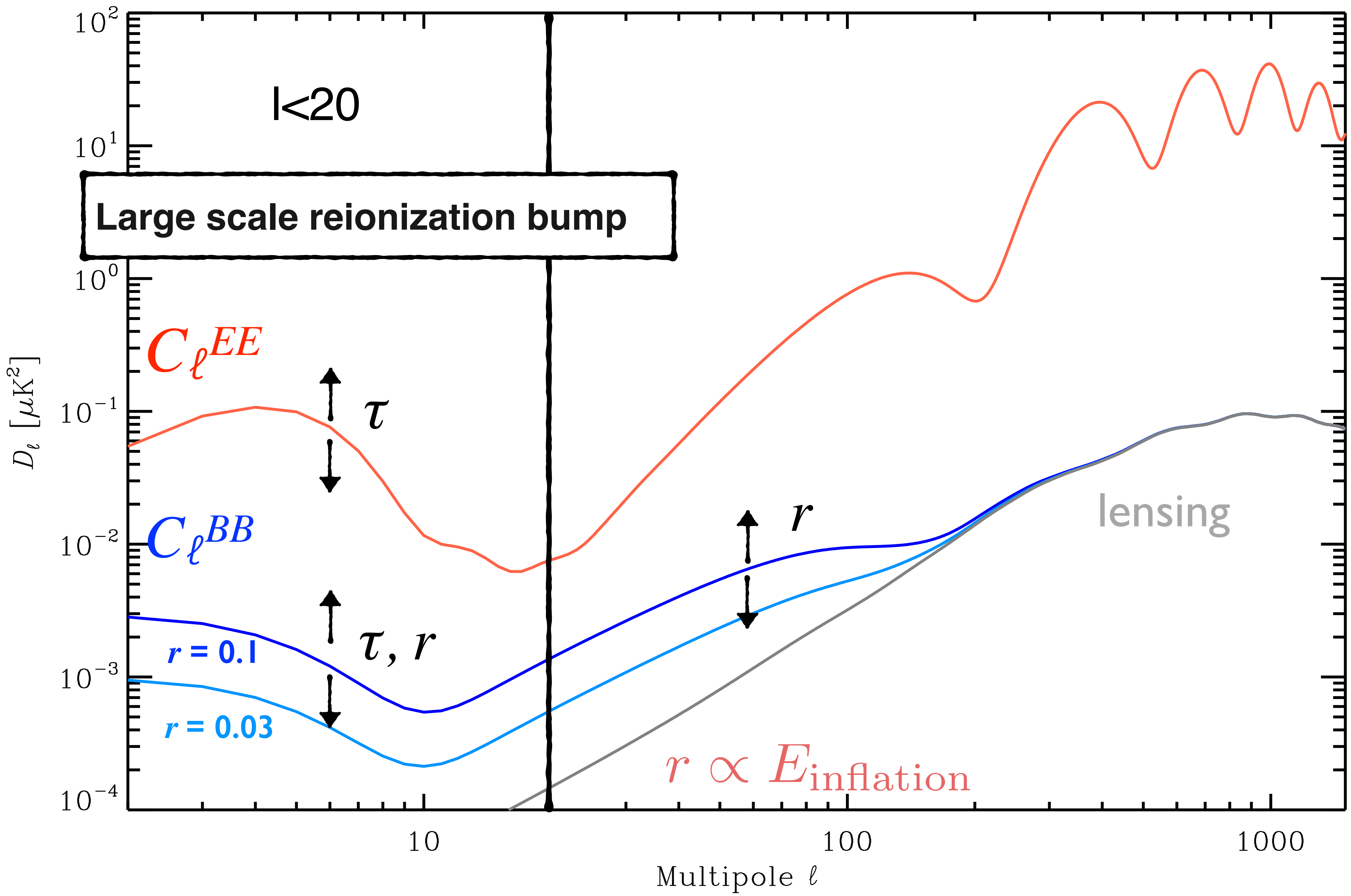


Scientific goals

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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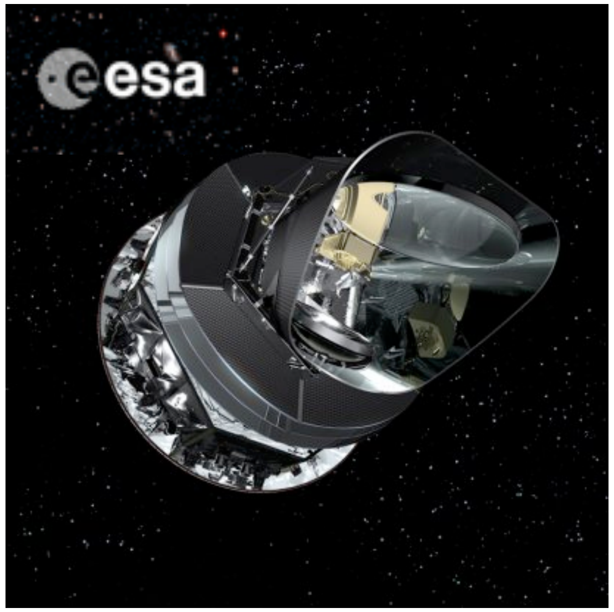
The Planck satellite

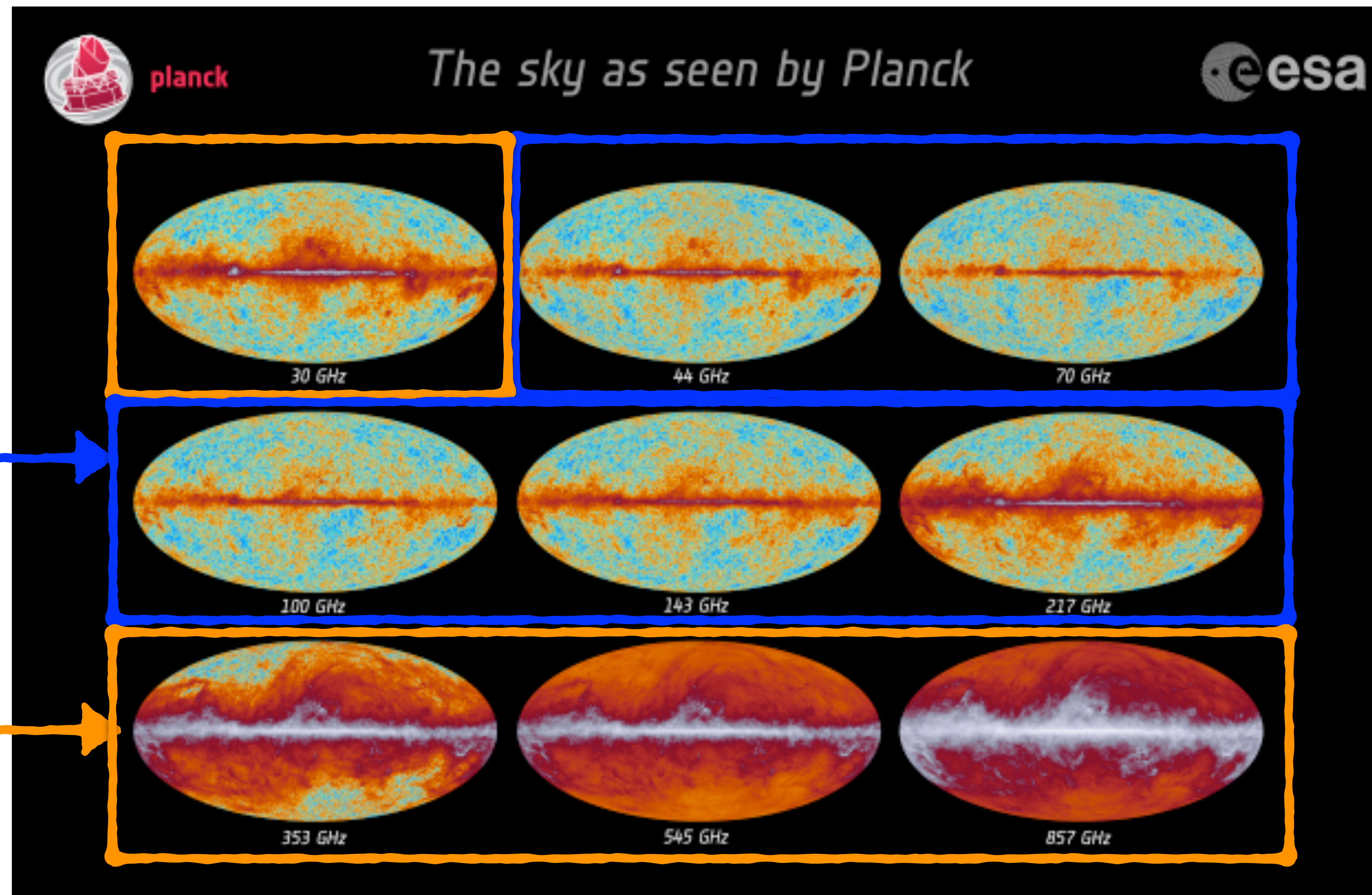


- ➡ 9 frequency bands
- ➡ Two instruments:

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

Channels for CMB characterisation

Foregrounds characterisation



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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

