In the dark of night and in the light of dawn: combining probes to reconstruct the reionization history

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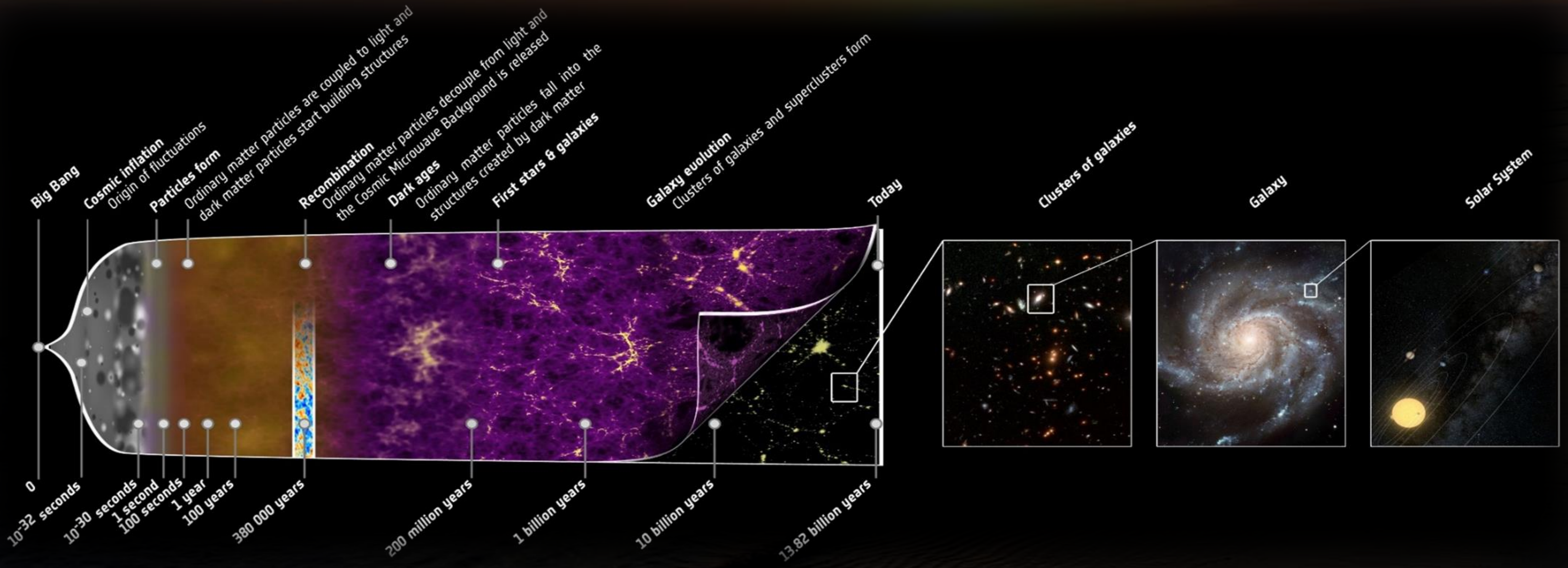
The end of the dark

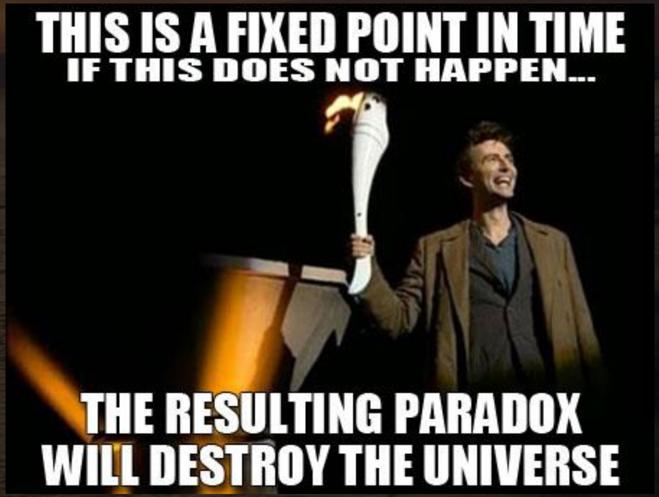
Reionization represents the end of the dark ages with the first sources of light turning up and reionizing the Universe



Reionization from a cosmological point of view

Reionization represents one of the main phase transition our Universe encountered.
The quest for understanding its development is open and several observations are dedicated to its mapping and the search of its sources.

