The new Planck 2015 release

http://www.cosmos.esa.int/web/planck/publications

and status of the CMB analysis at large angular scales

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ON BEHALF OF THE PLANCK COLLABORATION

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&
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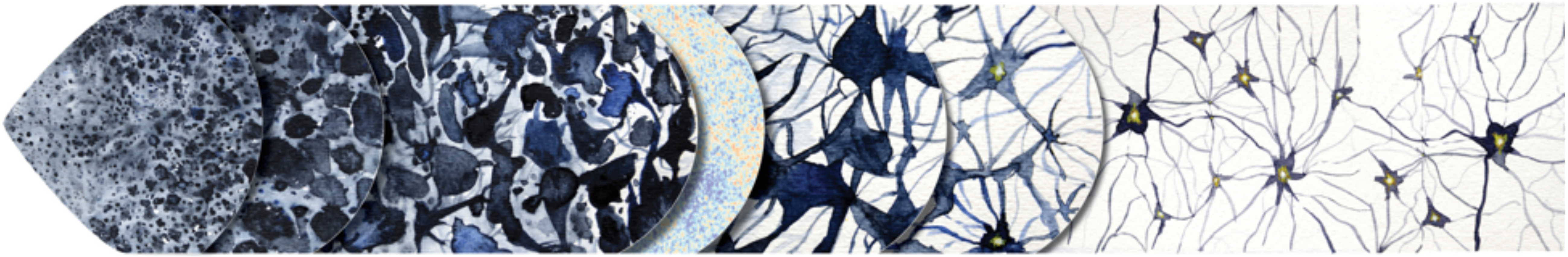
LAL 10th February 2015

The Universe history

10^{-32} seconds	1 second	100 seconds	380 000 years		300–500 million years	Billions of years	13.8 billion years



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

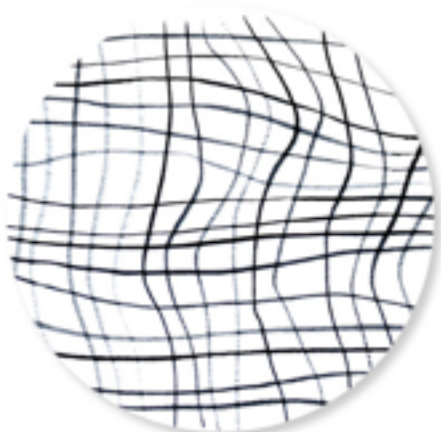
Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

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?*

The Hot Big-bang inflationary model

The Universe history

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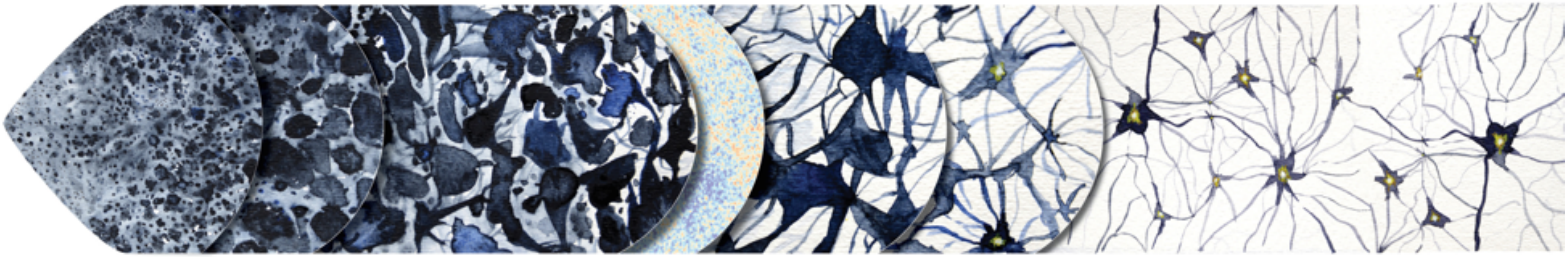

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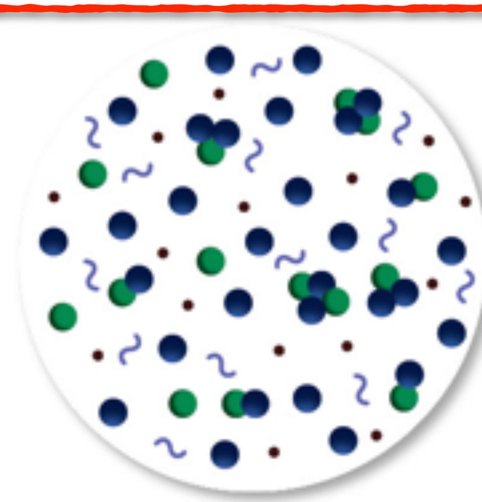
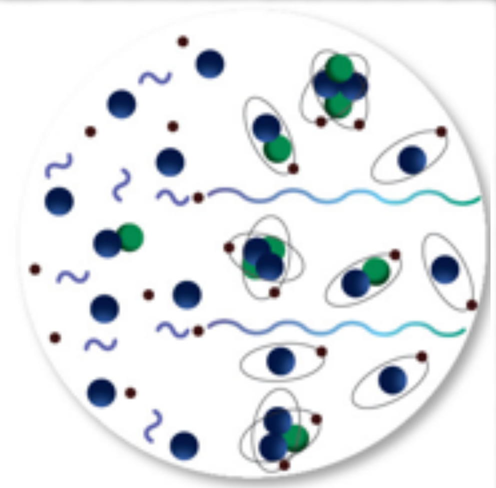
Frequent collisions between normal matter and light

The Cosmic Microwave Background (CMB)



As the Universe expands, particles collide less frequently

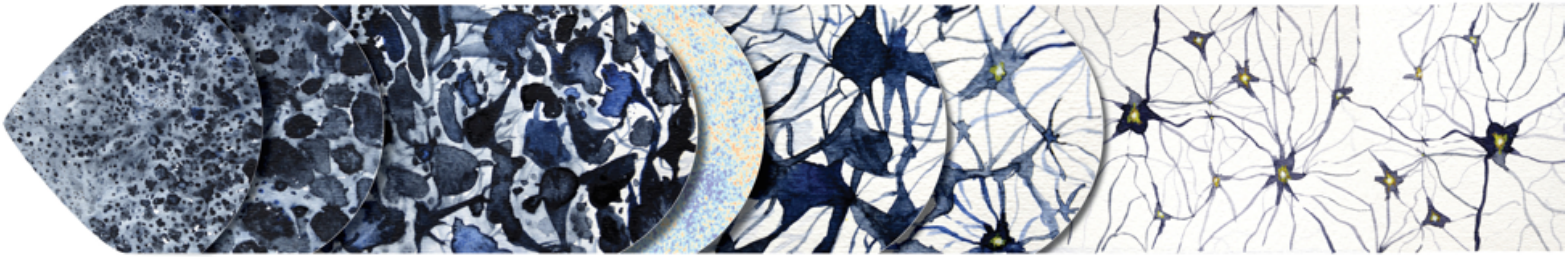


Last scattering of light off electrons

→ ***Polarisation***

The observable Universe

10⁻³² seconds | 1 second | 100 seconds | 380 000 years | 300–500 million years | Billions of years | 13.8 billion years



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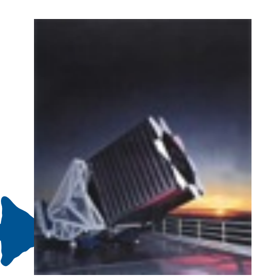
The present Universe

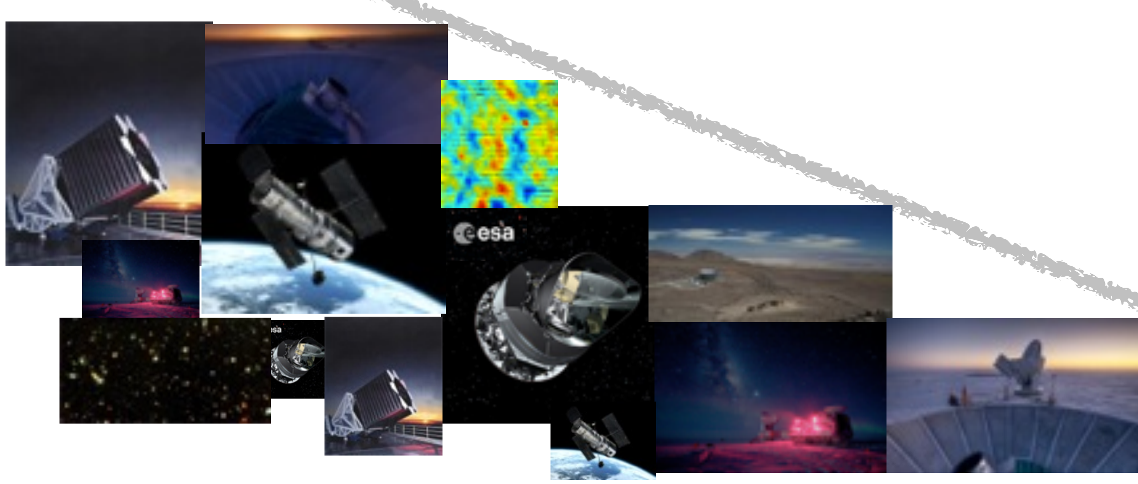
Gravitational waves,
ν background

The Cosmic Microwave Background (CMB)

Quasar
21-cm
Lymanα

Galaxies,
Clusters
Supernovae



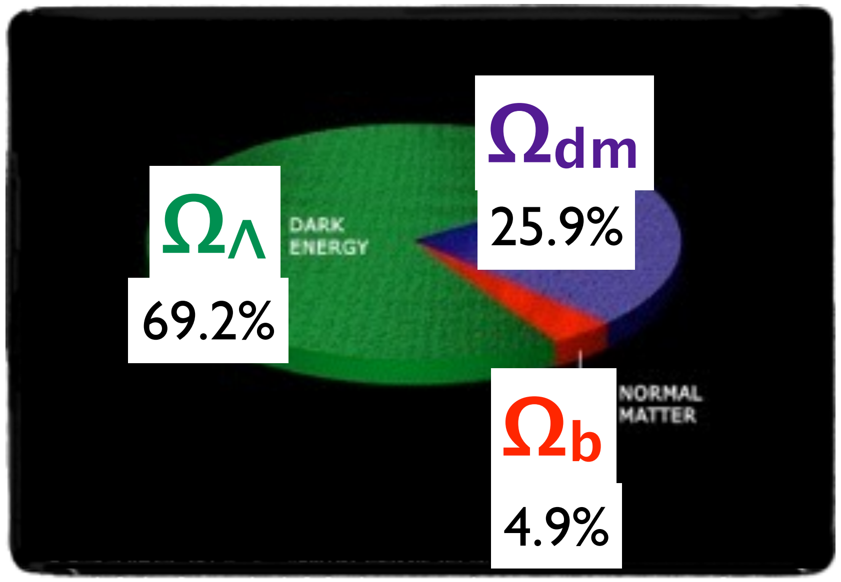


Concordance ΛCDM cosmological model

what is the universe made of?

ΛCDM

reference model



what is the nature of dark matter?

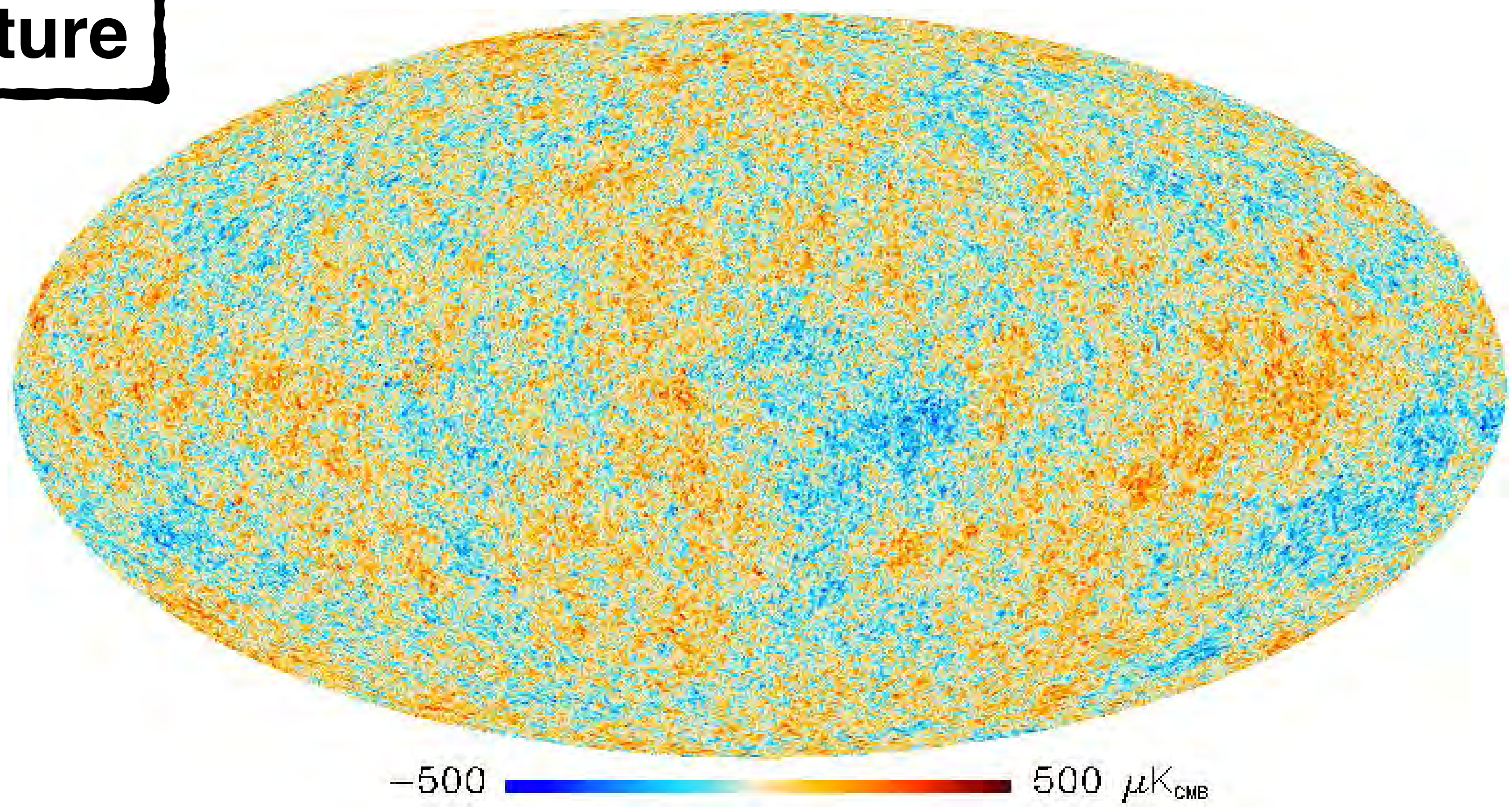
what is the nature of dark energy?

what is Inflation?