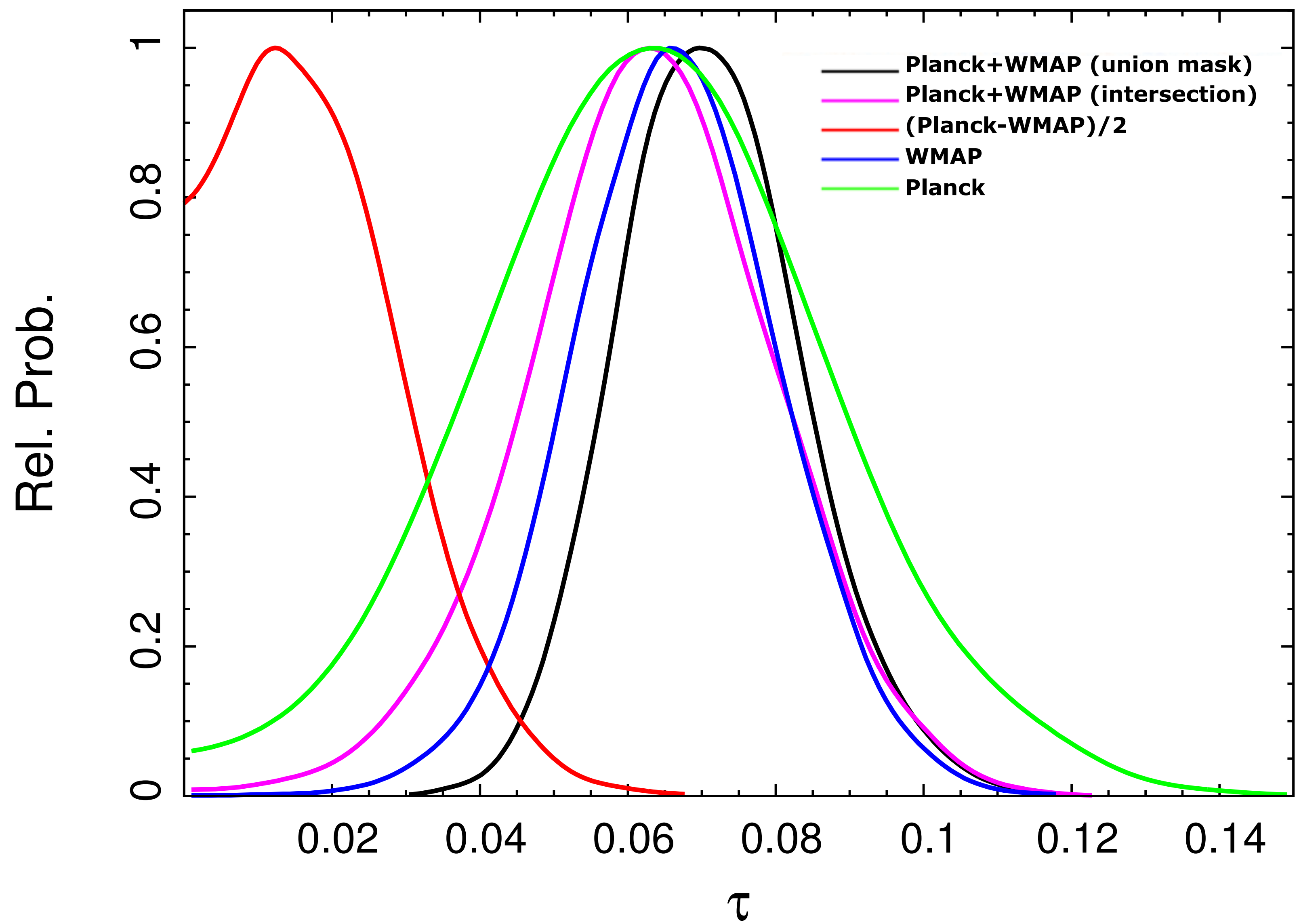
LFI: negligible residuals with respect to noise, **LFI 70GHz released**

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)**

Reionization optical depth from large scales 2015



The Planck Coll. XI, 2015

- ✓ **WMAP and Planck LFI-70GHz yield consistent estimates**
- ✓ **The τ signal disappears in the null map**

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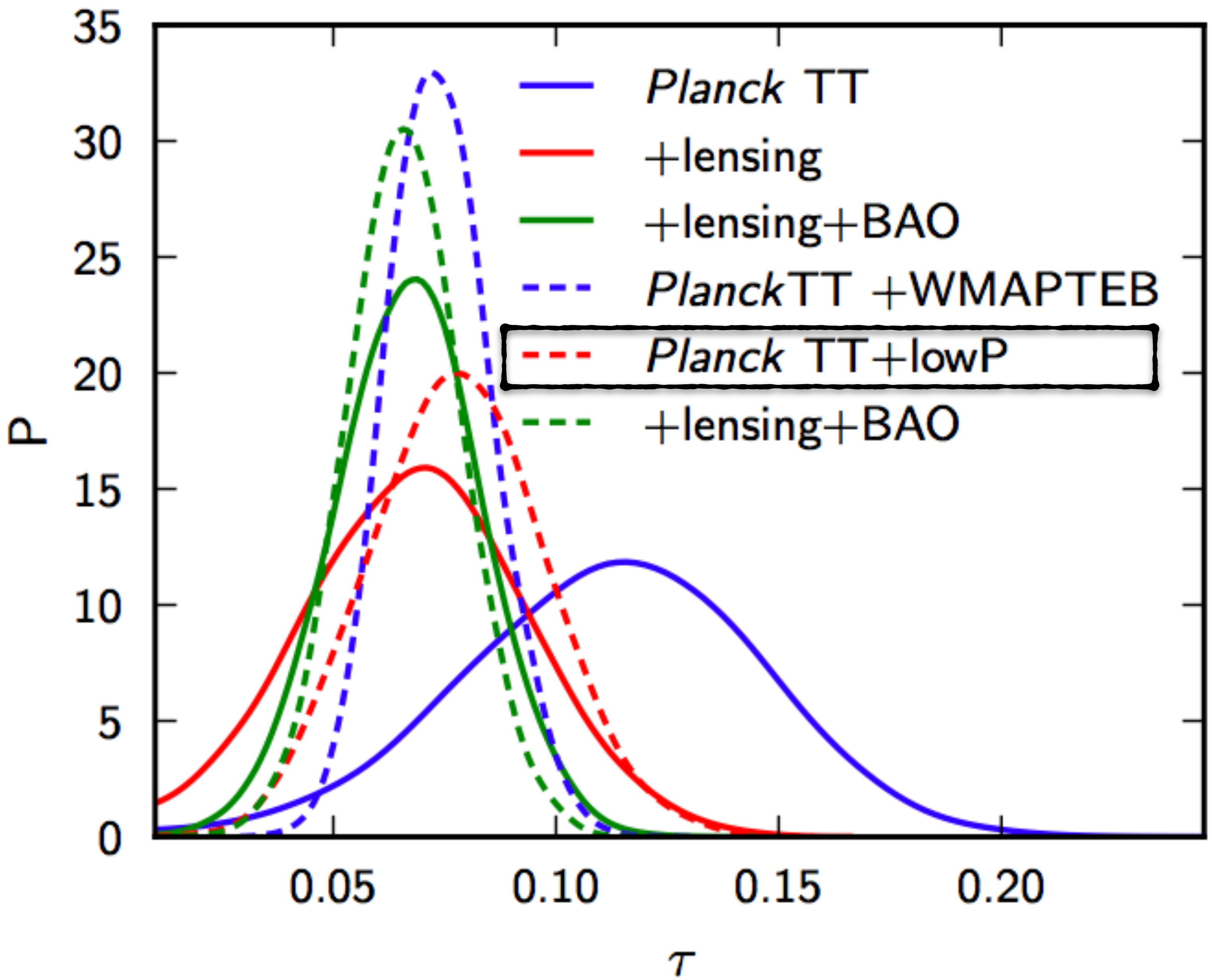
Planck 2015: reionization optical depth summary



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

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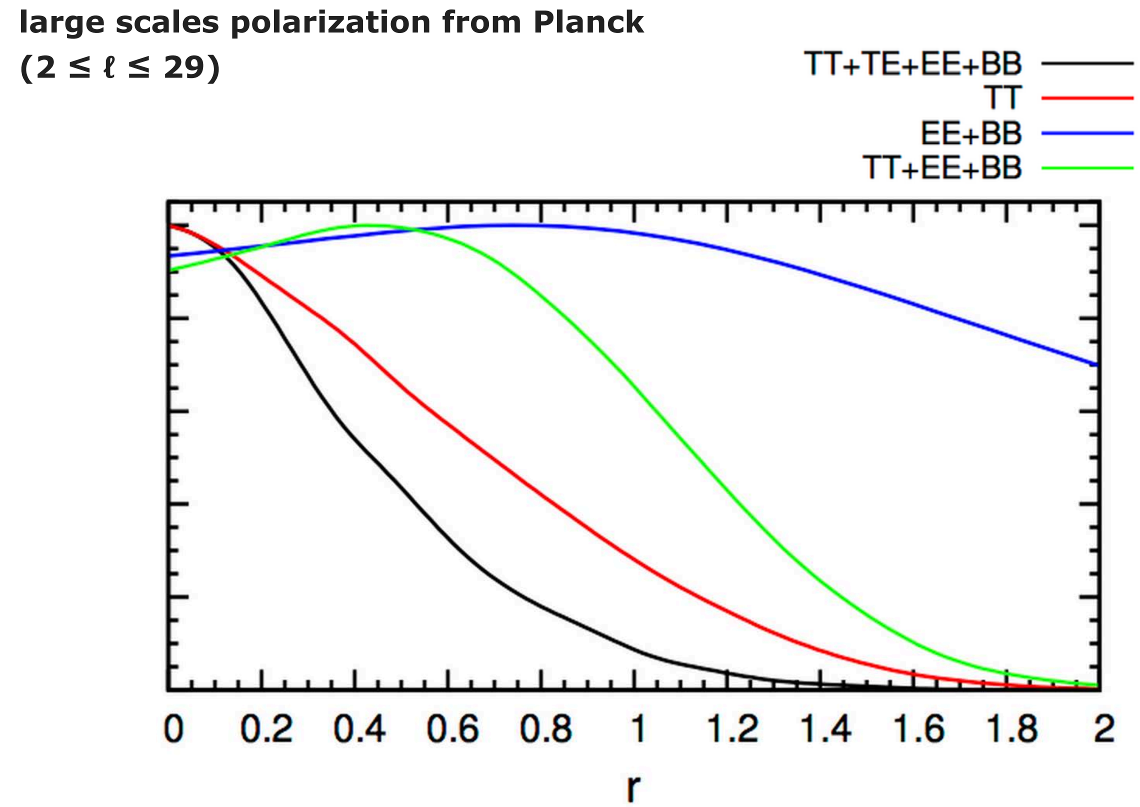
Planck 2015: Tensor-to-scalar ratio