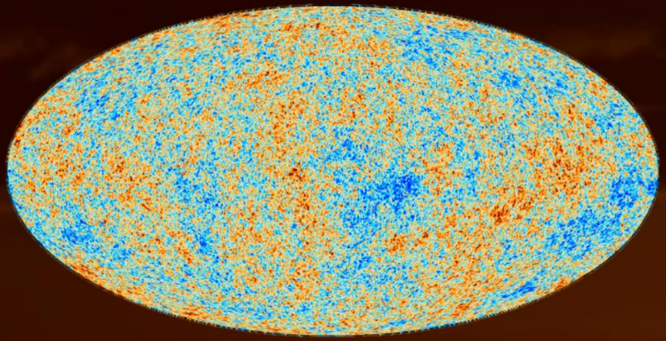
But reionization is one fixed point in cosmology timeline.
It is something we must deal with when fitting for a cosmological model the data.

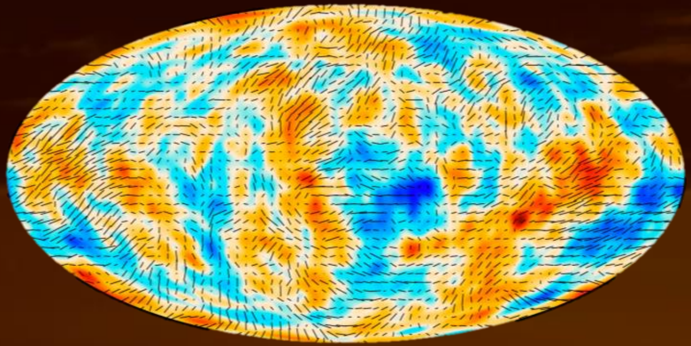


Reionization still represents one of the greatest sources of uncertainty in cosmology and in particular for the Cosmic Microwave Background