The CMB anisotropies

Temperature

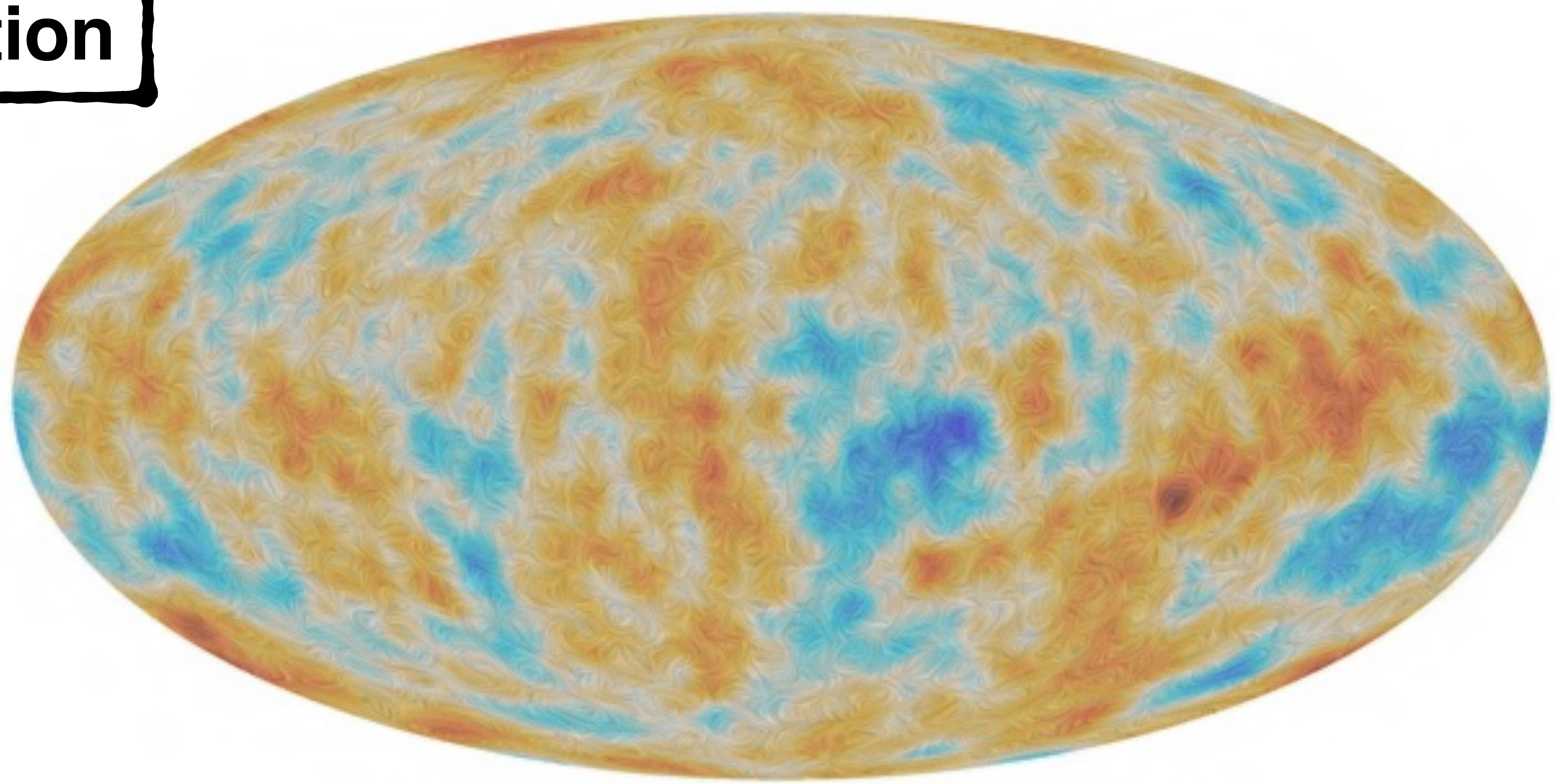
Planck



The CMB anisotropies

Polarization

Planck



CMB polarization signal: orders of magnitude weaker than temperature

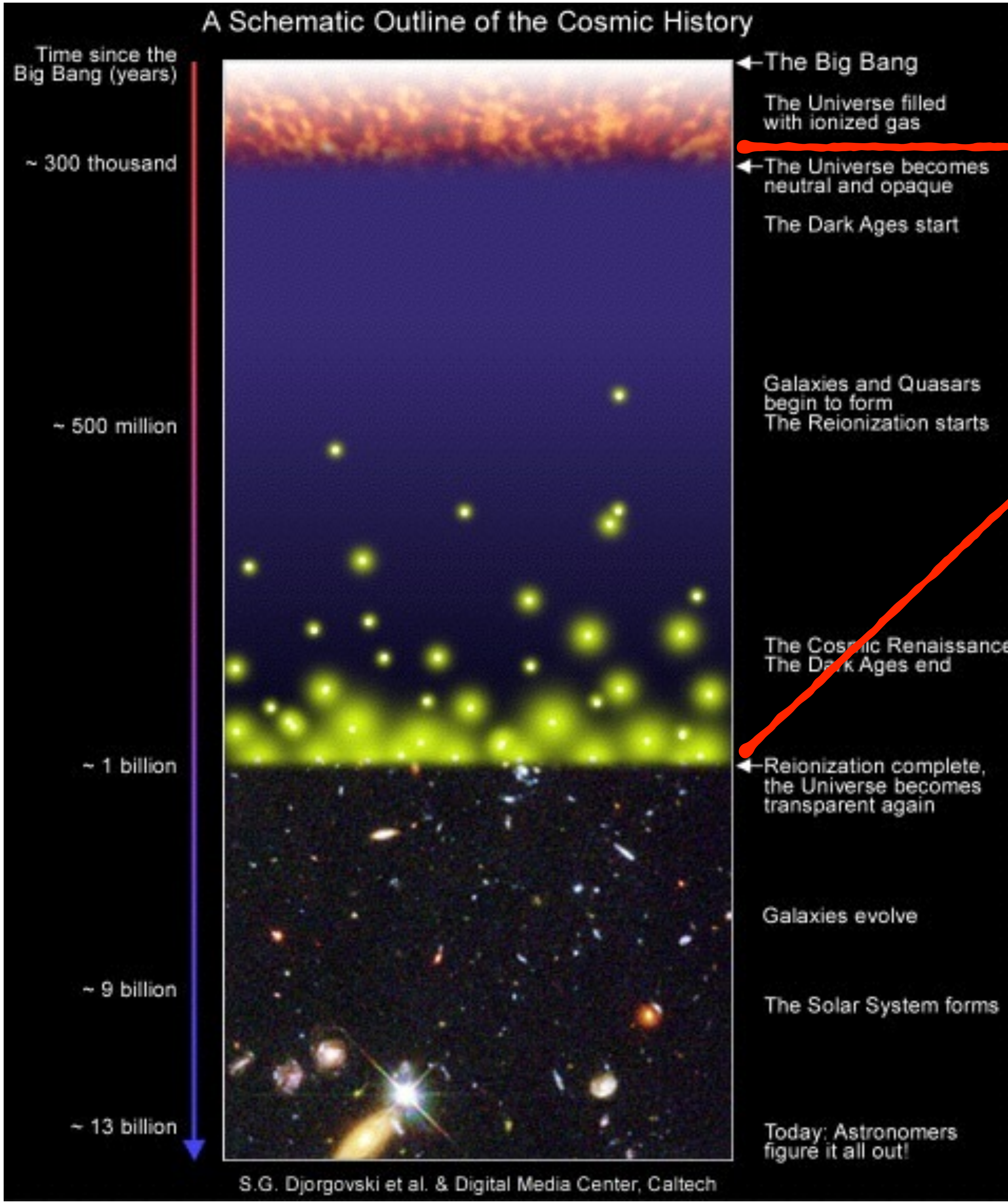
E-modes

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

B-modes

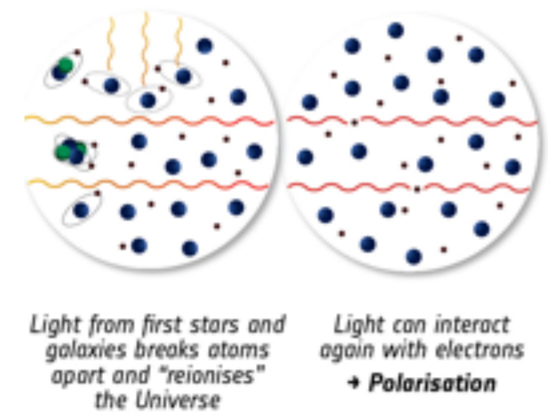
- Magnetic type polarization field.
- Can be generated only by primordial tensor modes i.e. **primordial gravitational waves**
- Contribution from lensing

Generation of the CMB polarization



DECOUPLING

REIONIZATION



Thomson scattering optical depth:

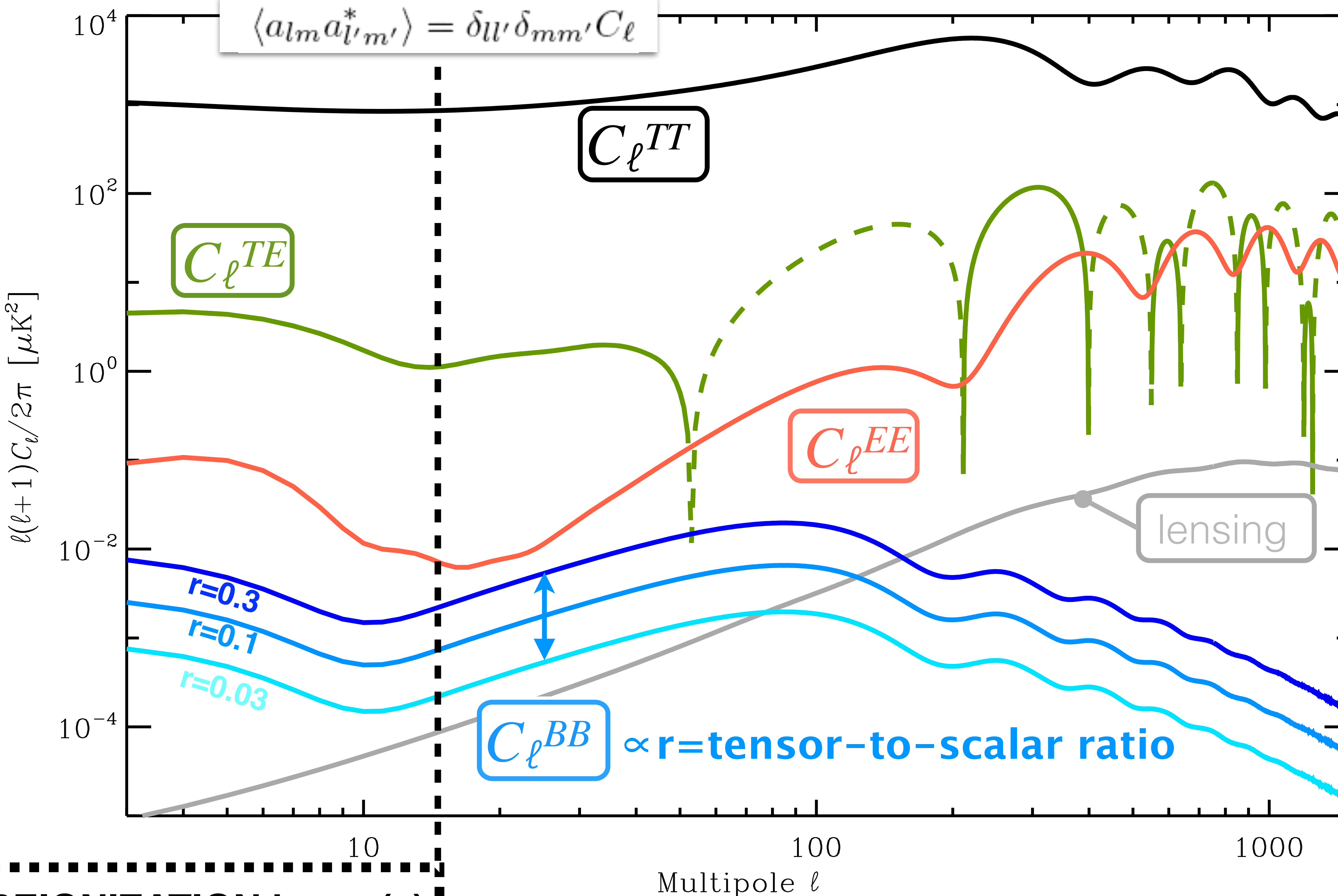
$$\tau = \int_0^{z\_reio} a n_e \sigma_T \, d\eta$$

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

The CMB angular power spectra

CMB anisotropies: $\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{n})$

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



REIONIZATION bump(s)
2<l<15

OUTLINE

➡ **PLANCK 2015: overview of general results**

↳ **The Planck and Bicep2 results**

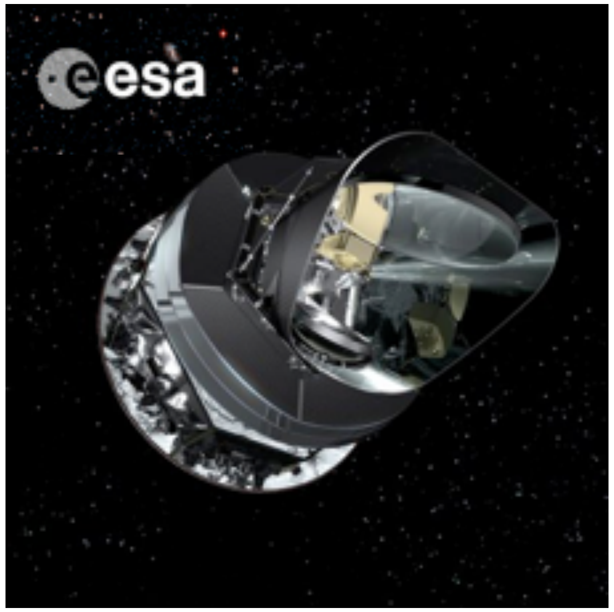
➡ **The next challenge:**
the CMB polarization at large angular scales

Why it is interesting

Statistical method(s)

Results

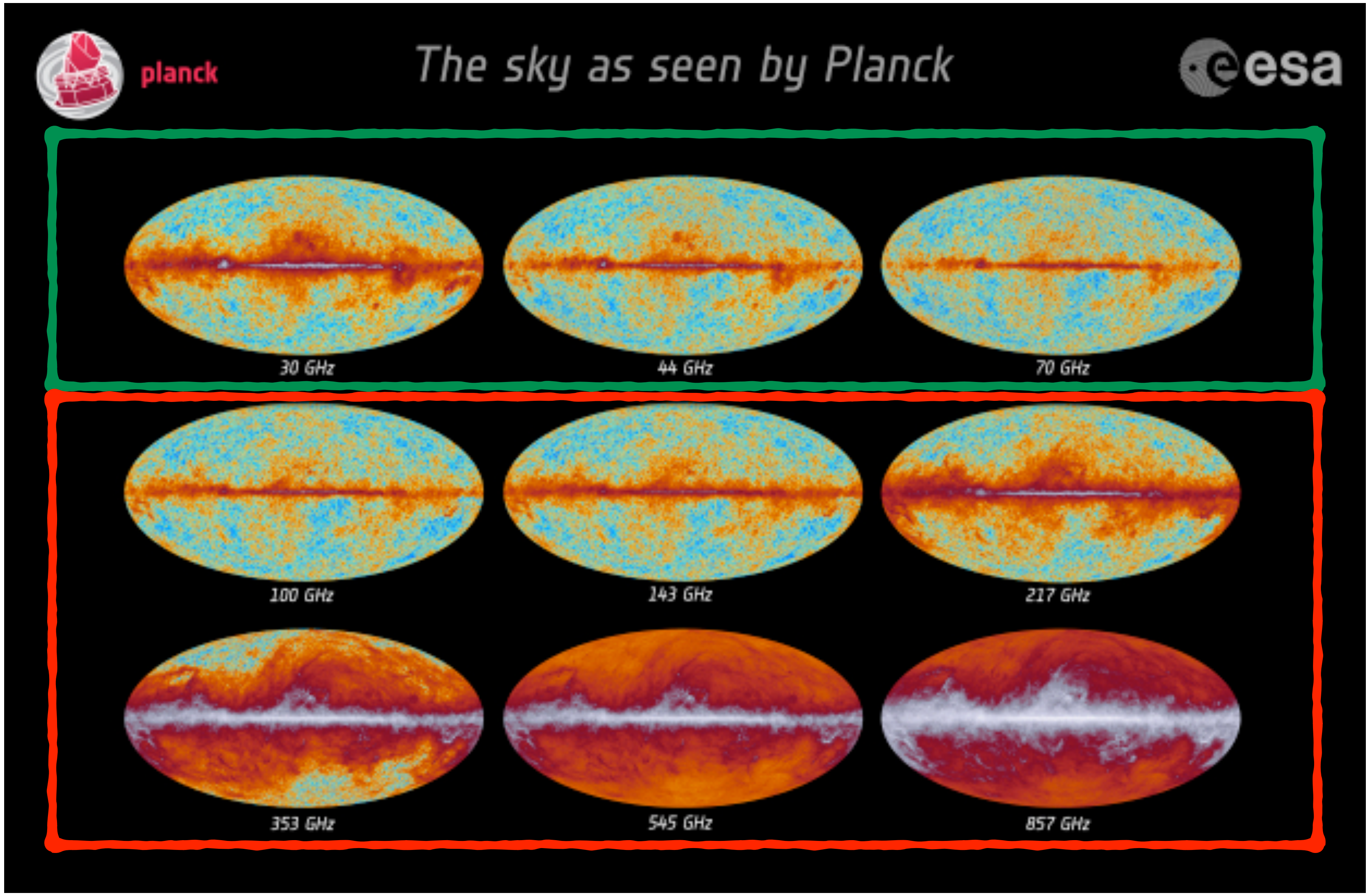
The Planck satellite



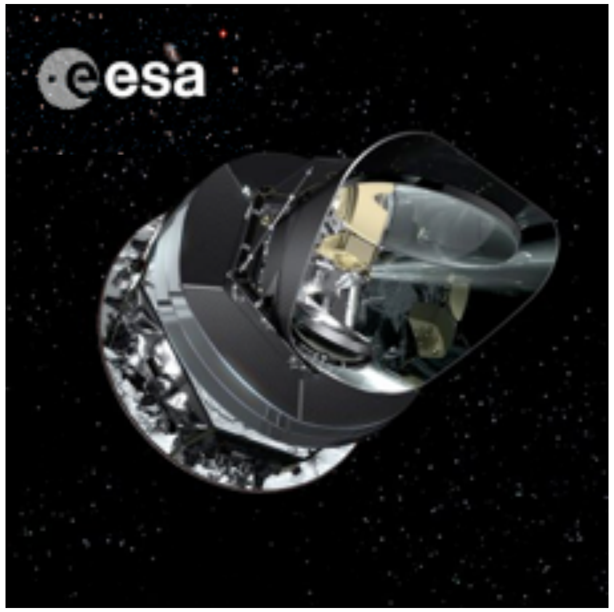
- ➡ 9 frequency bands
- ➡ Two instruments:

LFI: 30GHz, 44GHz, 70GHz

HFI: 100GHz, 143GHz, 217GHz
353GHz, 545GHz, 857GHz



The Planck satellite



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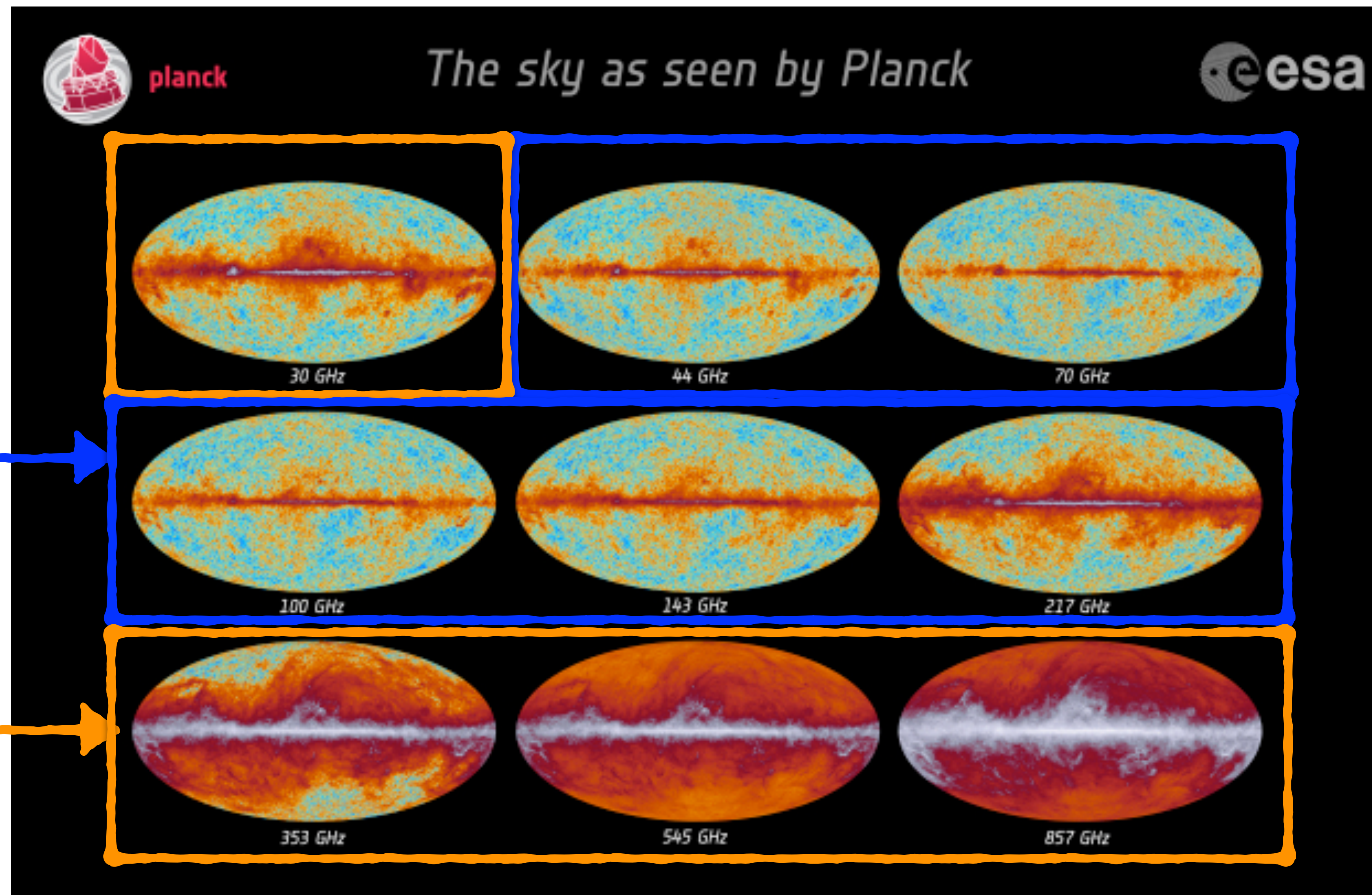
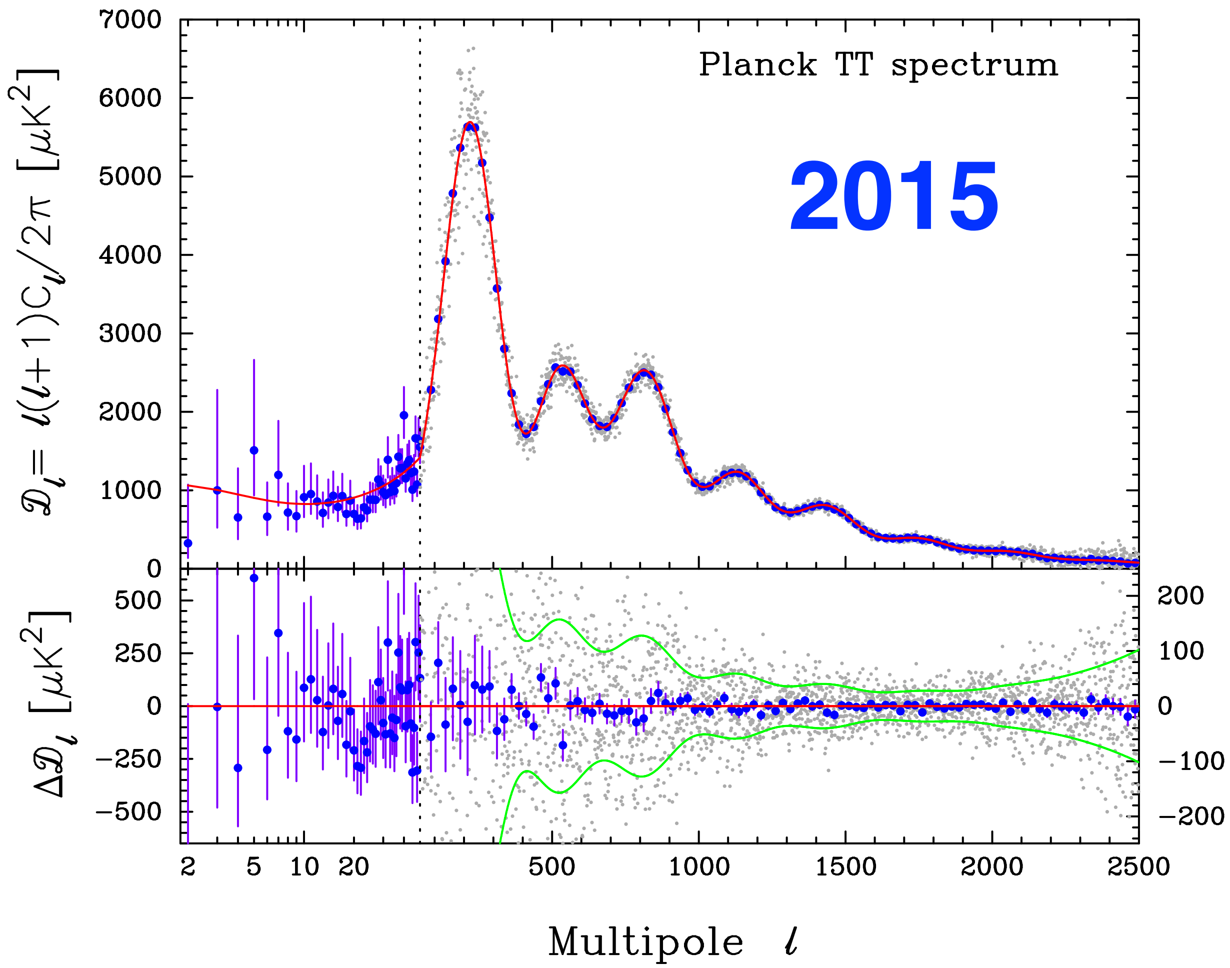
Channels for CMB charcterization