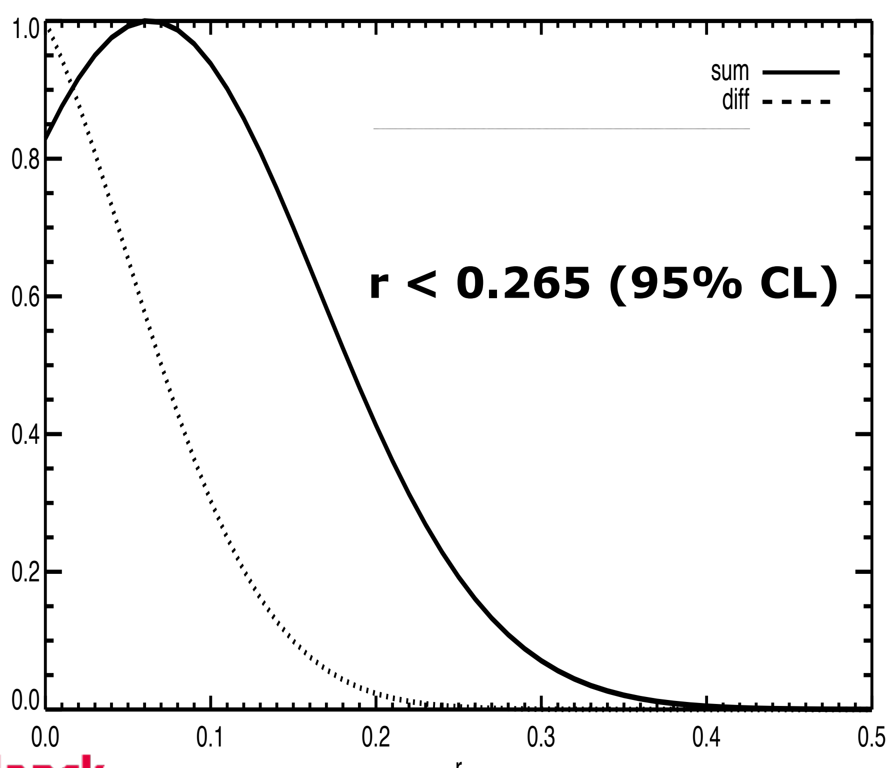
From large scales 70GHz: still far. But significant improvement on the way for 2016

The Planck Coll. XI 2015



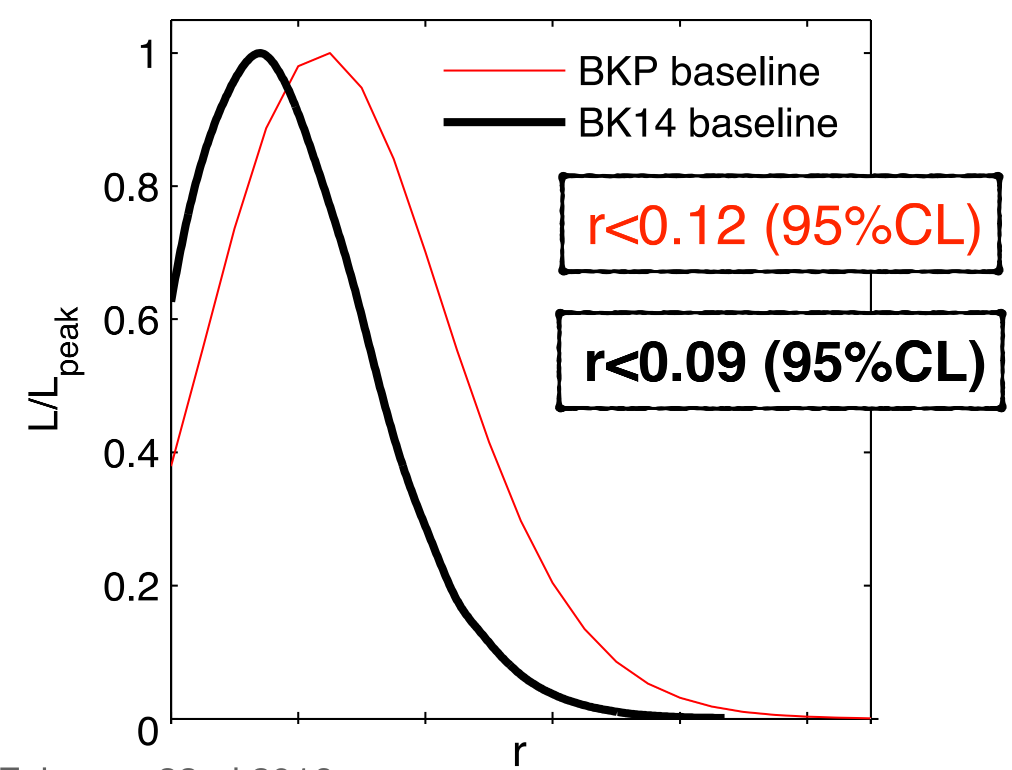
From intermediate scales:

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

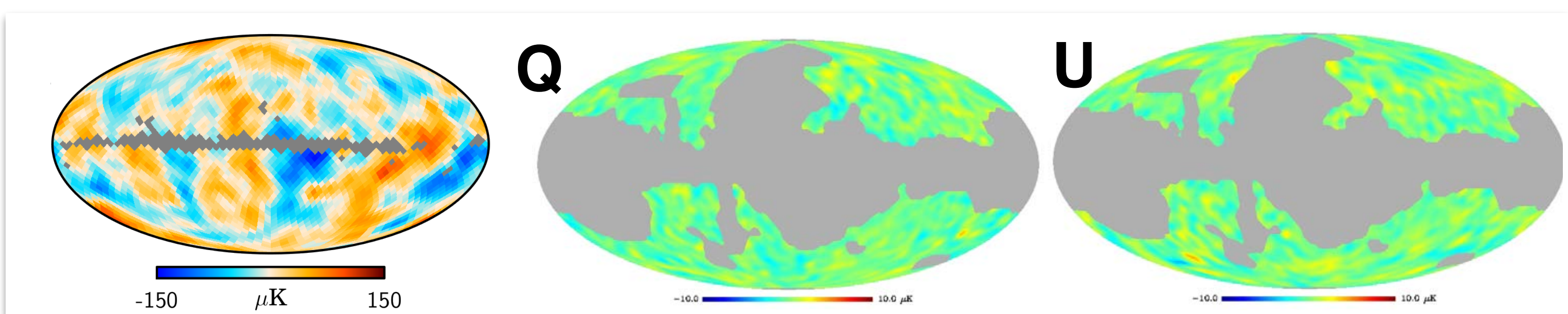
➡ **Data analysis**

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: $\propto$ 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