Just before the dark

REIONIZATION AND THE CMB

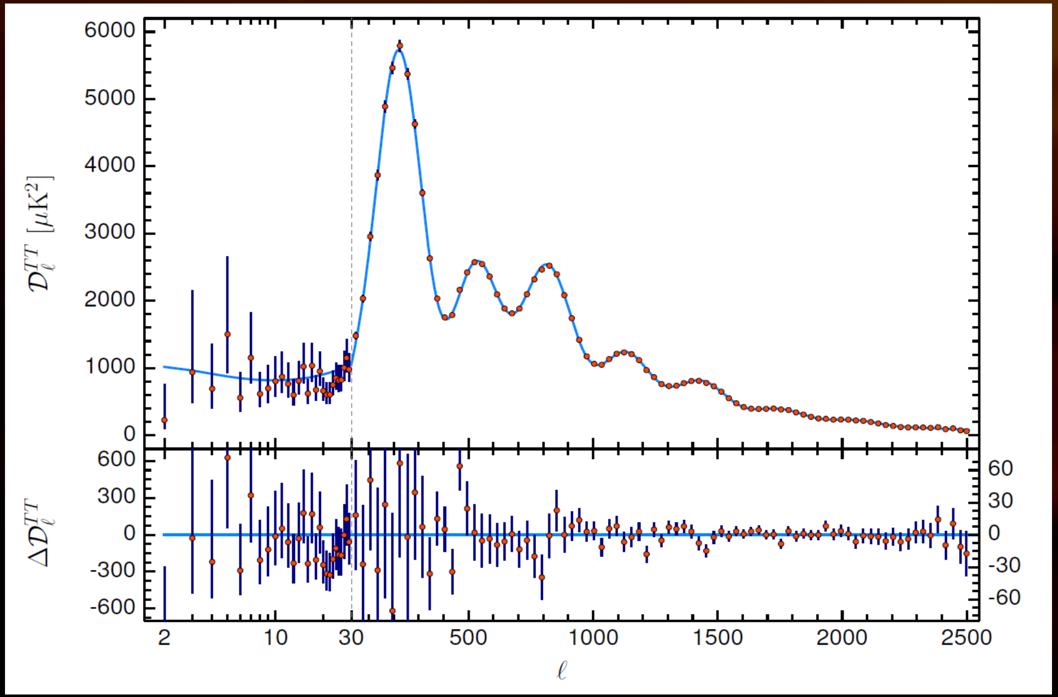




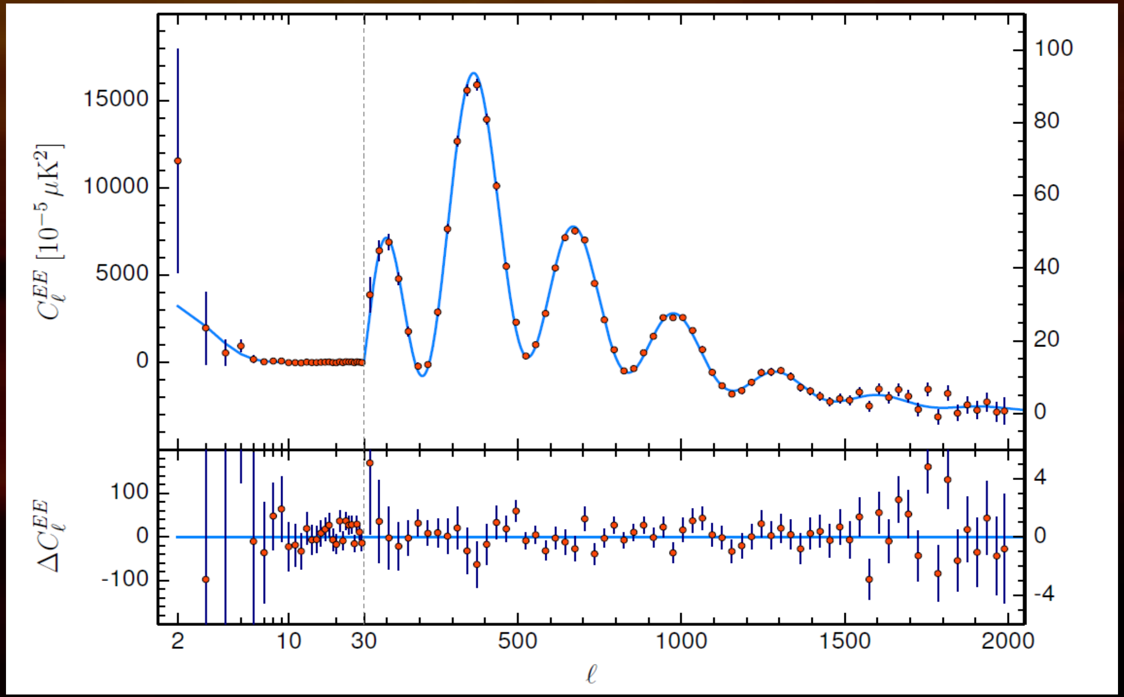
$$\Delta T(\vec{x},\hat{n},\tau) = \Sigma_{l=1}^{\infty}\Sigma_{m=-l}^{l} a_{lm}(\vec{x},\tau) Y_{lm}(\hat{n})$$

$$C_l = \frac{1}{2l+1}\Sigma_m \langle a_{lm}^* a_{lm} \rangle$$

Large angular scales   Small angular scales



Large angular scales   Small angular scales



Planck 2018 V

The effect of reionization in the CMB is the rescattering of photons by the newly free electrons
The impact is in both temperature and polarization
The CMB is sensitive to reionization through the integrated optical depth or τ