Foregrounds characterization



What's new

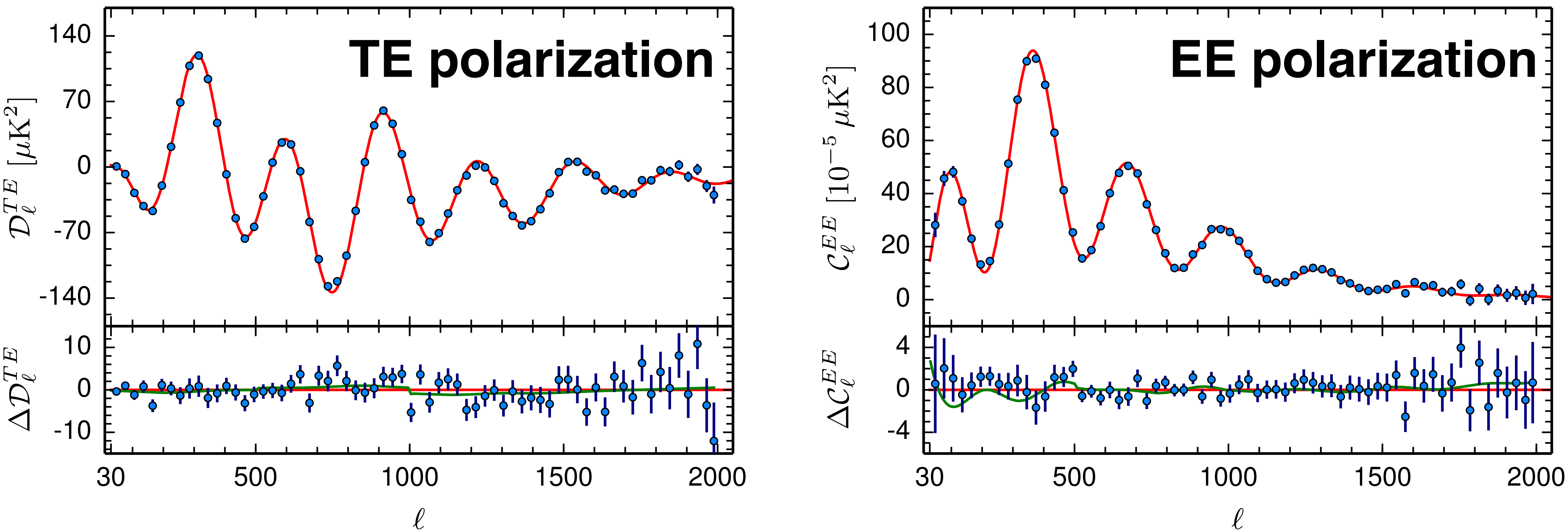


ΛCDM best fit (Planck Temperature spectrum)

Improvements:

- ➡ data calibration
- ➡ better control of systematics
- ➡ better beam characterization
- ➡ full mission data

What's new



ΛCDM best fit (Planck Temperature spectrum)

Planck 2015, first release of polarization data:

- ➡ only LFI 30,44,70 GHz + 353GHz HFI
- ➡ HFI EE, TE data used for analysis
- ➡ **No release of HFI 100,143, 217 GHz polarized data**
- ➡ HFI higher resolution: still systematics at large angular scales

↳ **The next challenge**

Planck 2015: the ΛCDM model

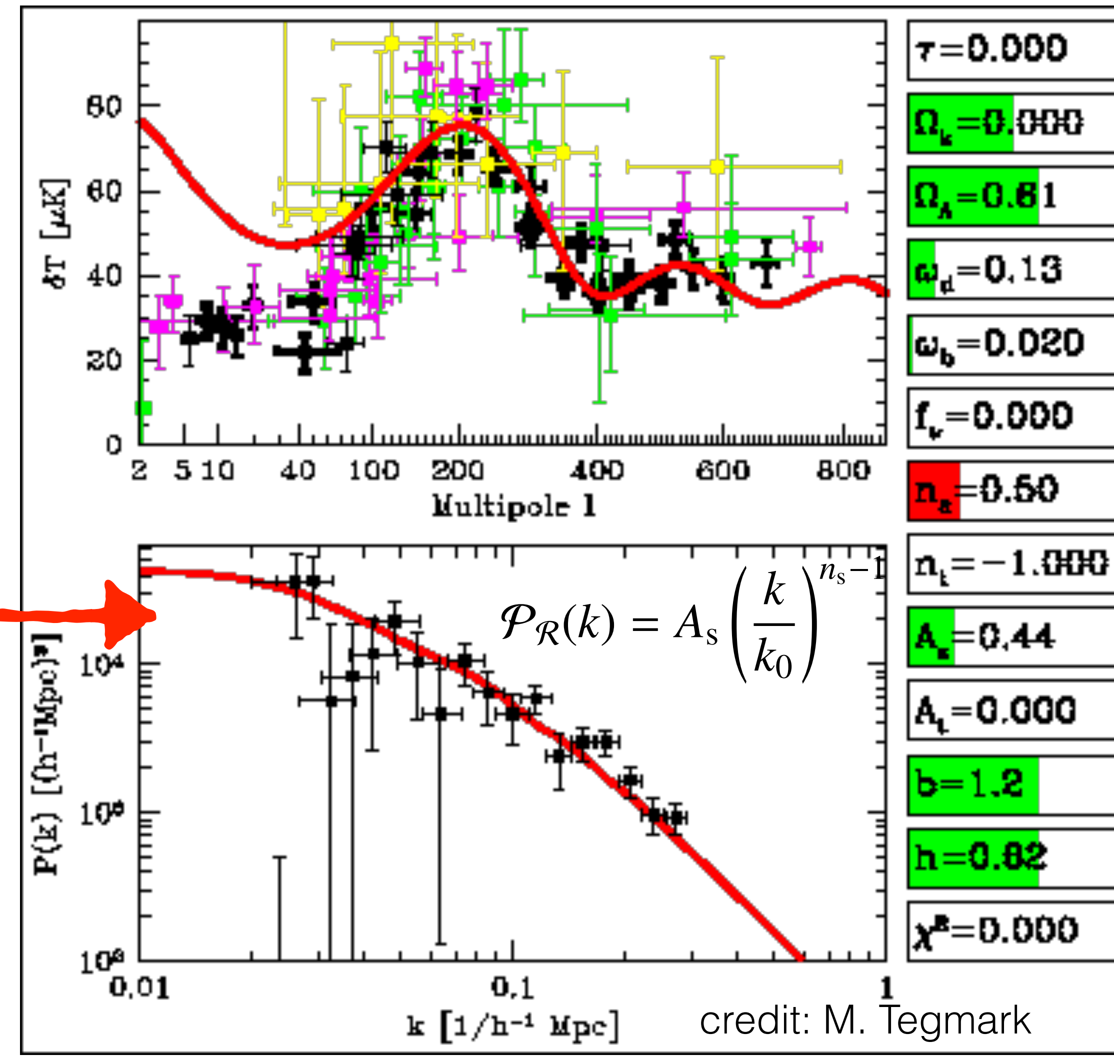
The base 6 parameters:

Ω_b Baryon energy density

Ω_c Cold Dark Matter energy density

$\ln(10^{10}A_s)$	Amplitude	of the primordial scalar perturbations
n_s	Spectral index	