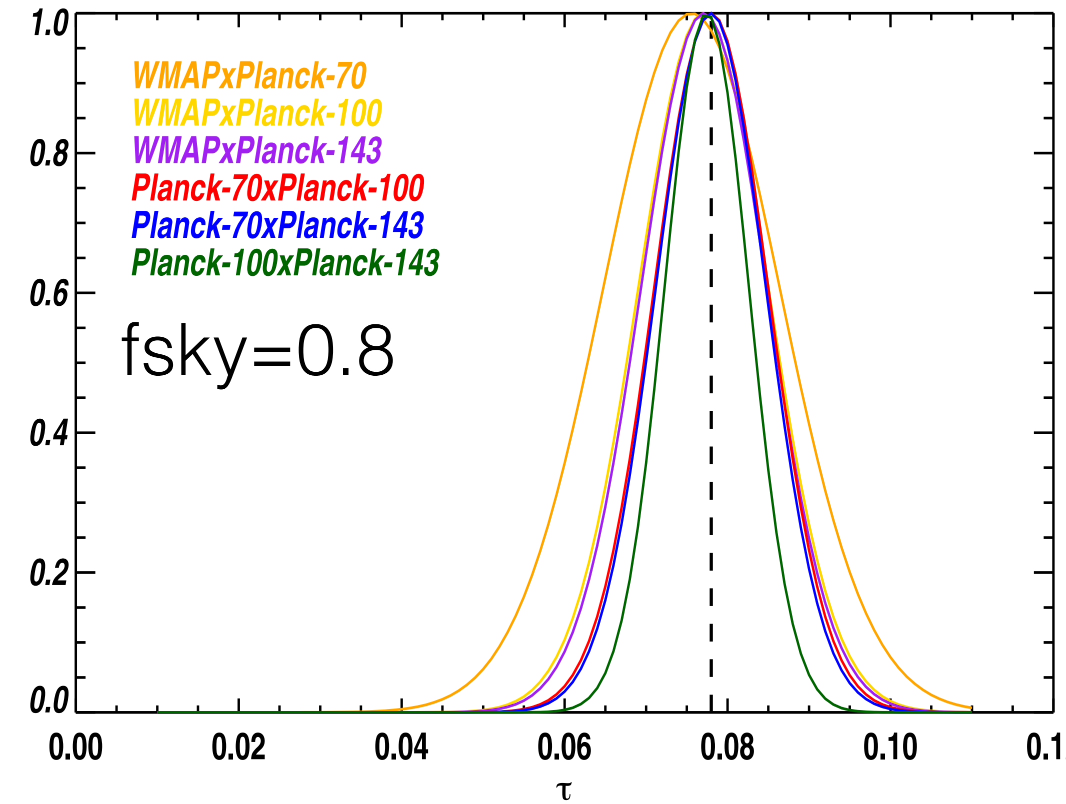
Cross-spectra oHL: τ estimation

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

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

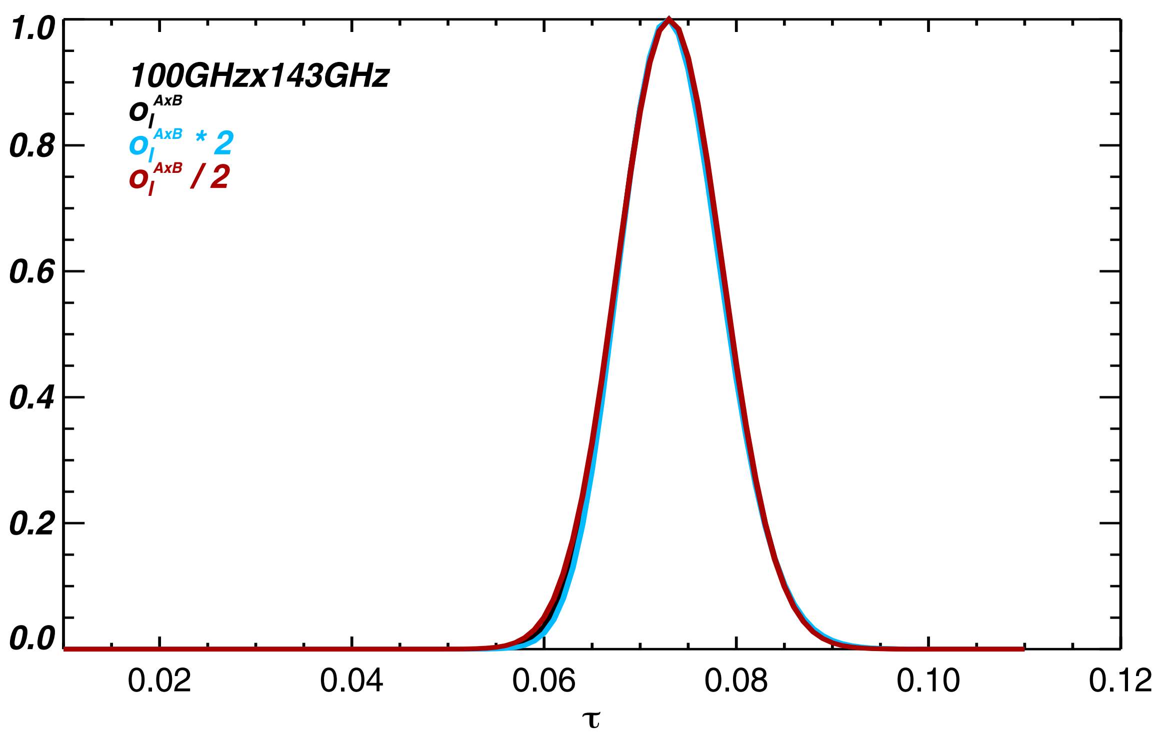
Unbiasedness

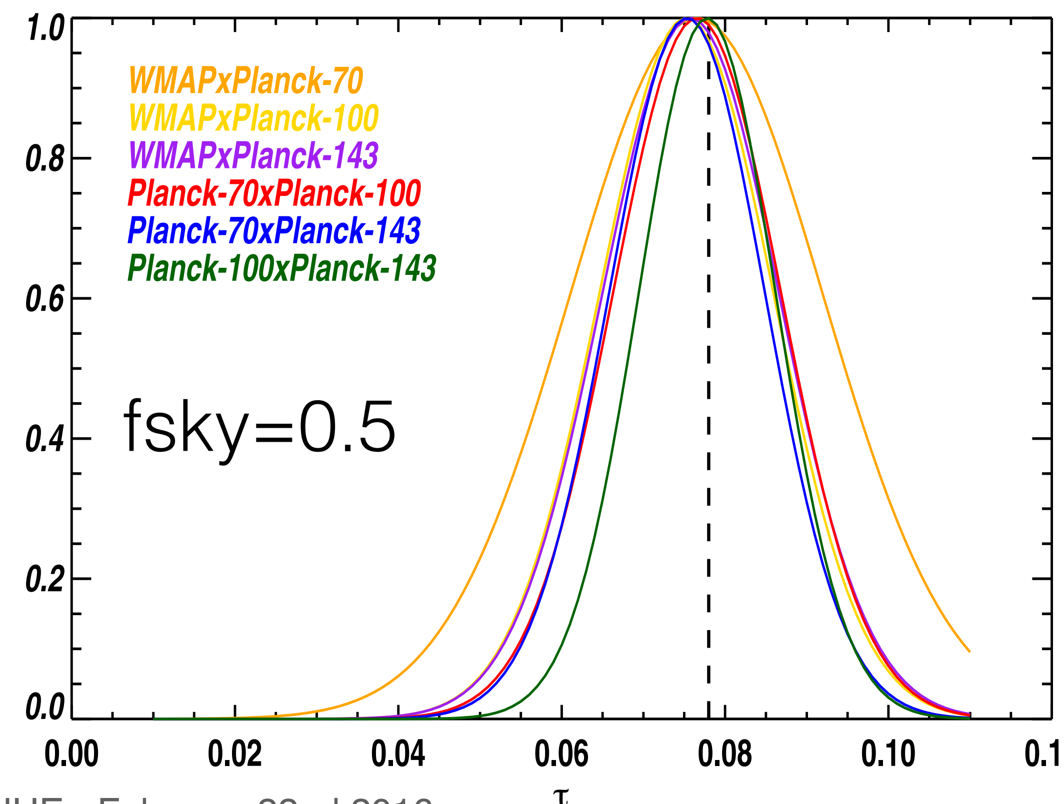
Best constraints expected from HFI
100GHzx143GHz