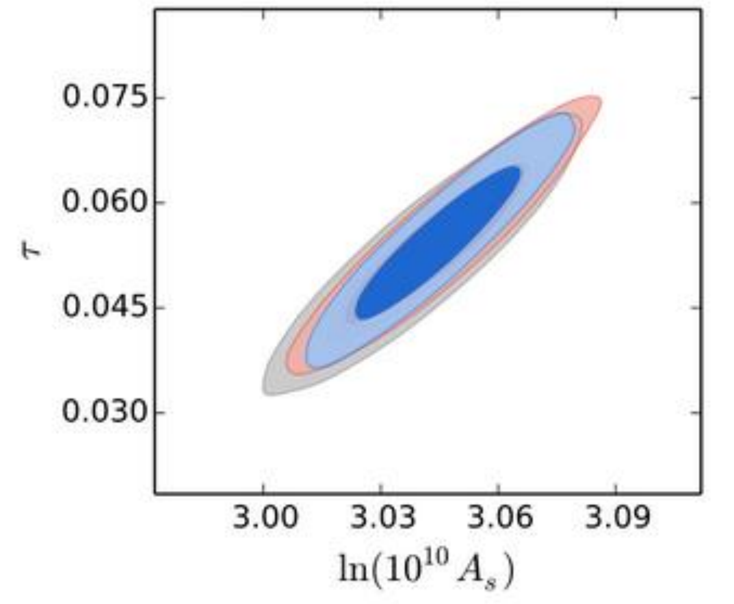
$$\tau = n_{\mathrm{H}}(0) c \sigma_{\mathrm{T}} \int_0^{z_{\max}} dz\, x_{\mathrm{e}}(z) \frac{(1+z)^2}{H(z)}$$

TEMPERATURE

The rescattering of photons has the effect to reduce the overall amplitude of the CMB anisotropies which are proportional to $A_s e^{-2\tau}$

Where As is the amplitude of the primordial power spectrum fluctuations.

$$\ln \mathcal{P}_{\mathcal{R}}(k) = \ln A_{\mathrm{s}} + (n_{\mathrm{s}} - 1) \ln(k/k_*)$$