τ Optical depth to reionization

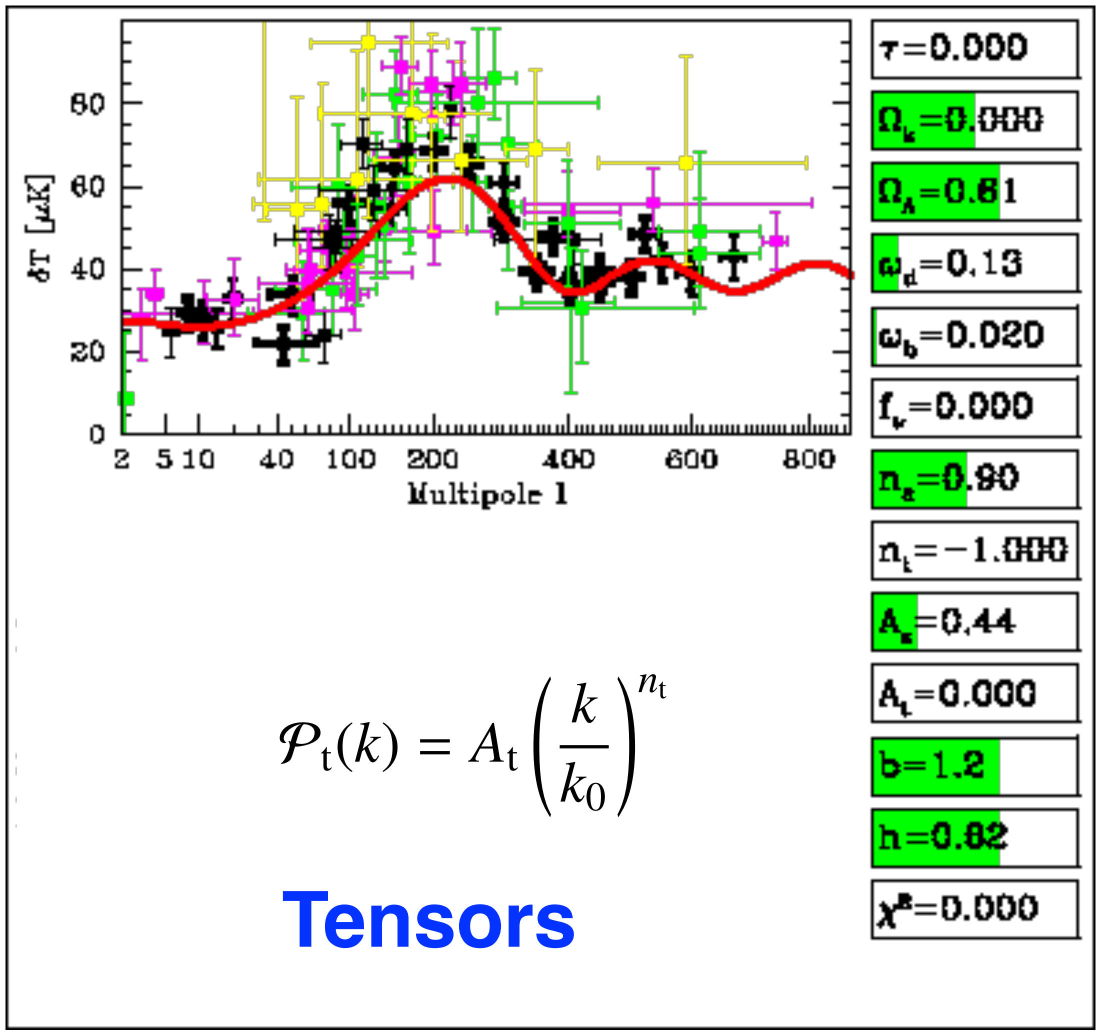


credit: M. Tegmark

$100\theta_{MC}$ characteristic angular size of the CMB fluctuations

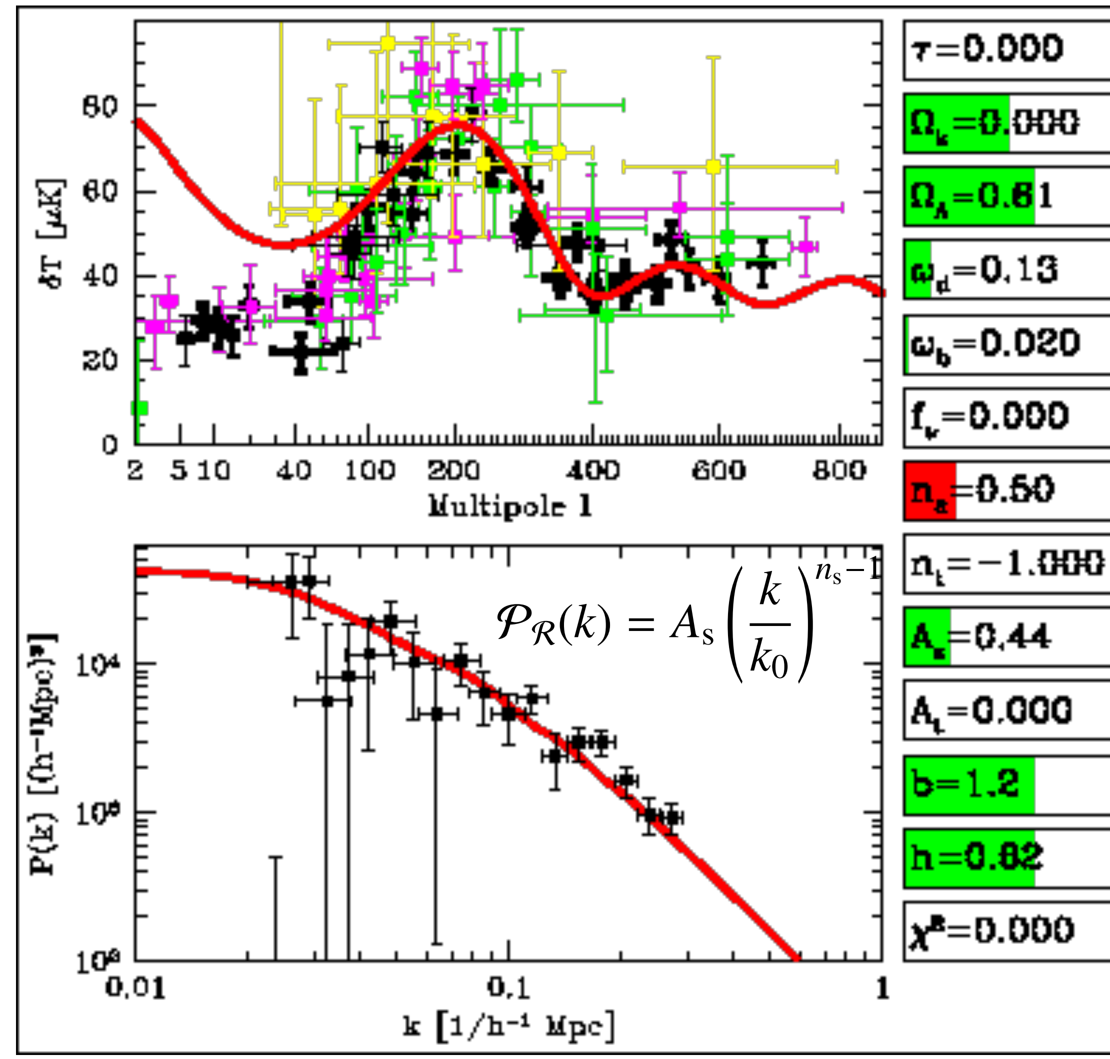
Planck 2015: the ΛCDM model

The base 6 parameters+tensors



$$\mathcal{P}_{\rm t}(k) = A_{\rm t}\left(\frac{k}{k_0}\right)^{n_{\rm t}}$$

Tensors



$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_0}\right)^{n_{\rm s}-1}$$

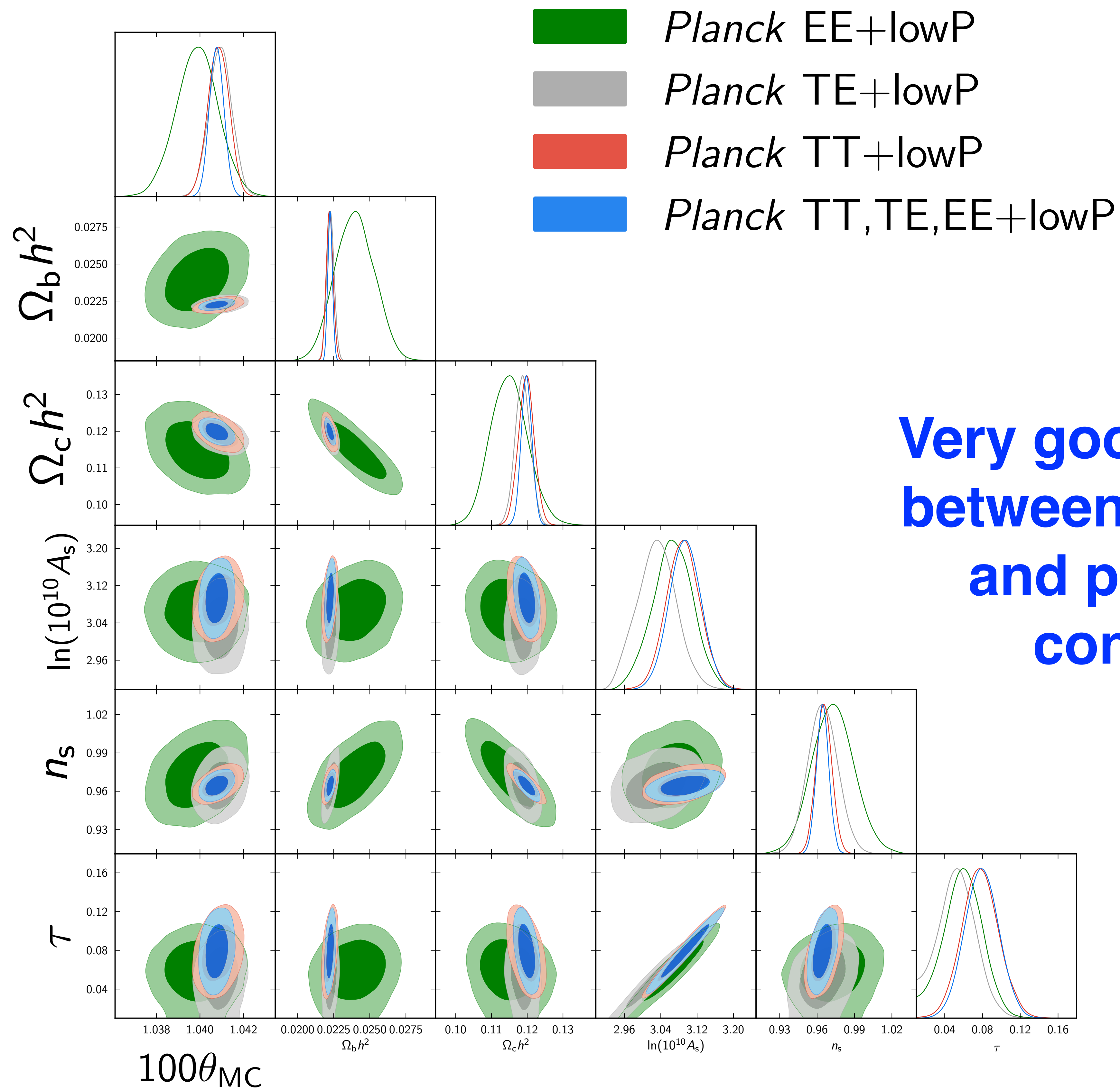
Adding tensor modes:

$$r = \frac{\mathcal{P}_{\rm t}(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)}$$

tensor-to-scalar ratio

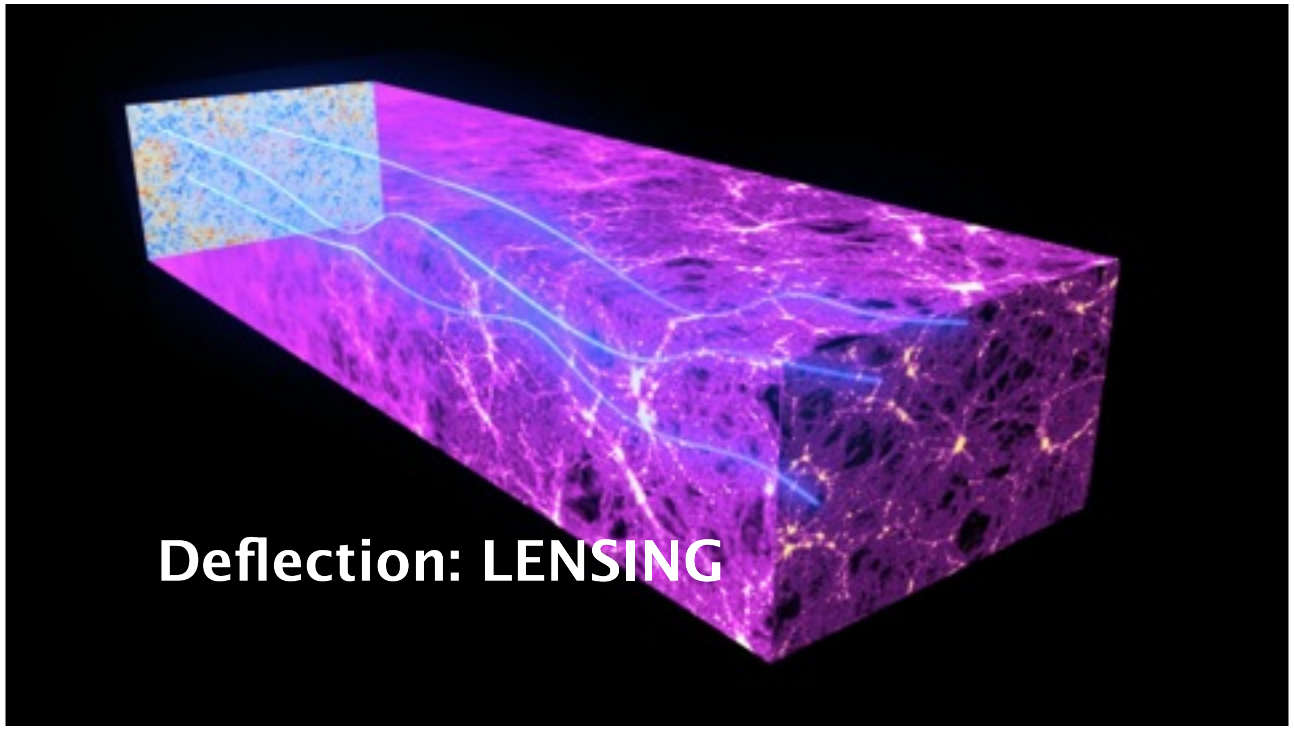
$r \propto E_{\rm inflation}$

Planck 2015: the ΛCDM model



Very good agreement between temperature and polarization constraints

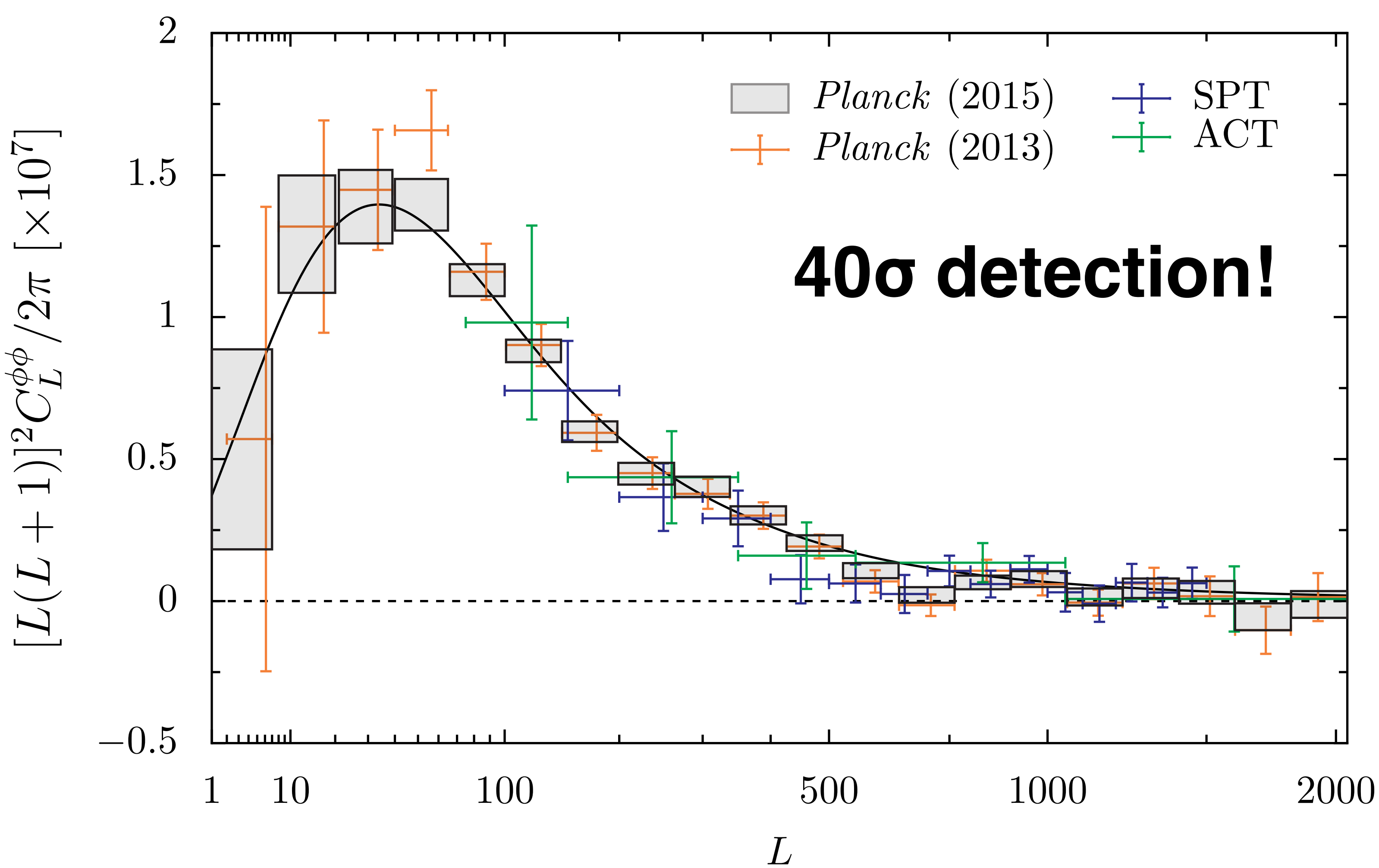
Planck 2015: gravitational lensing



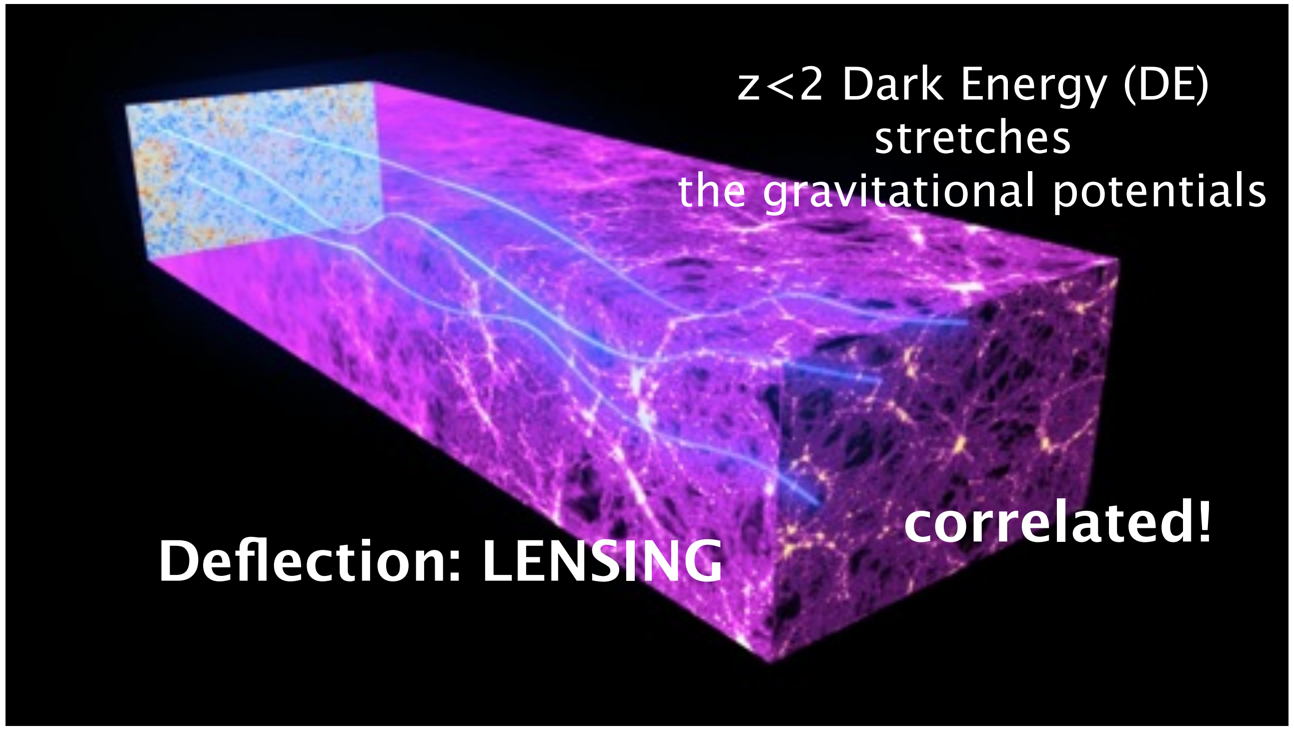
Deflection angle $\alpha = \nabla\phi$

Gravitational potential projection along the line of sight:

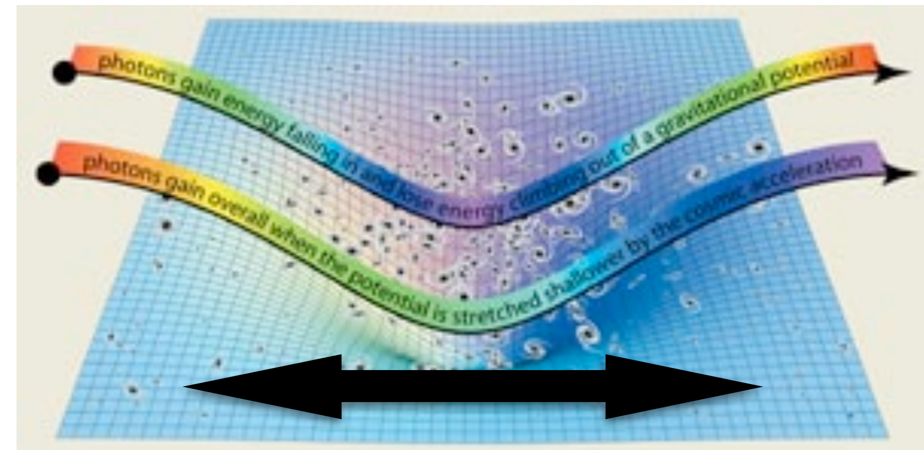
$$\phi(\hat{\mathbf{n}}) = -2\int_0^{r_{ls}} dr\,\frac{r(z_{ls}) - r(z)}{r(z)\,r(z_{ls})}\,\Phi(r, \hat{n}r)$$

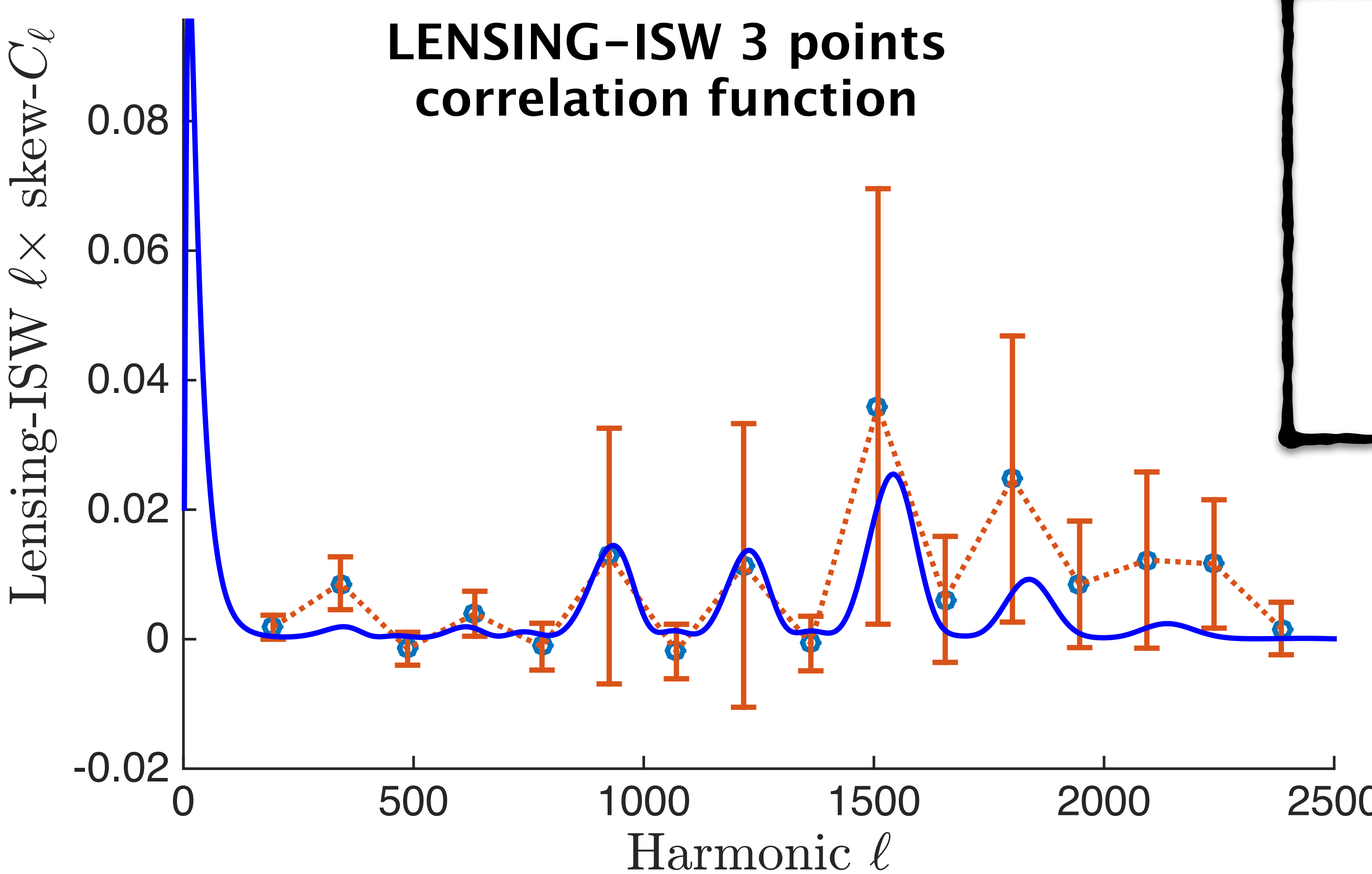


Planck 2015: gravitational lensing



ISW=Integrated Sachs Wolfe effect





The lensing-ISW non-Gaussianity

Mangilli&Verde 2009
Mangilli, Wandelt et al. 2013

Improved 3σ detection

$A_{L\text{-}ISW} = 0.82 \pm 0.27$

Constraints on primordial non-Gaussianity

f_{NL} = **amplitude of non-Gaussian signal**

	f_{NL}(KSW)	
Shape and method	Independent	ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	**0.71 ± 5.1**
Equilateral	−8.9 ± 44	**−9.5 ± 44**
Orthogonal	−35 ± 22	**−25 ± 22**