Robustness

Offset change





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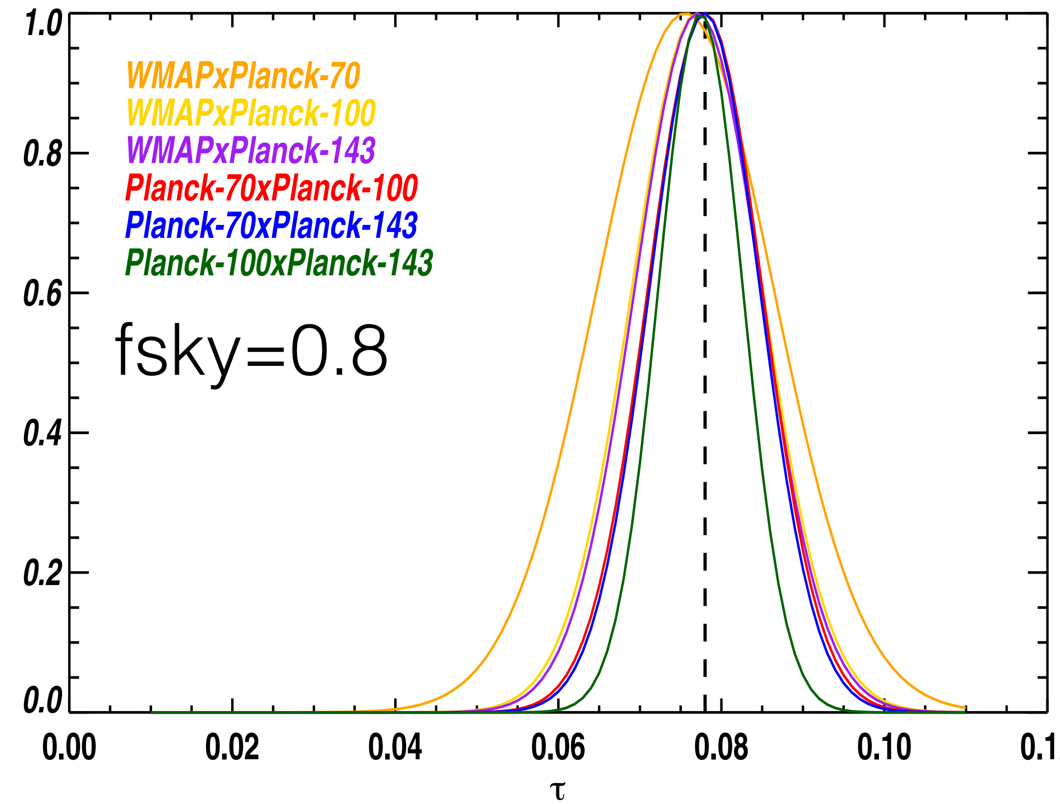
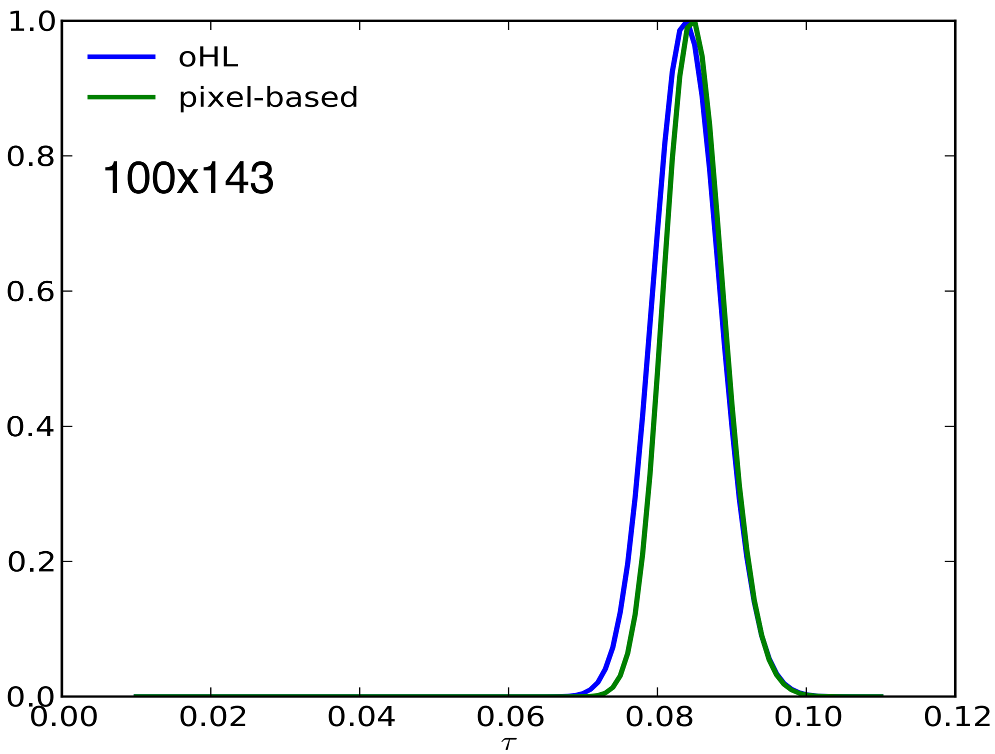


Best constraints expected from HFI 100GHzx143GHz

Optimality

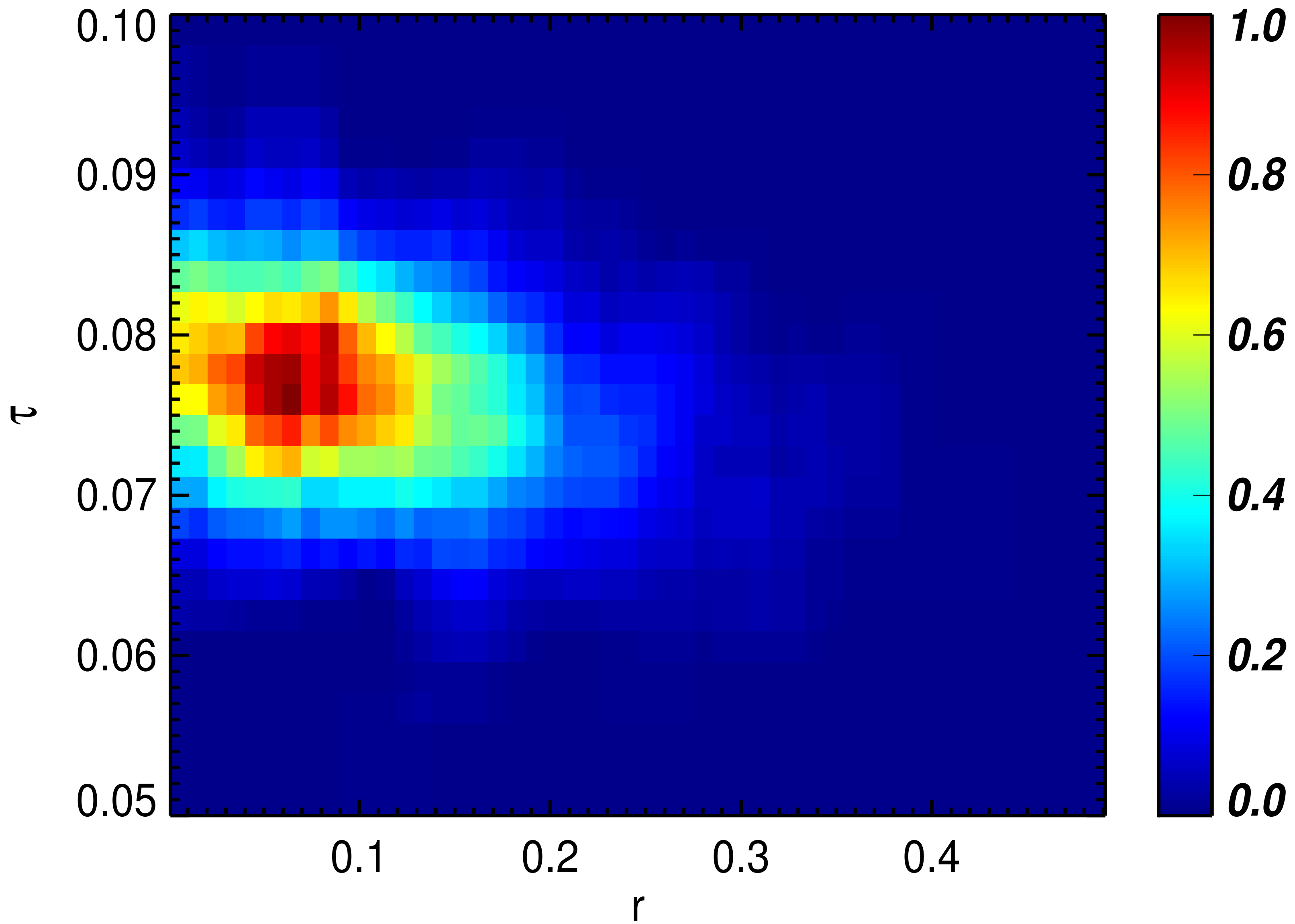


Comparison with the pixel-based approach: compatible error bars estimation at better than 10%

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

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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

PRELIMINARY

Improved and lower τ: impact on parameters

PRELIMINARY

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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 ~ 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", to be submitted A&A 2016

The Planck collaboration incl. A. Mangilli: "Reionization history constraints from Planck", to be submitted A&A 2016

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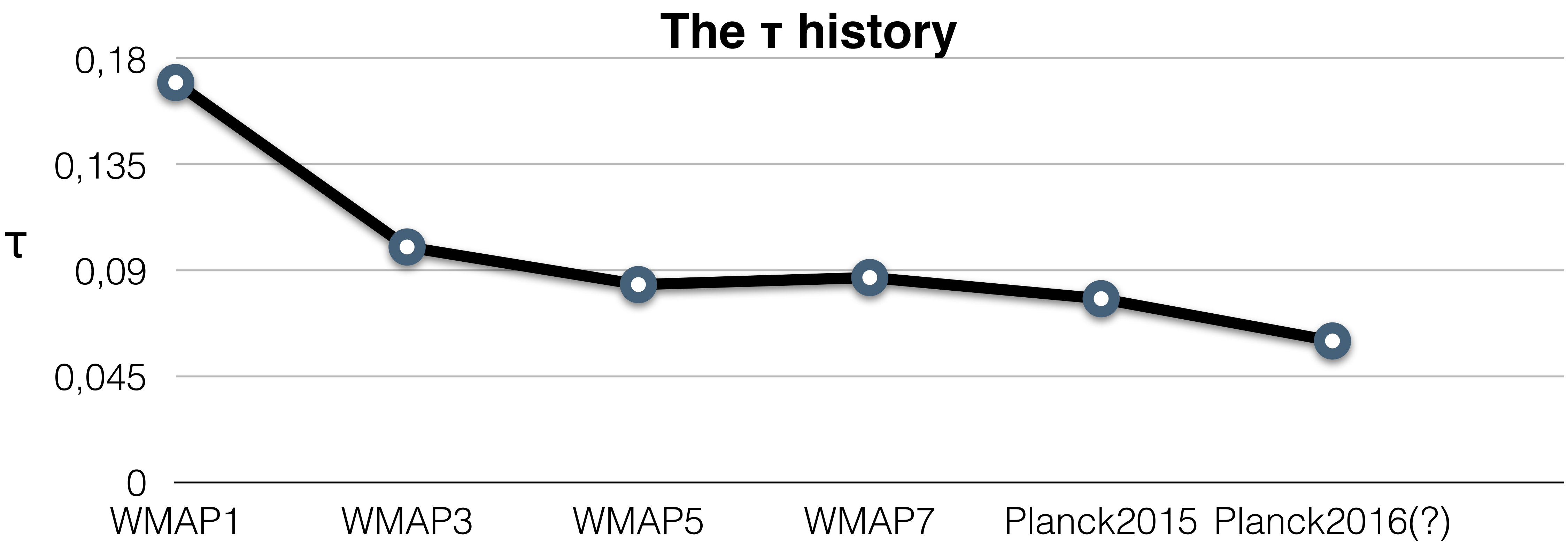
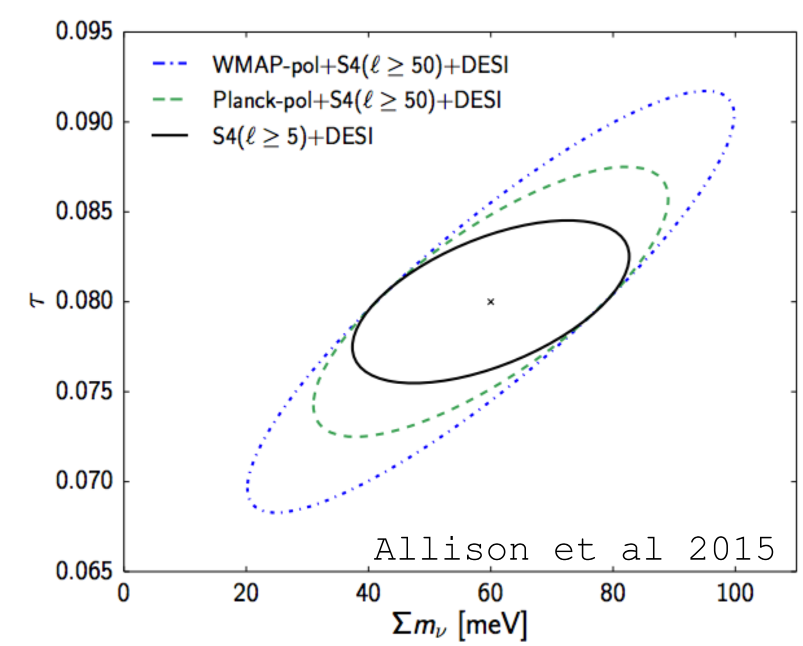
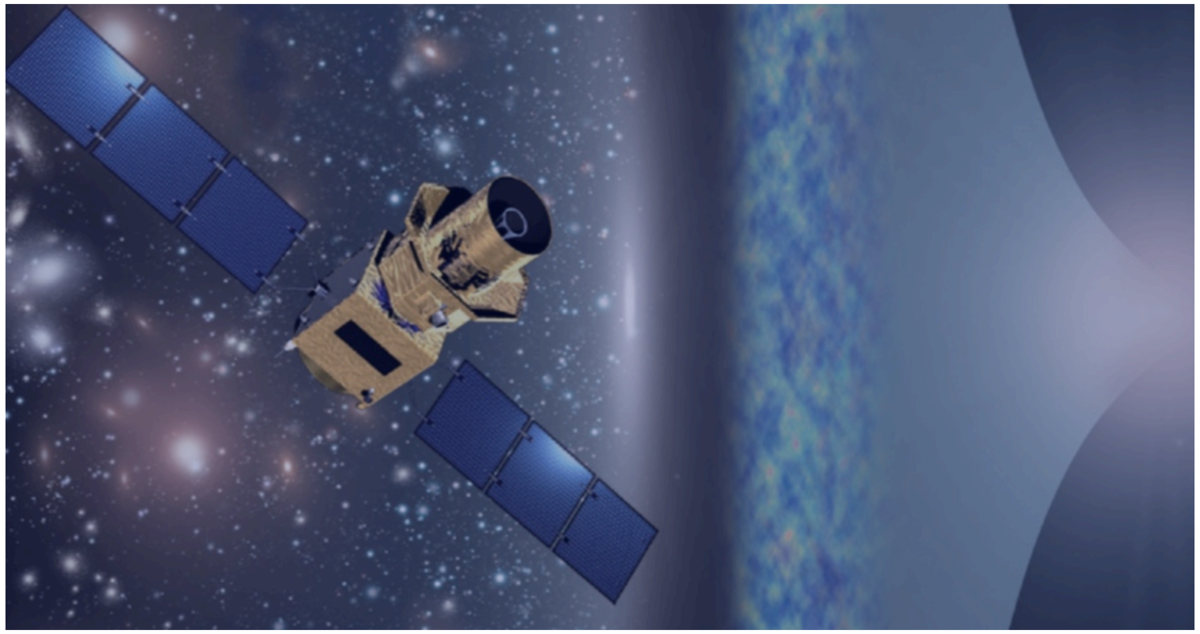
Future prospects: E-modes



- 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, …)



LiteBIRD: Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection



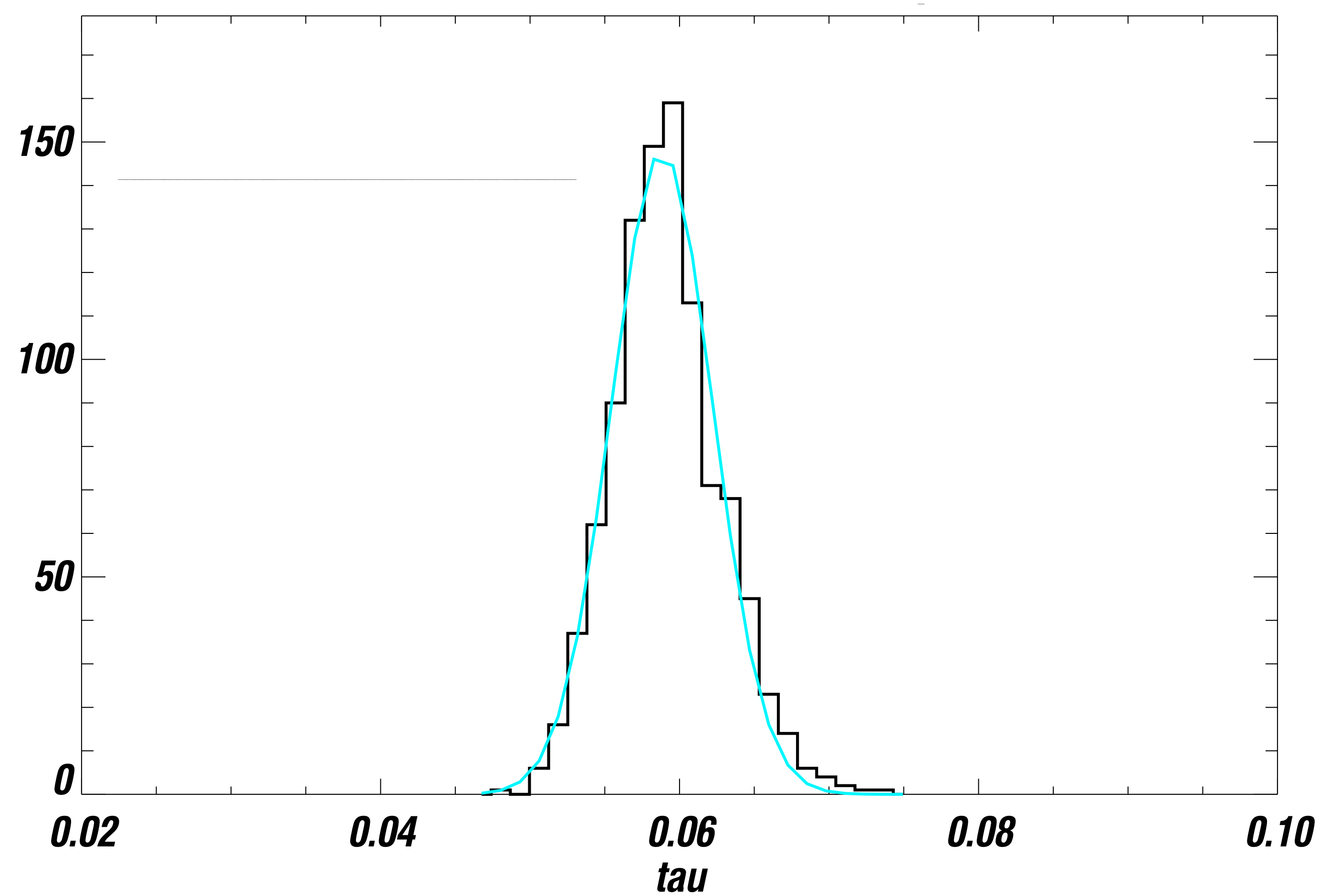
- Joint JAXA-NASA proposal: passed first selection in 2015 (now phase-A)
- Possible ESA collaboration
- Proposed launch year: 2022
- Full-sky, $2<l<300$
- E-modes & B-modes: τ & r at large-intermediate scales
- Planck expertise: dedicated group involved in LiteBIRD WG