Temperature only

Temperature + Polarization

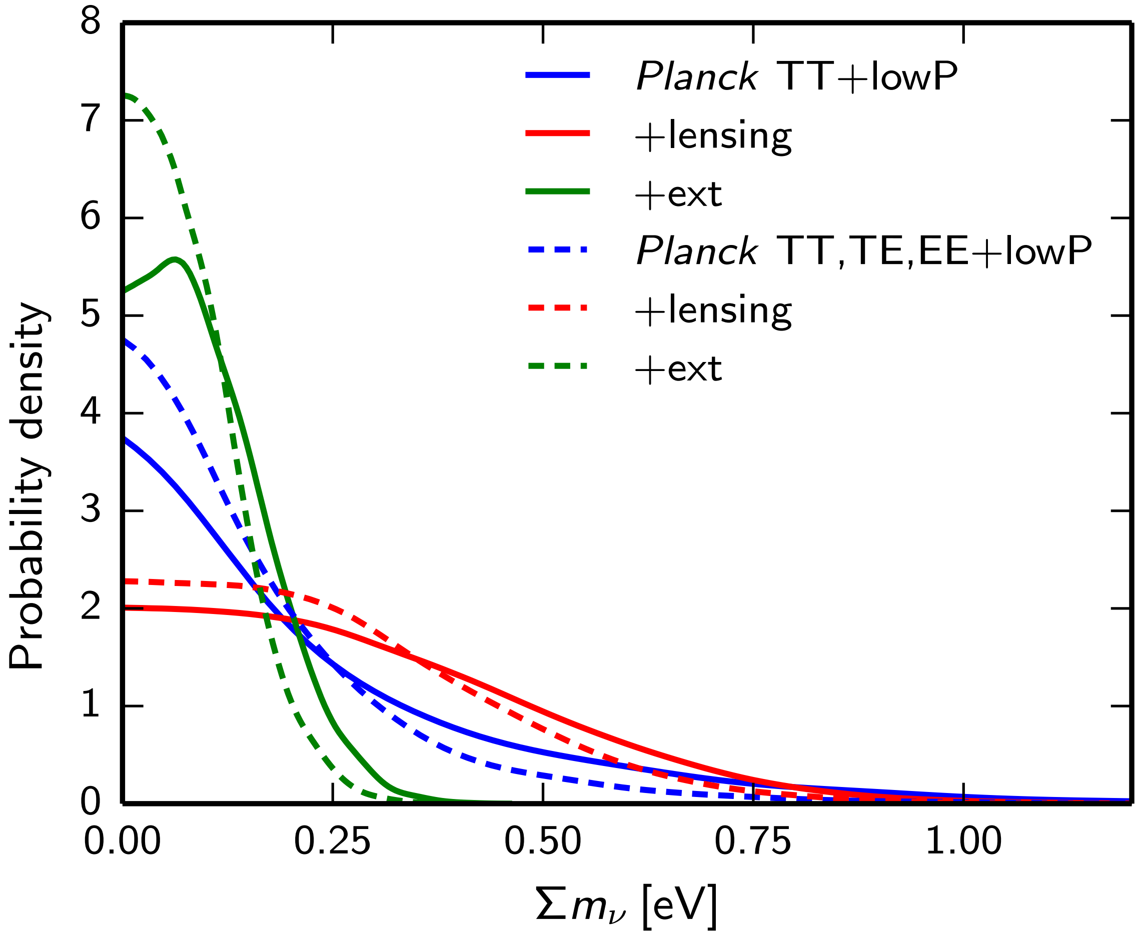
- **No hints of primordial non-Gaussianity** (Planck 2013 results confirmed)
- **Adding polarization** improve the constraints

Planck 2015 constraints on neutrinos

Total neutrino mass: $\Sigma_\nu m_\nu$

Joint constraint *Planck* Temperaure +lensing+BAO:

$\Sigma m_\nu < 0.23$eV(95%CL)



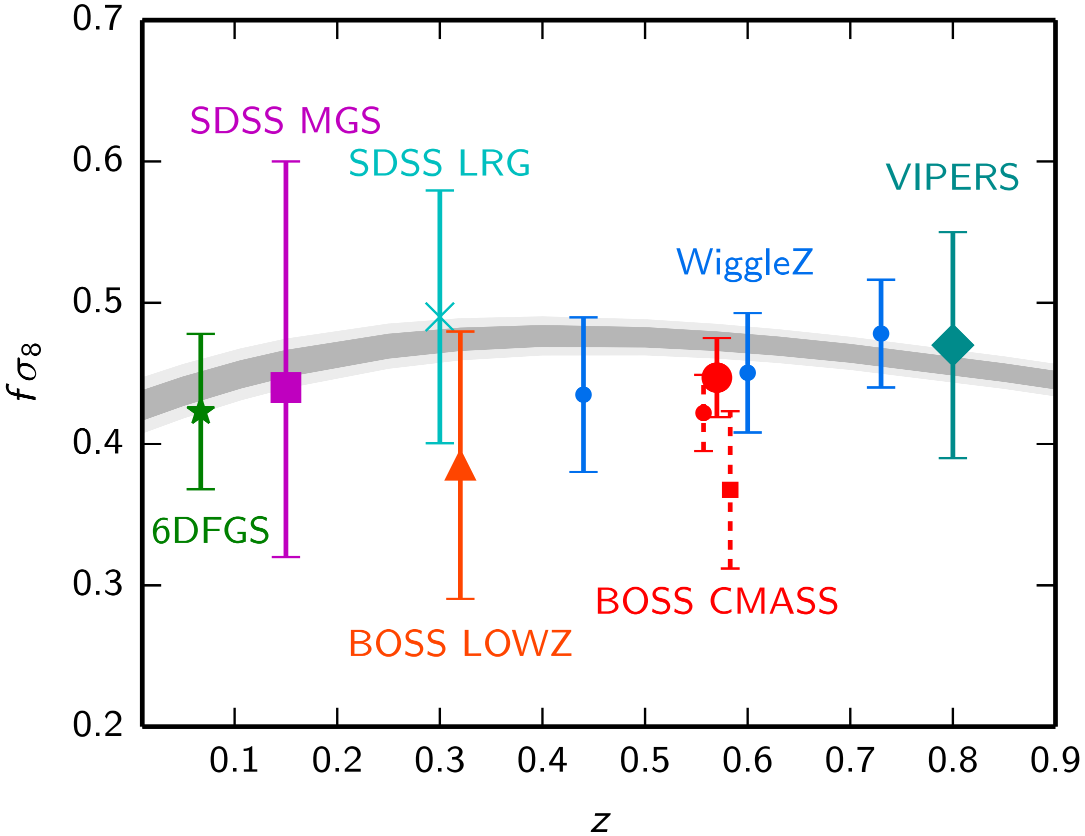
NO Extra relativistic species: N_{eff}

parameter for relativistic density at early times

Planck temperature + polarization: $N_{\rm eff} = 2.99 \pm 0.20$ (expected $N_{eff} = 3.04$)

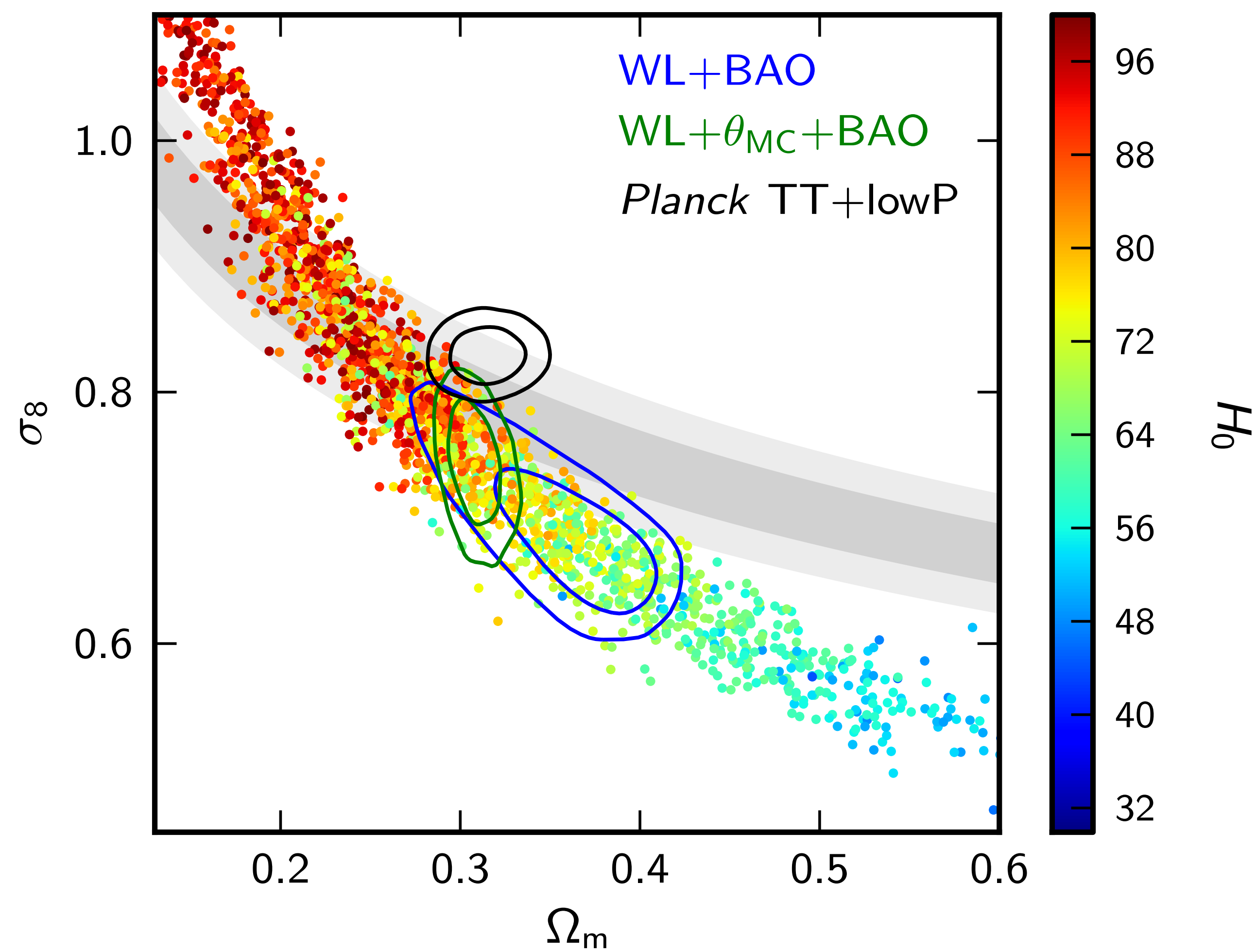
E.g. massless sterile neutrino not favored by Planck data

Planck in combination with other datasets



Good agreement with Baryon Acoustic Oscillation (BAO) data

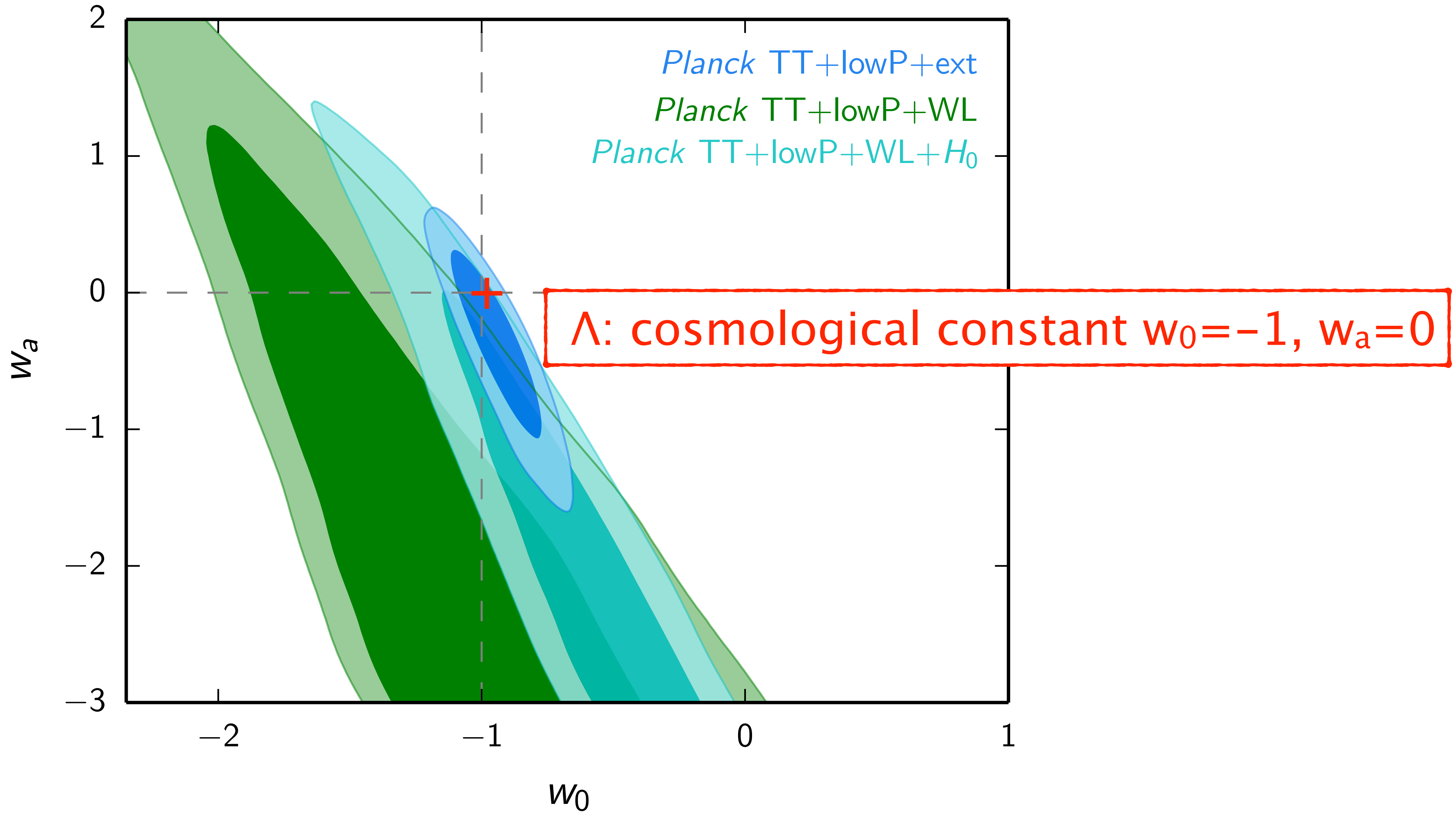
…some tensions



Planck in combination with other datasets

…some tensions

and possible implications…



Dark Energy:

w= equation of state

$$w = w_0 + (1-a)w_a$$

OUTLINE

➡ **PLANCK 2015: overview of general results**

↳ **The Planck and Bicep2 joint analysis**

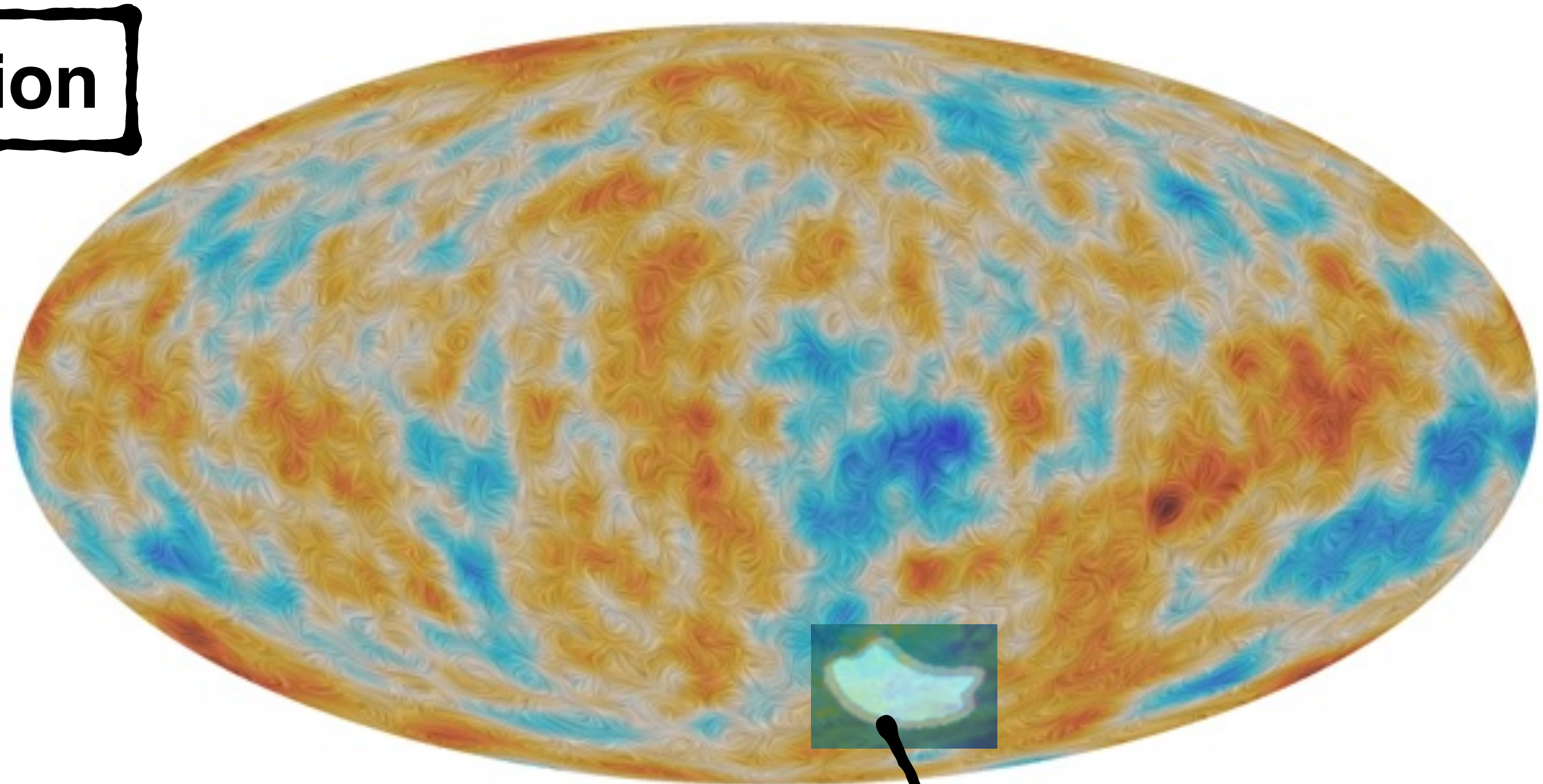
http://www.cosmos.esa.int/web/planck/publications#JB2KPlanck2015

➡ **The next challenge:**
the CMB polarization at large angular scales

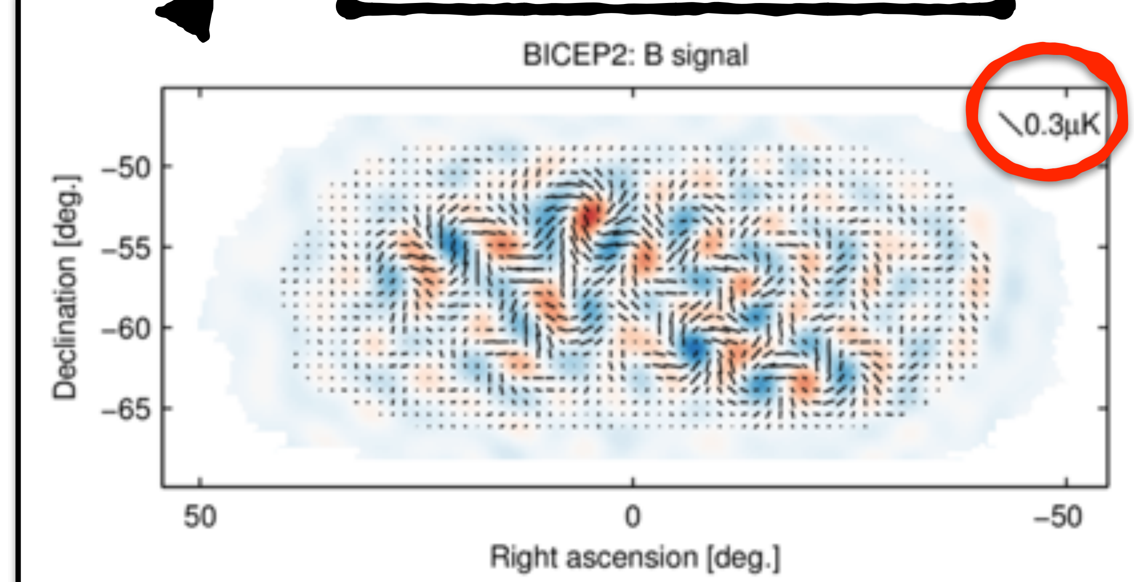
Why it is interesting
Statistical method(s)
Results

The Bicep2/Keck experiment

CMB Polarization



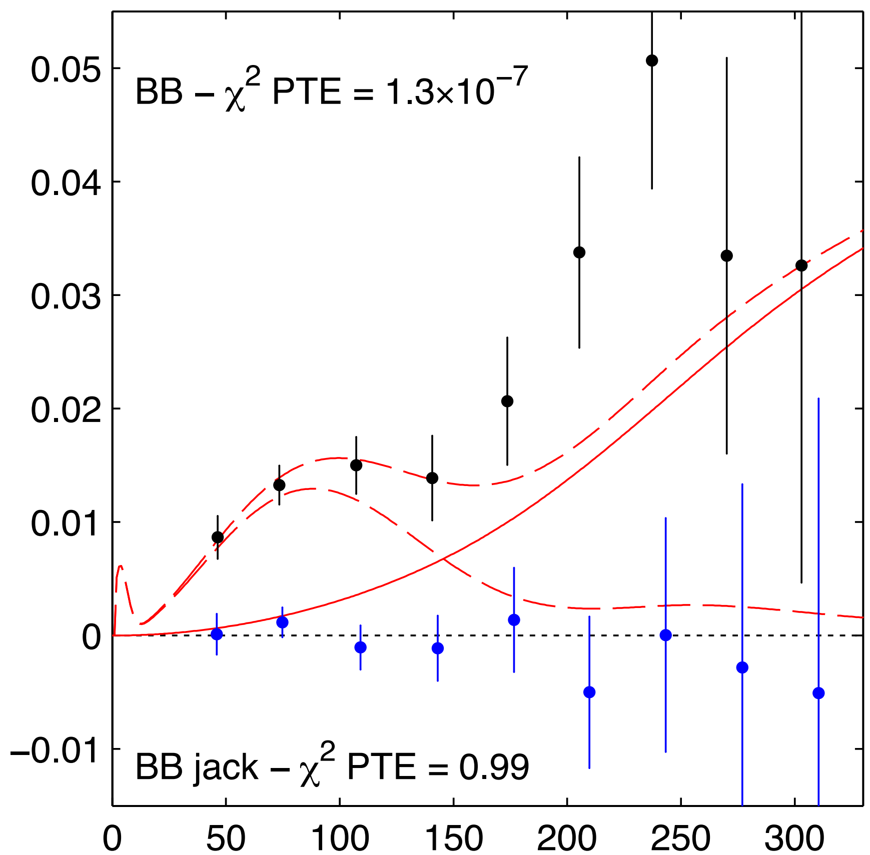
Bicep2 B-modes

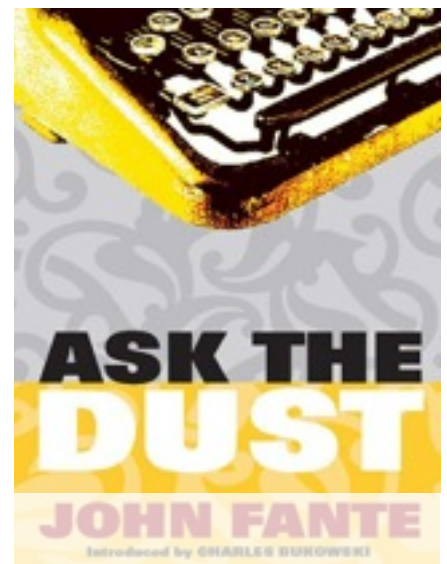


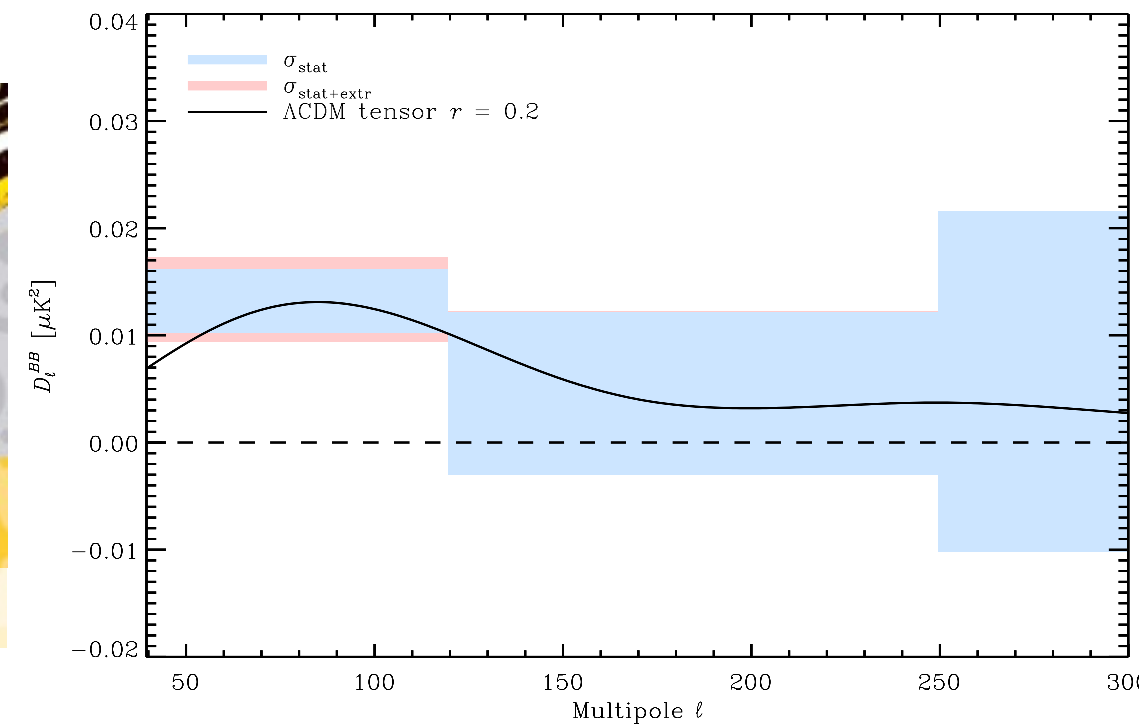
Very high resolution

Tensor-to-scalar ratio r

Bicep2 VS Planck





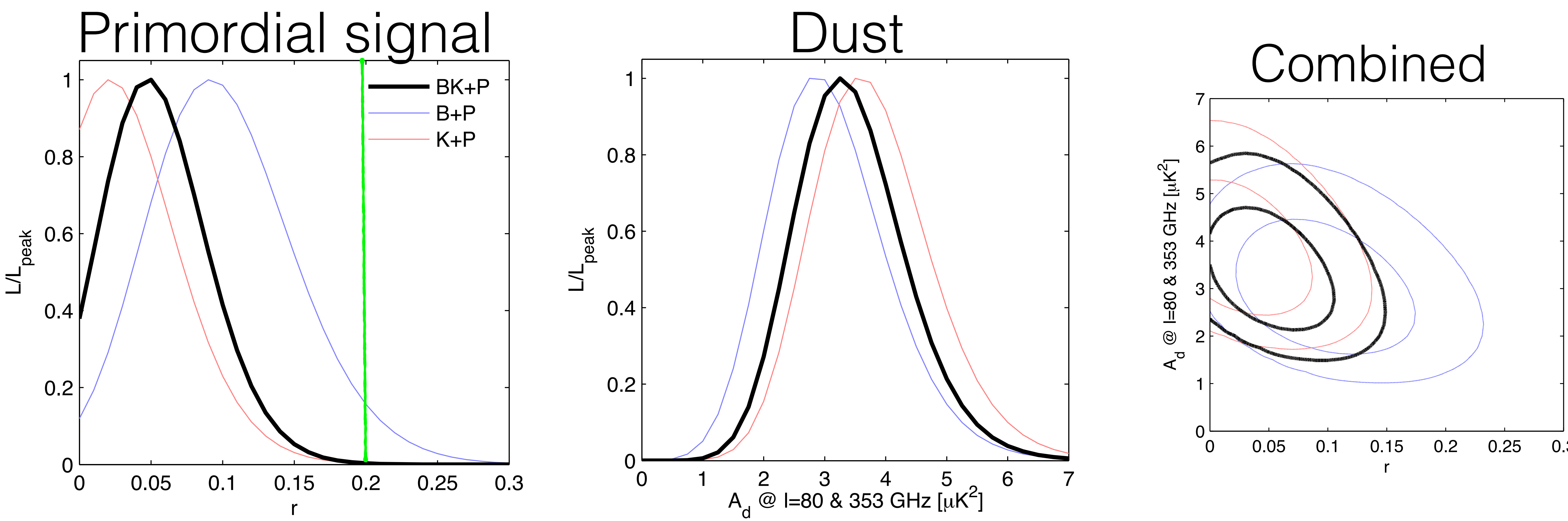


March 2014:
BICEP2 claimed 5σ detection of primordial B-modes with r=0.2

September 2014:
Planck showed that polarized dust cannot be neglected. BICEP2 results: compatible with polarized dust emission

Tensor-to-scalar ratio r: Bicep2 with Planck 353GHz

Joint analysis



r < 0.12 95% CL

Tensor-to-scalar ratio r

Planck alone
B-modes
(DIRECT)

Not public data

REMOVED

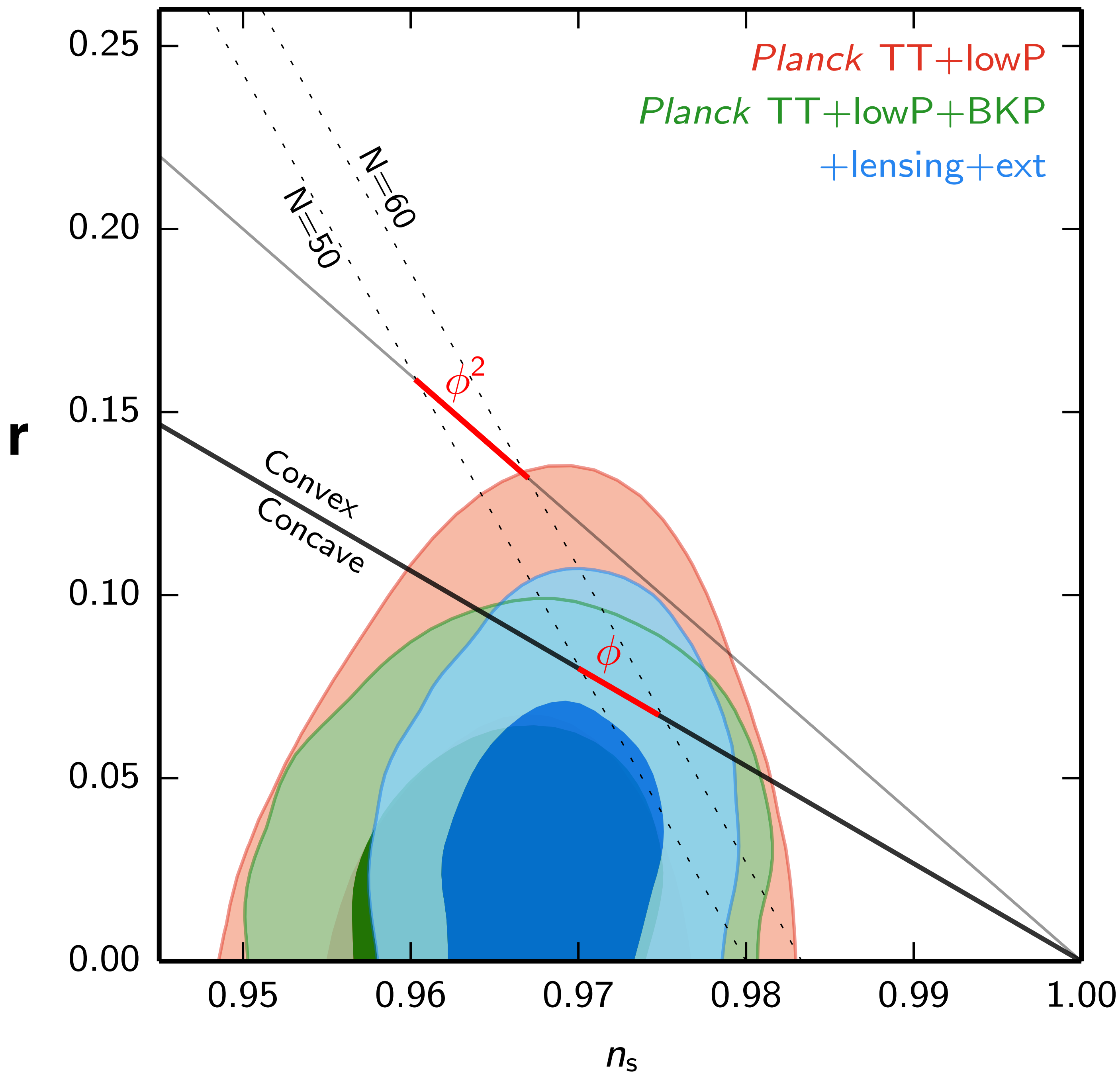
Planck temperature (TT $l \lesssim 100$) INDIRECT
model dependent!

$$r < 0.10 \quad 95\% \text{ CL}$$

ALL COMBINED: Planck BB,TT & Bicep2/Keck

$$r < 0.08 \quad 95\% \text{ CL}$$

Early Universe physics summary



Constraint from temperature alone are model dependent

Direct measurement of r from B-modes is really important!

OUTLINE

➡ PLANCK 2015: overview of general results

↳ The Planck

➡ **The next challenge:**
the CMB polarization at large angular scales

Why it is interesting

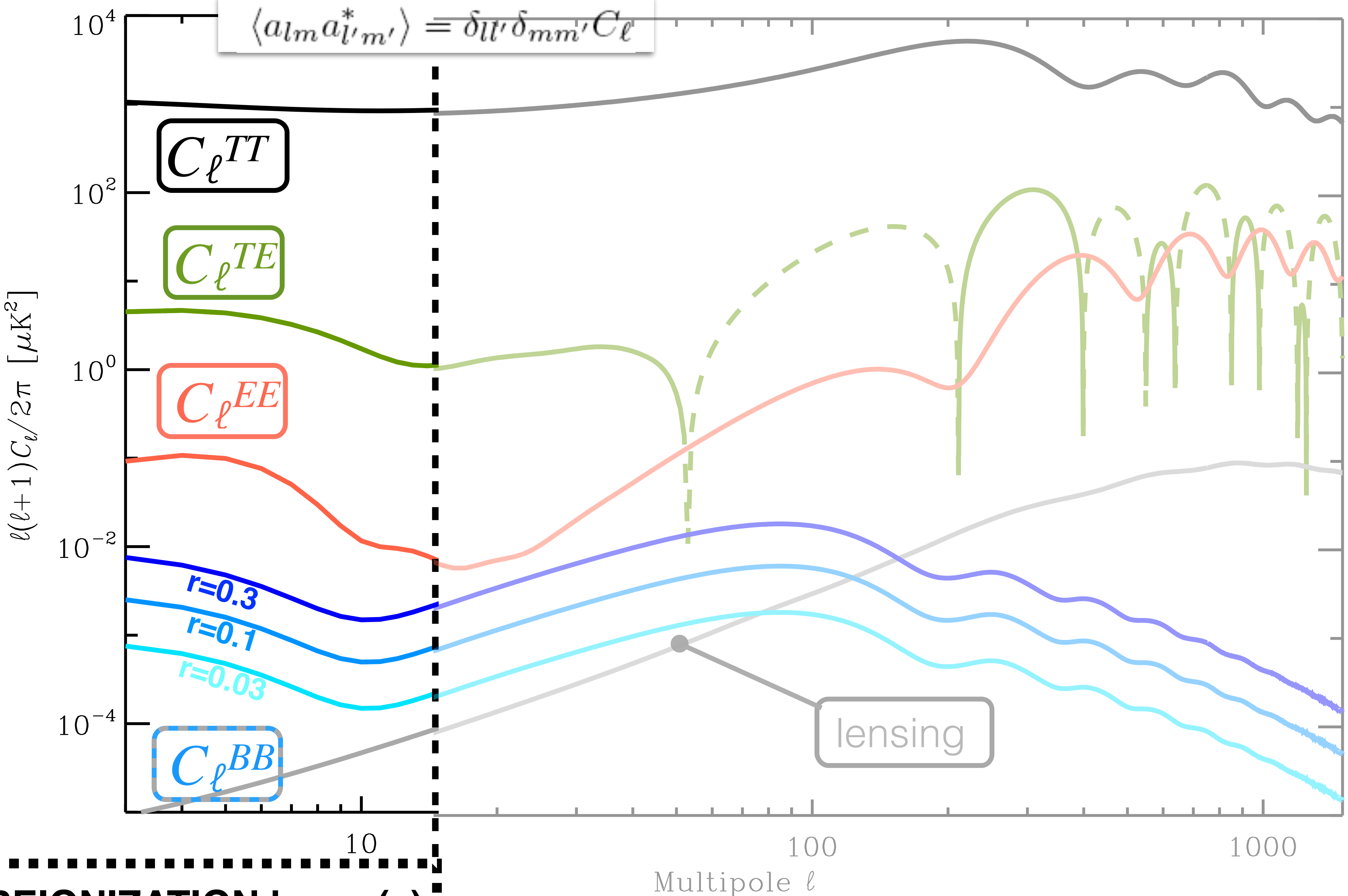
Statistical method(s)