+CoRE++, PIXIE

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)`

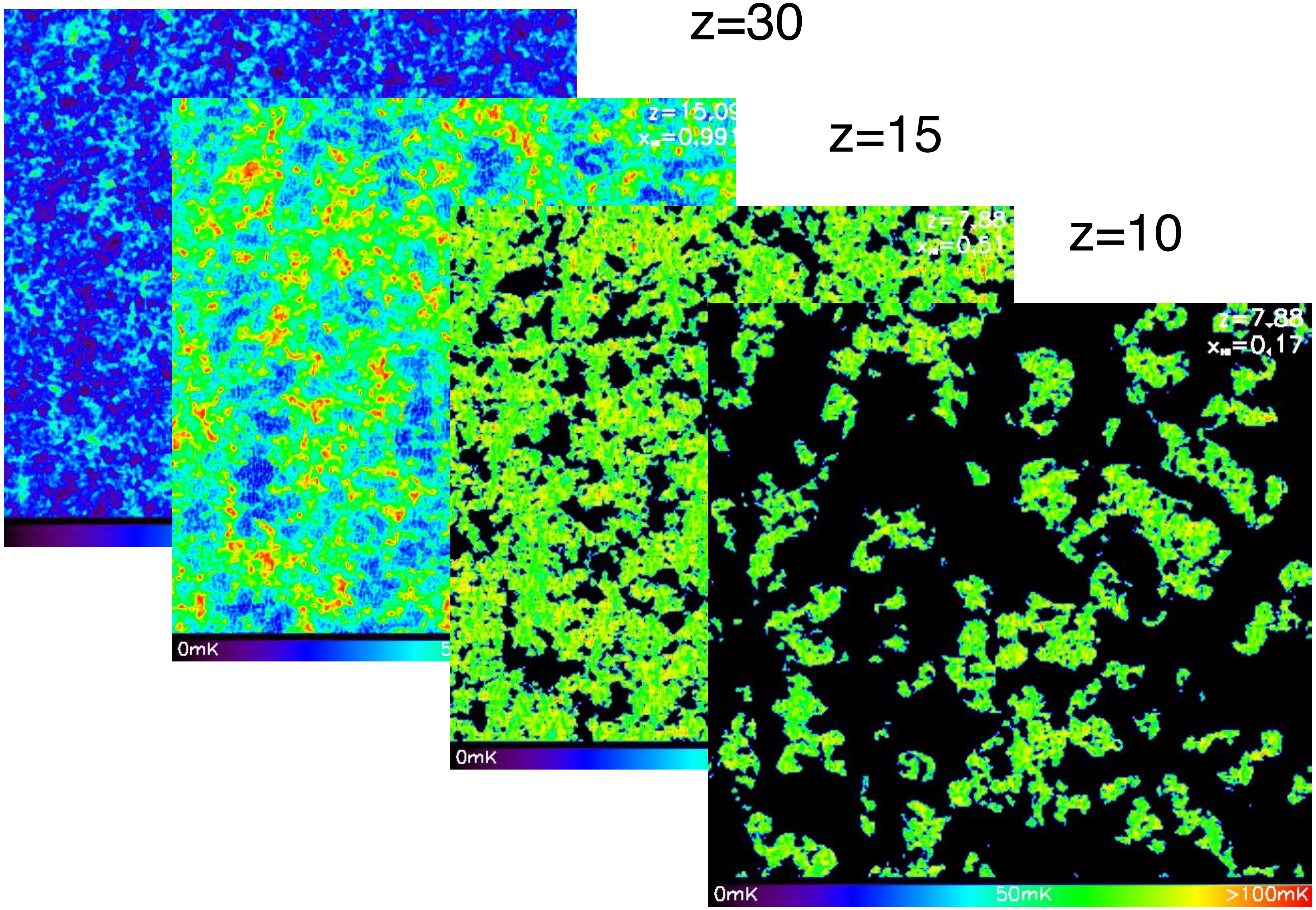
Band GHz	Bandwidth $\Delta\nu/\nu$	NET $\mu K\sqrt{s}$	Pixels/wafer	N_{wf}	N_{bolo}	NET_{arr} $\mu K\sqrt{s}$	Sensitivity with margin $\mu K \cdot arcmin$
60	0.23	94	19	8	304	5.4	15.7
78	0.23	59	19	8	304	3.4	9.9
100	0.23	42	19	8	304	2.4	7.1
140	0.30	37	37	5	370	1.9	5.6
195	0.30	31	37	5	370	1.6	4.7
280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

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



z=30

z=15

z=10

z=8

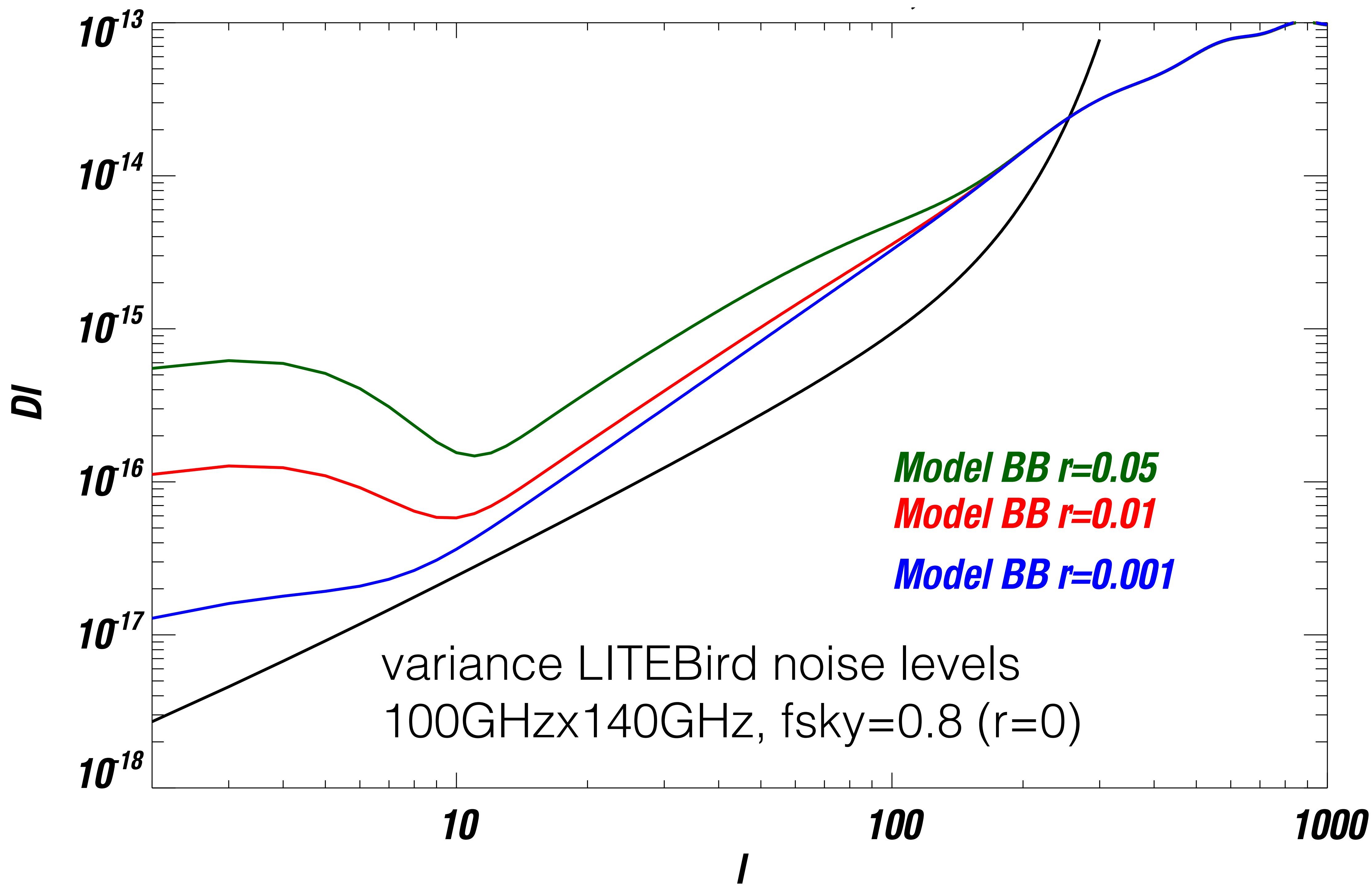
Evolution of the reionization and structure formation process