Results

The CMB angular power spectra at large scales

CMB anisotropies: $$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{n})$$

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



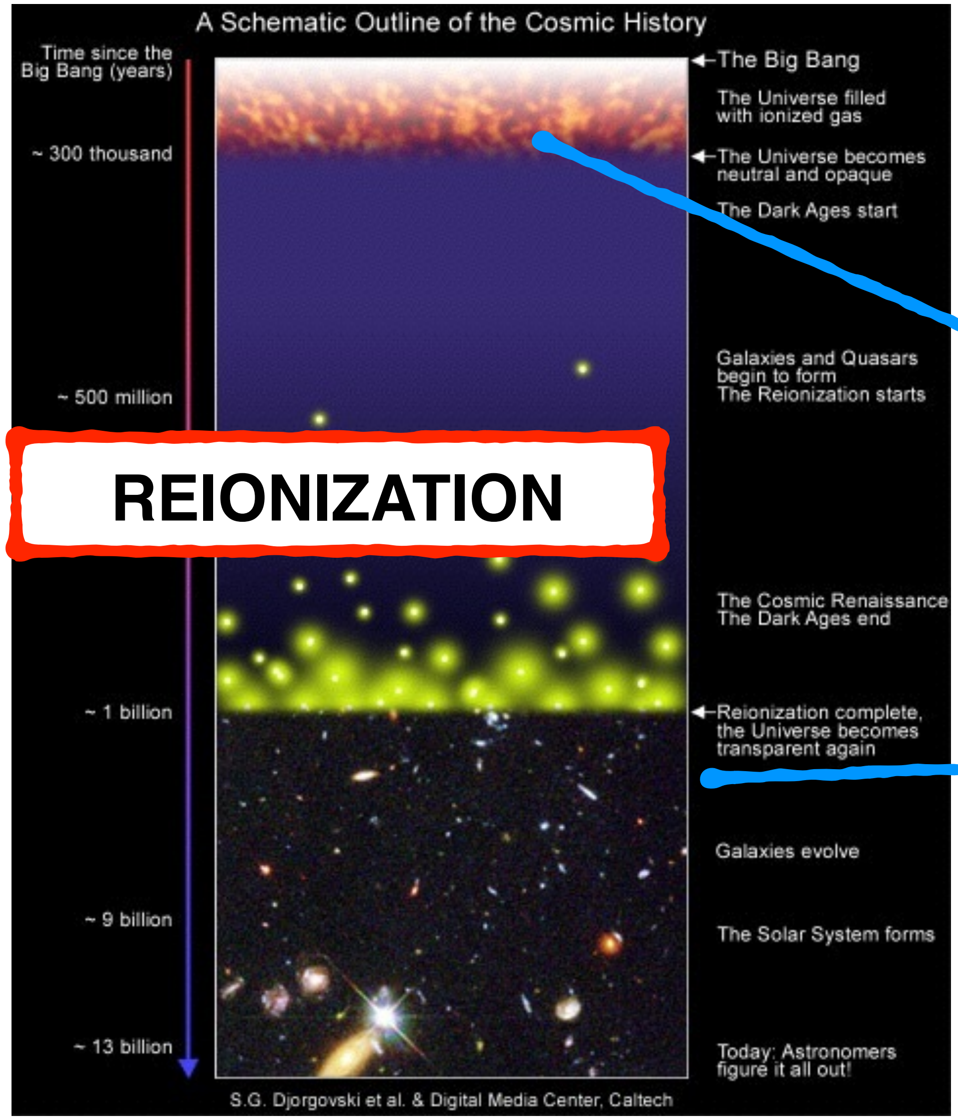
REIONIZATION bump(s)
2<l<15

Reionization "status"

Reionization process not fully understood

Thomson scattering optical depth:

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



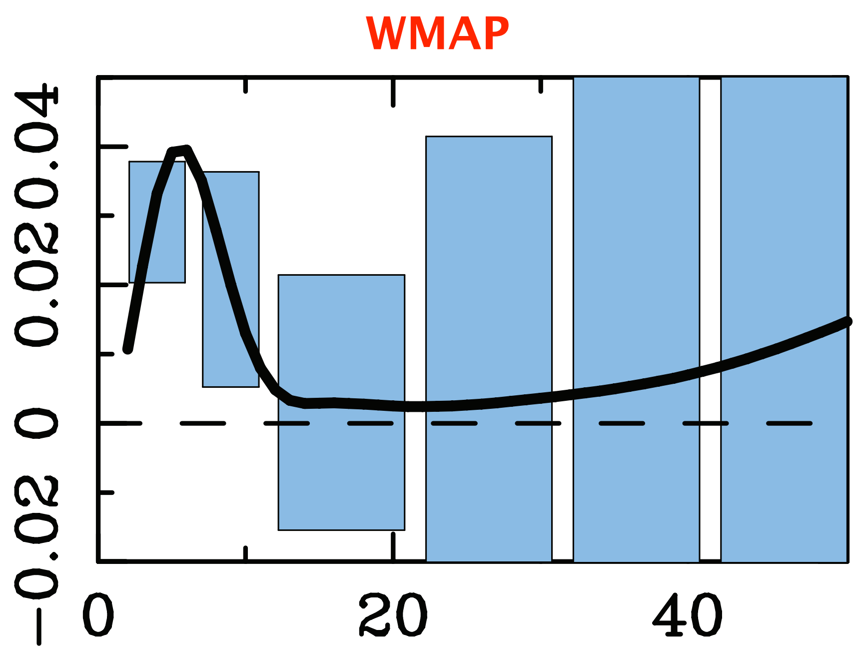
Discrepancy in τ measurements:

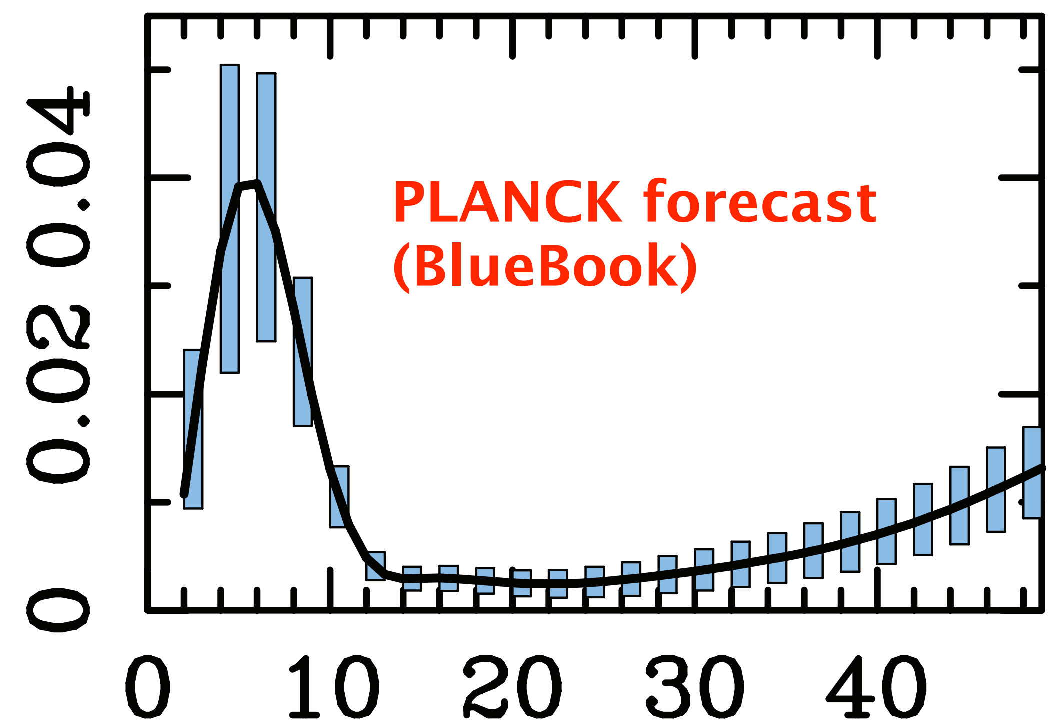
Constraint from CMB. So far (Planck 2013 & WMAP) pointed to high τ values: first stars formed early

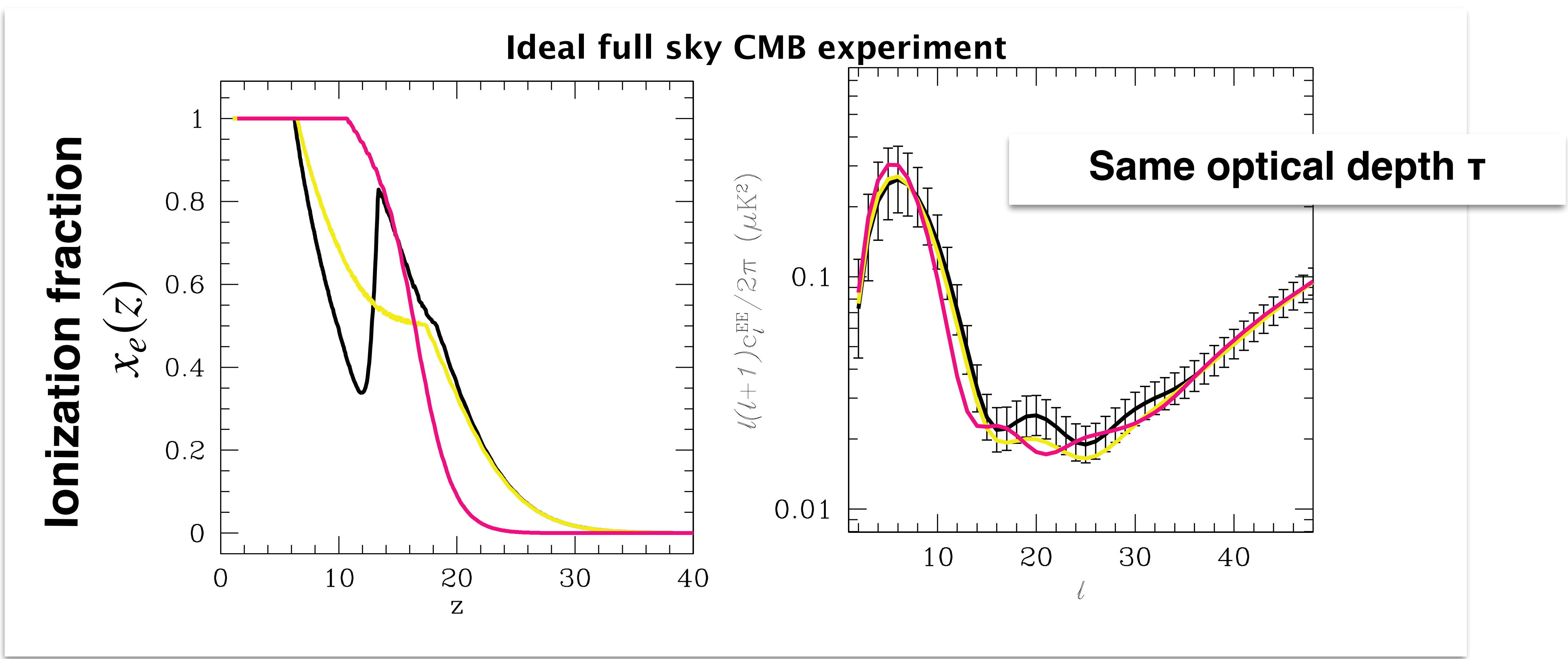
Constraint from astrophysical measurements (e.g. HST Ultra Deep Field) so far pointed to low τ values

Planck, future CMB polarization and Large Scale Structures experiments are expected to provide more precise answers

The E-modes spectrum







The challenge

➡ **Data quality**

Control of systematics

Accurate foreground subtraction/modeling

Planck 2015:

No HFI polarization data released

Still residual systematics @ large scales

➡ **Data analysis**

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

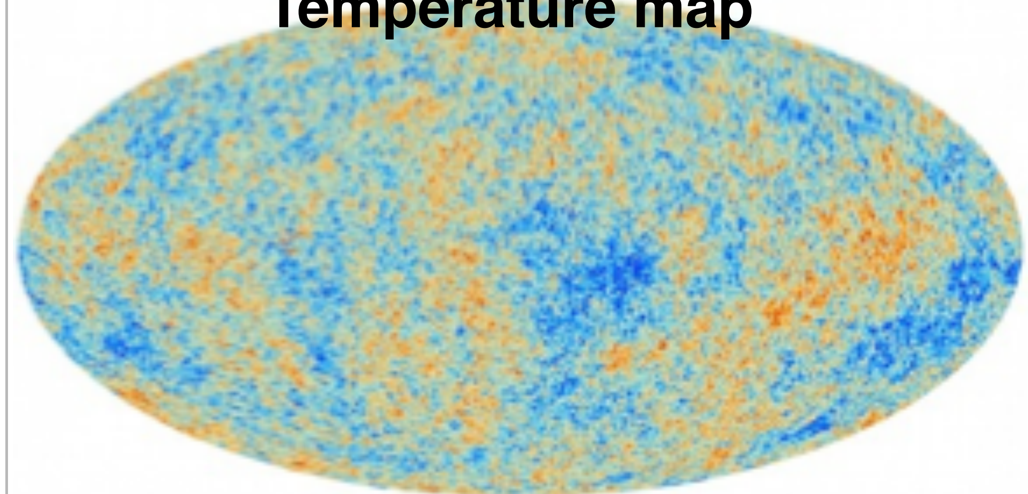
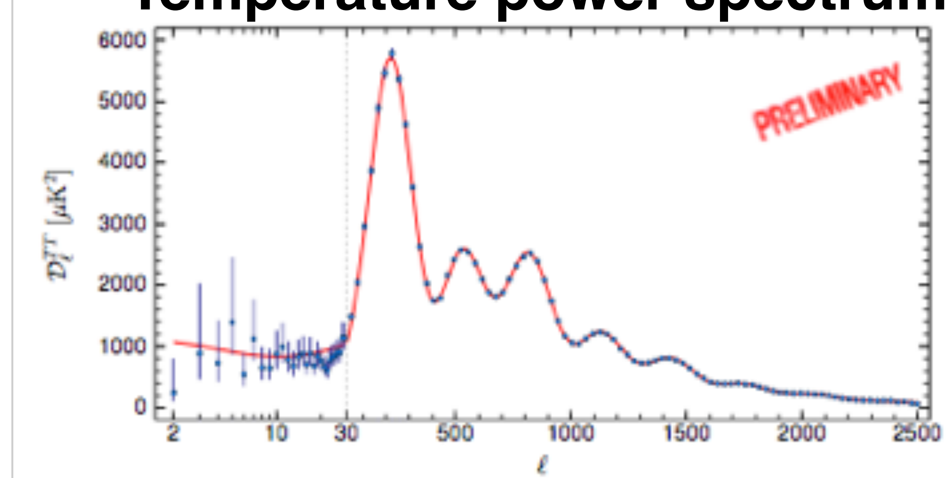
Mangilli, Plaszczynski, Tristram. In prep.

Some definitions …

CMB Likelihood:

Quantifies the match between the **data** and a given theoretical model Cl($\vec{\alpha}$)

$$L(C_\ell) \;=\; P(\mathbf{d}|C_\ell(\alpha))$$

CMB map: $\mathbf{m} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{p})$	**Temperature map** 	pixel based likelihood
CMB power spectrum: $\hat{C}_\ell^{XY} = \langle a^X_{\ell m} a^Y_{\ell' m'} \rangle \delta_{\ell\ell'}$ **[X,Y]={T,E,B}**	**Temperature power spectrum** 	spectra based likelihood

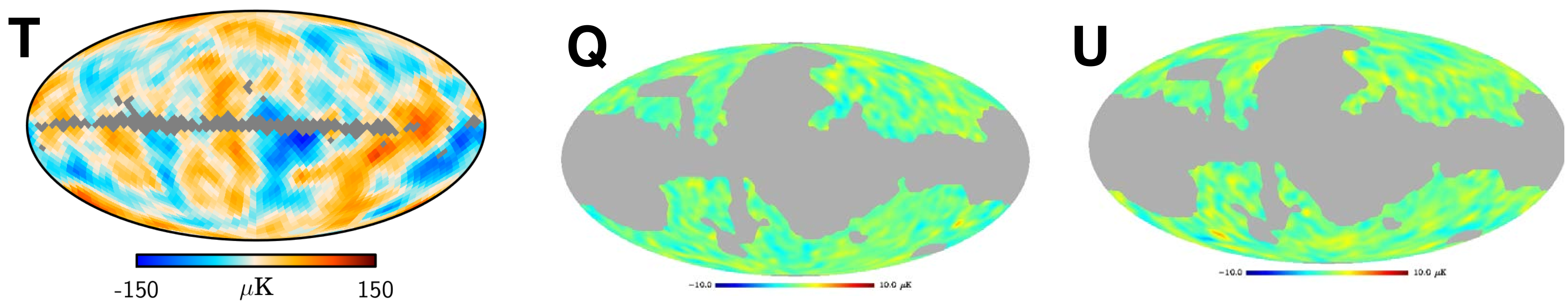
Constraining the CMB at large scales

The "**pixel-based**" likelihood:

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

Few multipoles. **Gaussian** likelihood, can be computed exactly.

m=[T,Q,U], here e.g. Planck 2015. Polarization from 70GHz only:



Planck maps= signal+**Noise**

Difficult handling of noise bias/residual systematics: can compromise parameter reconstruction

Constraining the CMB at large scales

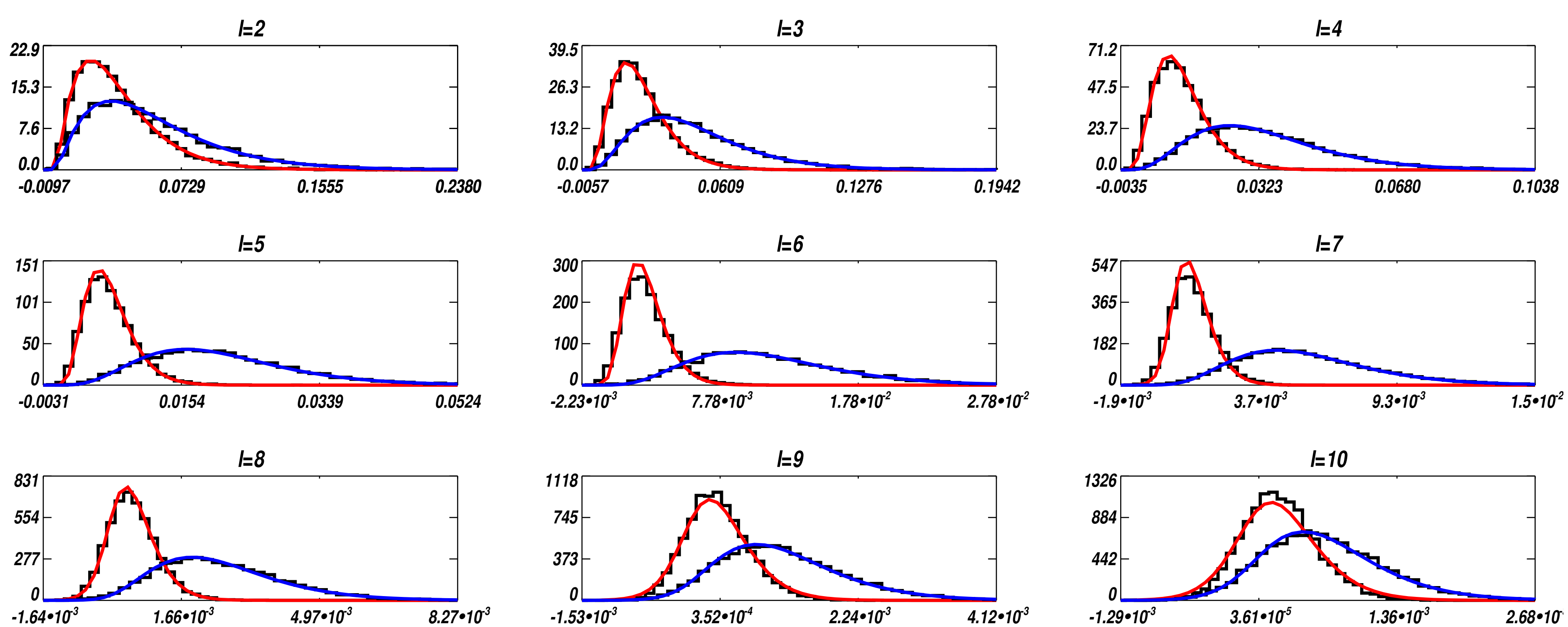
The “**spectra-based**” likelihood

Used at small angular scales (50<l<2000)

The likelihood is non-Gaussian @ large angular scales

Mangilli, Plaszczynski, Tristram. In prep.

Correct modeling of the non-Gaussian likelihood



Constraining the CMB at large scales

The "**spectra-based**" likelihood

Used at small angular scales (50<l<2000)

The likelihood is non-Gaussian @ large angular scales

Mangilli, Plaszczynski, Tristram. In prep.

Correct modeling of the non-Gaussian likelihood

Use CROSS-SPECTRA: $\hat{C}_\ell^{XY} = \langle a^X_{\ell m} a^Y_{\ell' m'} \rangle \delta_{\ell\ell'}$

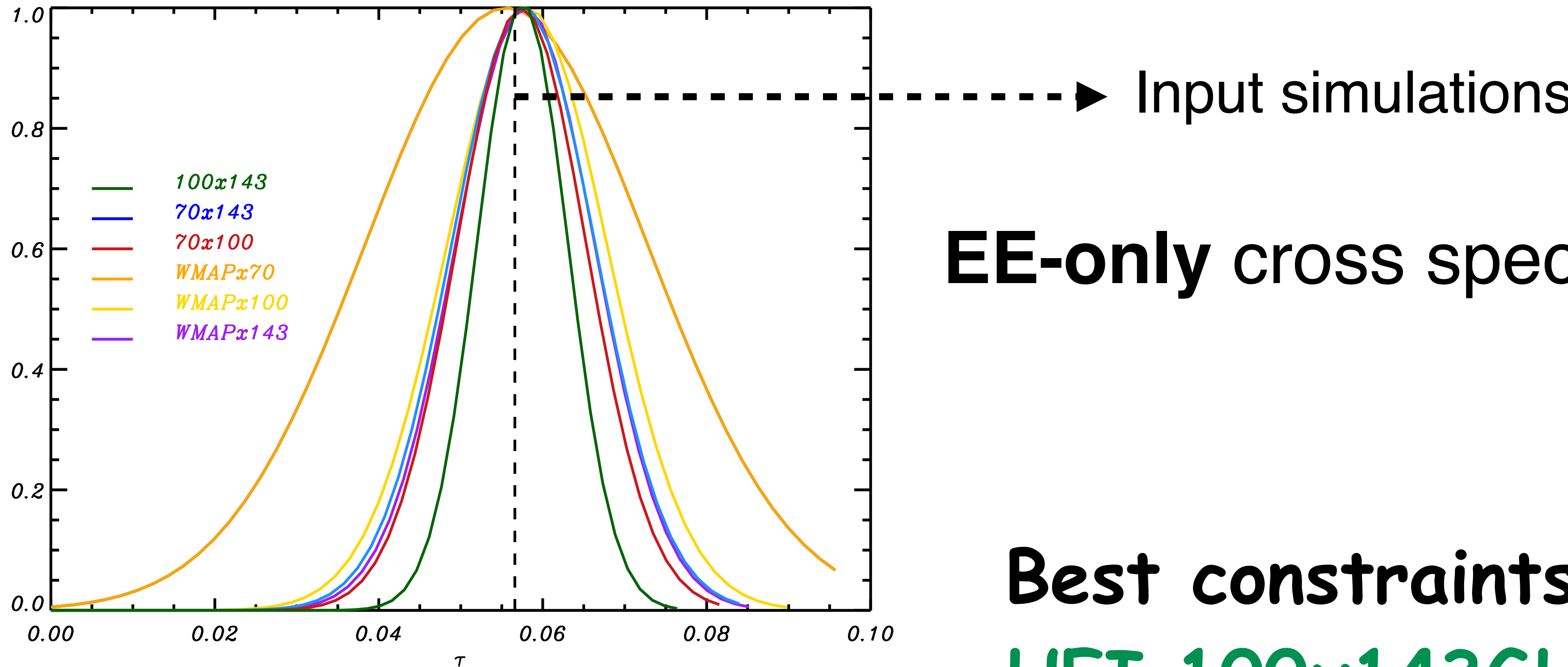
X≠Y, [X,Y]={70GHz,100GHz,143GHz,WMAP, …}

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

The cross spectra-based approach

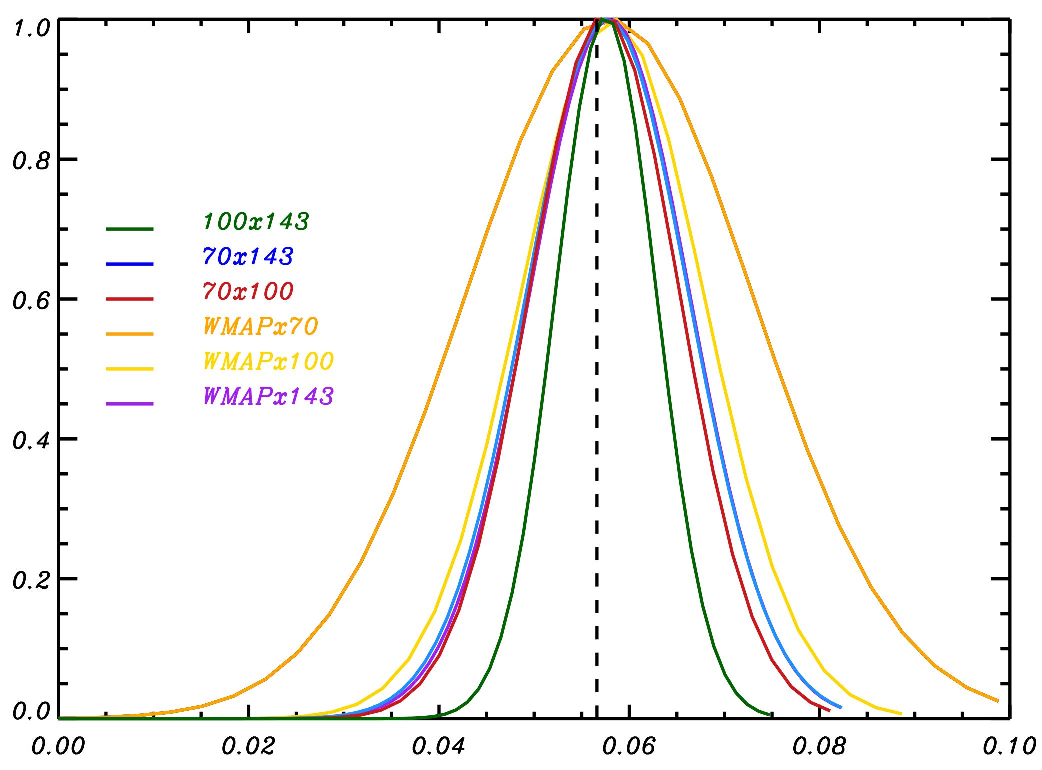
Mangilli, Plaszczynski, Tristram. In prep.

Best-fit τ, 2000 simulations for different cross spectra:



EE-only cross spectra C_ℓ^{EE}

Best constraints expected from HFI 100x143GHz



Full analysis: TT+EE+BB+TE+EB+TB

Slight (~7%) improvement on error-bar estimation

Planck 2015: reionization optical depth from large scales polarization

First constraints from large scale HFI polarization only!

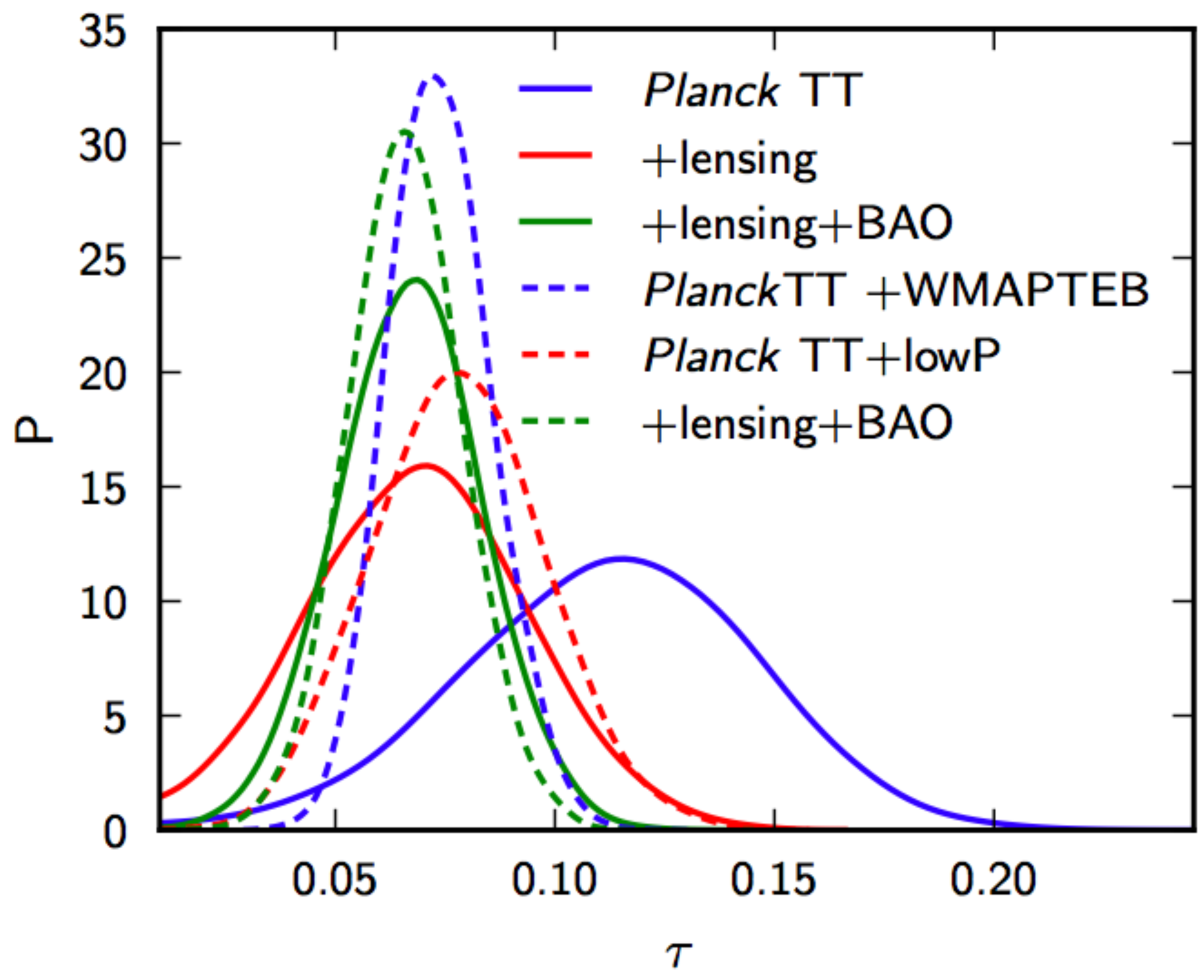
HFI EE only, 100x143GHz

Planck Temperature

Error bars still not optimal because of residual systematics

Planck 2015: reionization optical depth

$\tau = 0.069^{+0.009}_{-0.010}, \; z_{re} = 9.1 \pm 0.9.$ *Planck* TT +lowP+WP+lensing+BAO

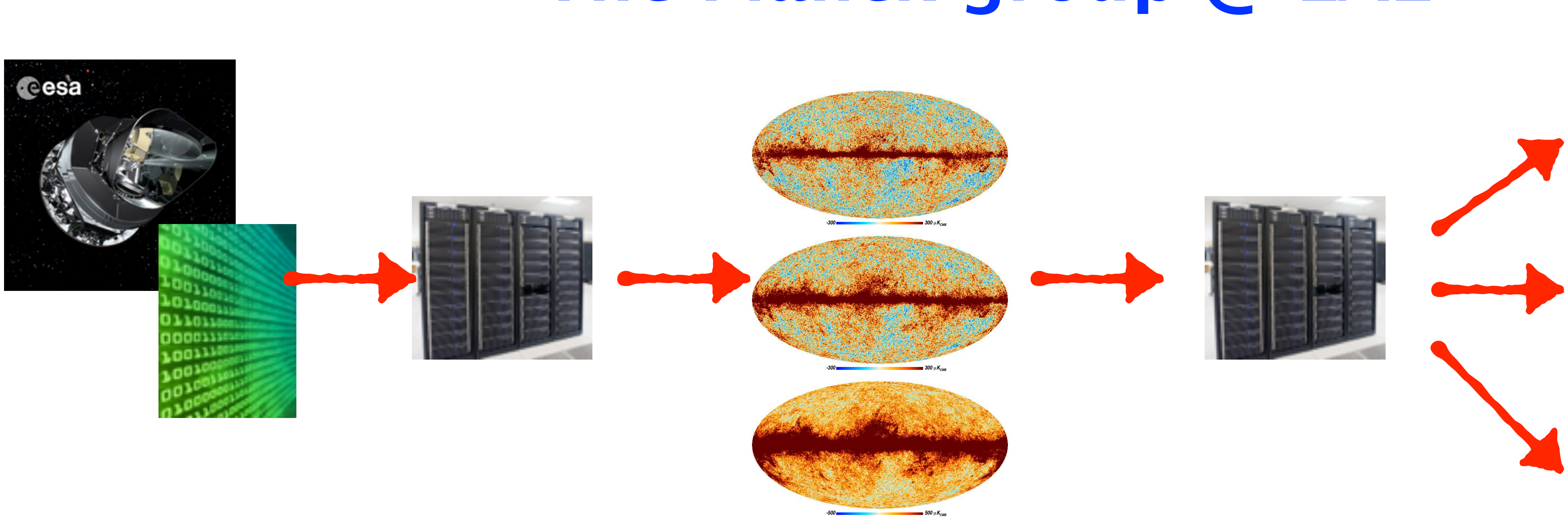


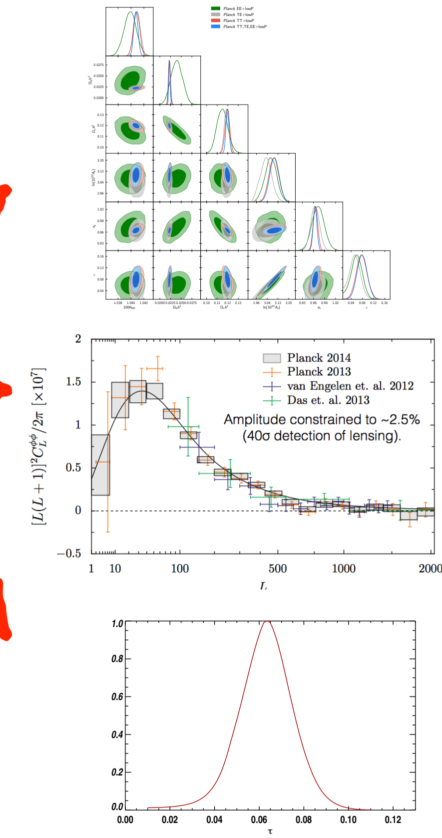
… Planck results seems to point to lower τ.

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

Residual systematics in the Planck 2015 (low-l) polarization data: specific Planck analysis @ end 2015

The Planck group @ LAL





➡ **Strong involvement in:**

- ➡ Map making, spectra reconstruction
- ➡ Data analysis and validation
- ➡ Likelihood development @ large and small scales
- ➡ Statistics tools: bayesian vs frequentist
- ➡ Foreground modeling
- ➡ CMB lensing
- ➡ Reionization (in synergy with IAS)
- ➡ Neutrinos
- ➡ CMB non-Gaussianity
- ➡ Constraint on tensor to scalar ratio, Planck-Bicep2

Summary

➡ **Planck 2015: great results!**

- General consistency with ΛCDM and Planck 2013: both temperature and polarization!
- Best detection so far of CMB lensing: 40σ! (x2 improvement)
- Lensing-ISW detection improved at 3σ
- No primordial Non-Gaussianity
- In general: simplest model of inflation favored
- Point to lower values of the reionization redshift
- Total neutrino mass bound: <0.23 eV (95%CL)
- Planck Temperature+B-modes+Bicep2: r<0.08 (95%CL)

➡ **The challenge: CMB polarization at large angular scales**

- Very interesting to constraint reionization (τ) and inflation (r)

What's next

planck

At least 2 more releases by the end of 2015 and 2016:
Overall improvement of polarization data

➡ **Main target: the CMB polarization at large angular scales**

- Improving HFI data on the way
- Better HFI systematics control at the map making level
- New statistical method: extensive data validation
- Constraints on reionization from HFI: τ error bars improved > X2
- Upper bounds for r from the B-modes at reionization bump
- Joint r-τ analysis from reionization bumps

➡ **QUBIC CMB ground telescope (end 2016?)**

➡ **COrE+: ultimate CMB space mission (2026?)**

Future Large Scale structure Surveys: LSST, Euclid, SKA …

THANK YOU!