Powerful probe of dark matter, neutrinos

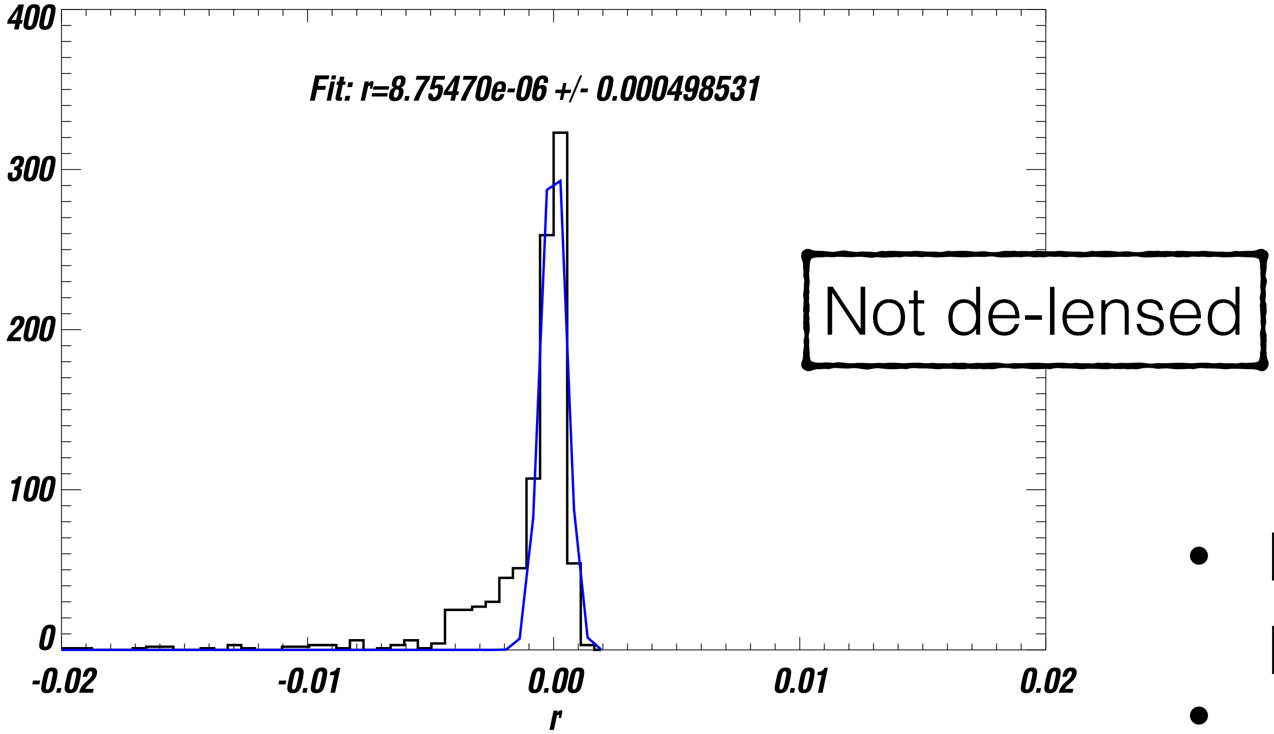
Accurate astrophysical modeling needed for cosmological predictions

Future prospects: B-modes

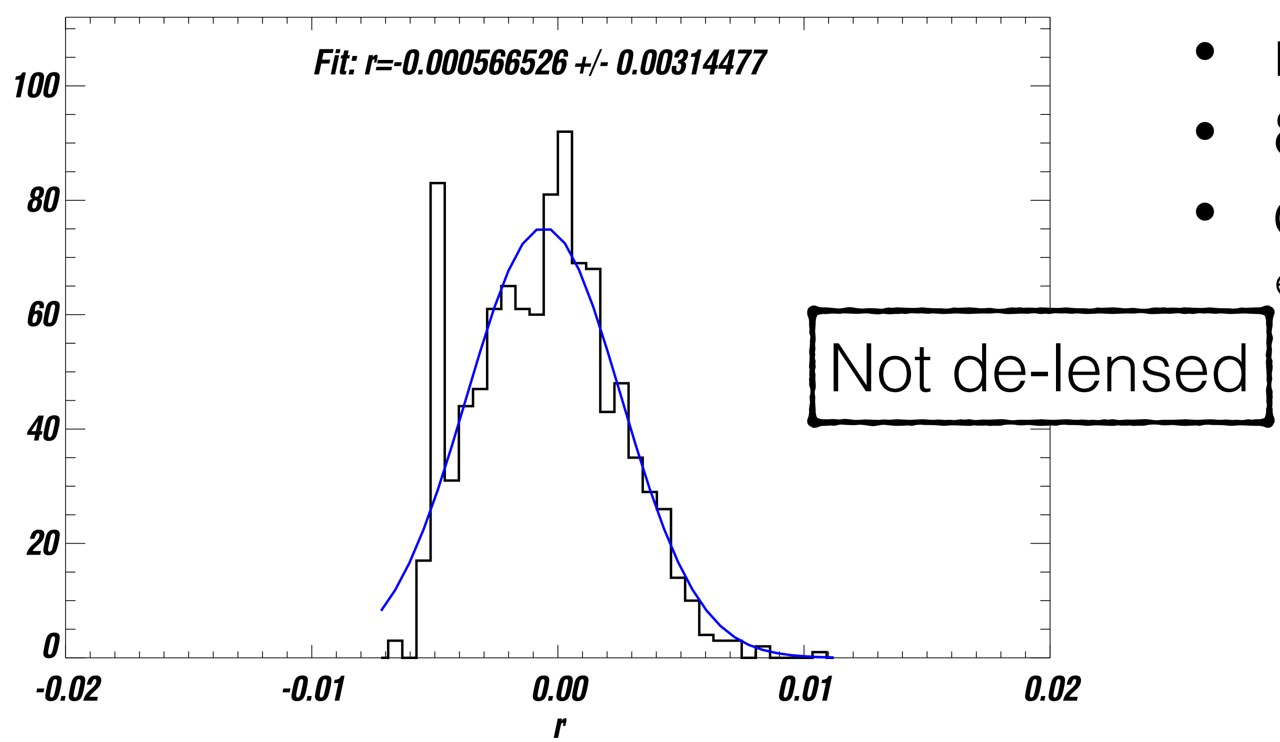
Future proposed CMB experiment as LiteBIRD



l=[2,300]



l=[30,300]

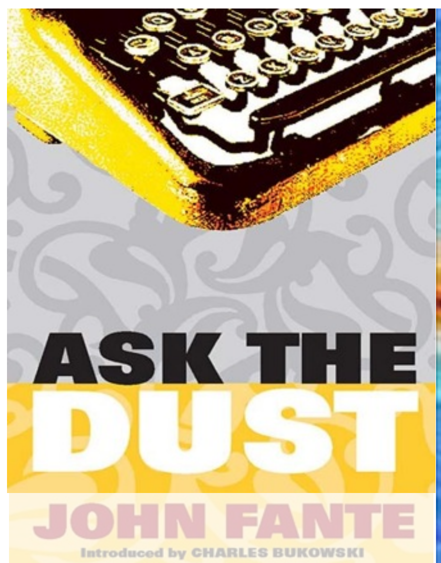


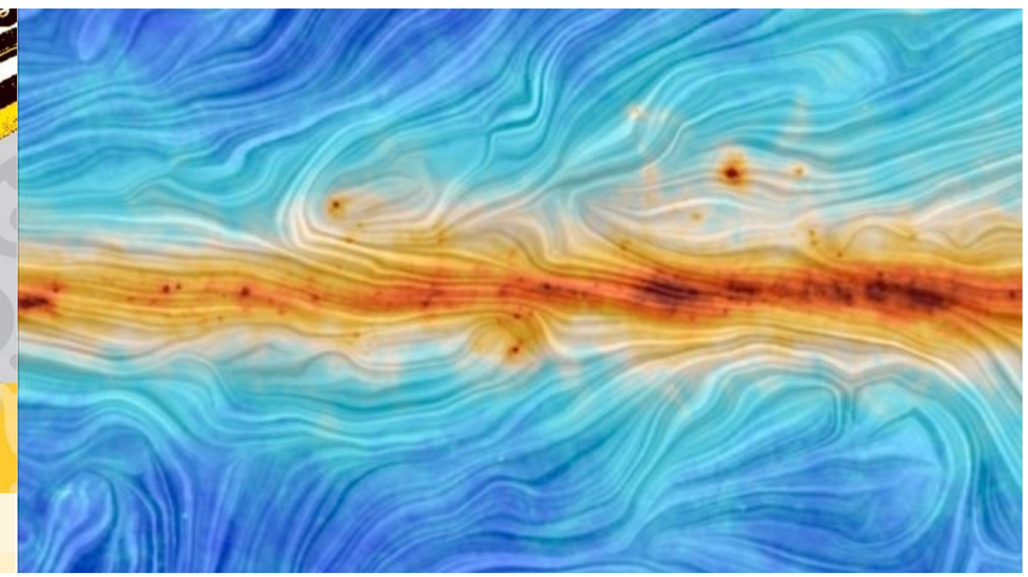
- MC sims without primordial signal (r=0)
- 100GHzx140GHz LiteBIRD cross-spectrum
- realistic noise levels
- 80% sky
- oHL Likelihood (Mangilli et al. MNRAS 2015)

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 (under revision process as Planck paper)
Mangilli, Aumont, Tristram, Grain, Boulanger 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 LiteBIRD, CoRE++, PIXIE… (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)

Thank you!

<u>Selection of relevant bibliography:</u>

- **A. Mangilli et al.** "Large-scale CMB temperature and polarization cross-spectra likelihoods", MNRAS 483 2015

- 2015 Planck papers: **The Planck collaboration incl. A. Mangilli (A&A 2015)**
  - "Constraints on cosmological parameters"
  - "Power spectra and likelihood"
  - "Bicep2 and Planck joint analysis"

- **The Planck collaboration incl. A. Mangilli:** "Improved large angular scale polarization data and the reionization optical depth", to be submitted A&A 2016

- **The Planck collaboration incl. A. Mangilli:** "Reionization history constraints from Planck", to be submitted A&A 2016

- L. Montier, J. Aumont, F. Boulanger, **A. Mangilli** et al. "The impact of the dust modeling for future CMB experiments I: B-modes measurements", in prep. 2016

- **A. Mangilli,** J. Aumont, M. Tristram et al. "The impact of the dust modeling for future CMB experiments II: likelihood analysis and realistic forecasts for the tensor-to-scalar ratio", in prep. 2016

esa

planck

cnes

asi agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

INAF Istituto Nazionale di Astrofisica

CSIC

National Research Council of Italy

Gobierno de España
Ministerio de Ciencia e Innovación

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

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