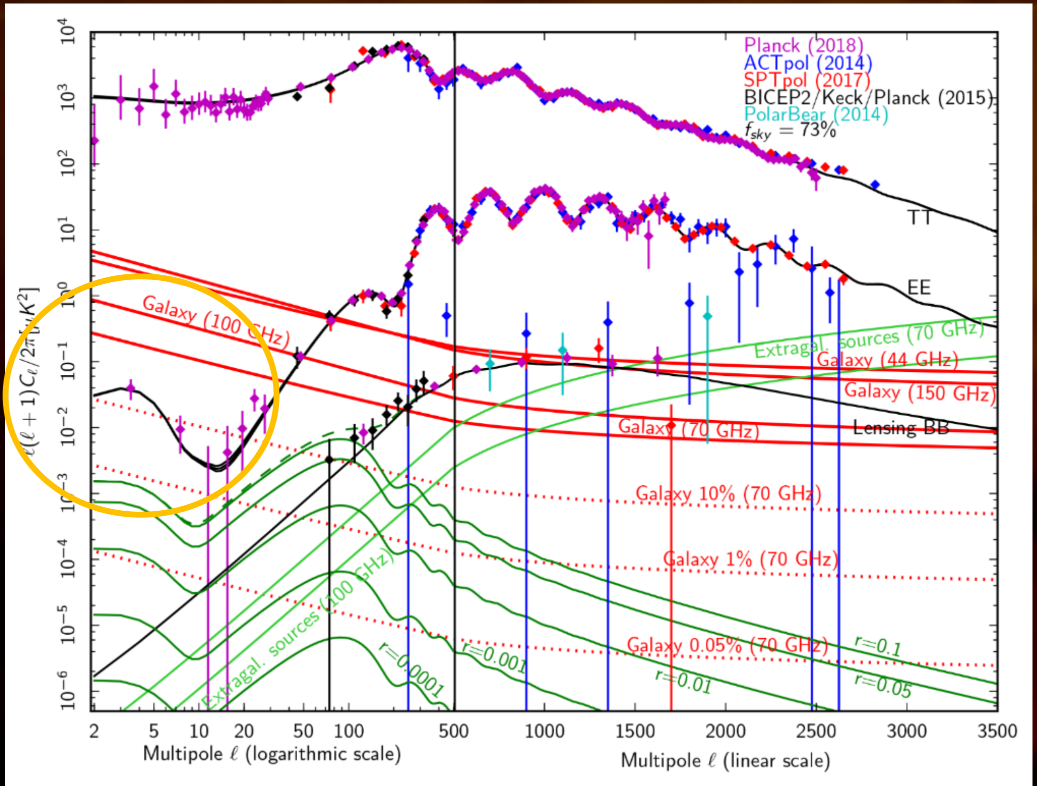


The degeneracy between the two parameters is one of the most relevant in current cosmology.
But we will see how reionization affects also other parameters that describe the cosmological model

POLARIZATION

If Planck exhausted the temperature anisotropies chapter by providing a cosmic variance-foreground limited measurement, future experiments are all devoted to the measurement of CMB polarization

Polarization is strongly sensitive to reionization. The rescattering of the photons quadrupole enhances the anisotropies at a scale corresponding to the redshift of reionization in the so-called reionization bump



Molinari, Mandolesi and Burigana

The amplitude of the bump goes as the optical depth squared

Its peak is dependent on the reionization redshift

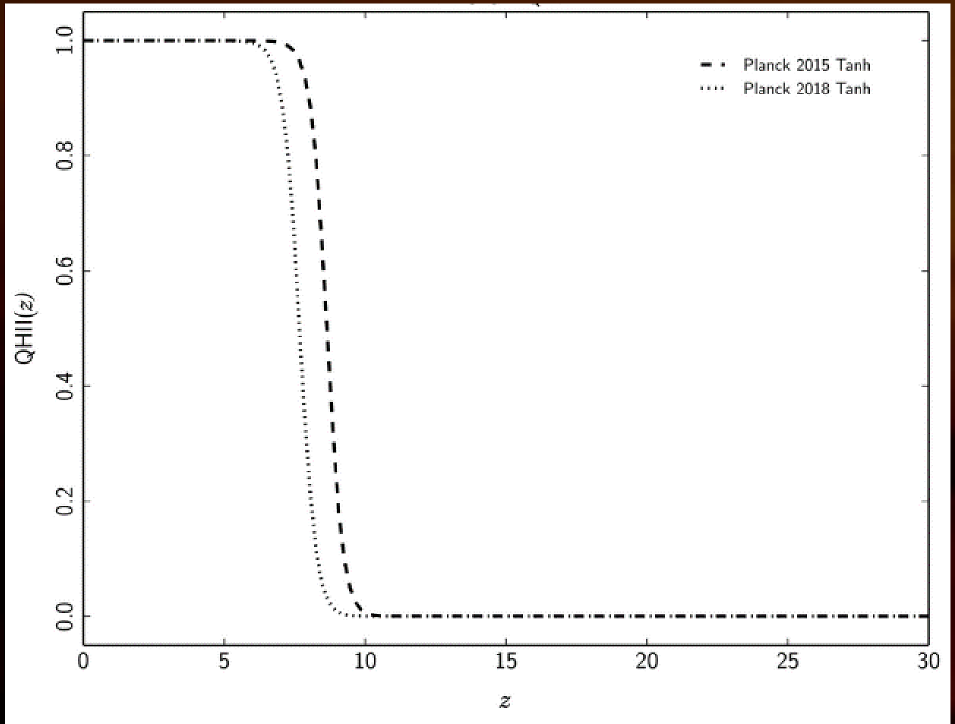
Keep in mind also that the optical depth is degenerate with the fluctuations amplitude.

The amplitude of B-modes is described by the tensor to scalar ratio r.

This means that the detection fo the holy grail of inflation actually depends also on reionization!

LEVEL ZERO- The reionization in the standard cosmological model

In the standard cosmological model reionization is assumed as a sharp transition from almost zero ionization fraction to 1 (with a little additional delta due to helium reionization)
The transition is assumed as an hyperbolic tangent with fixed width in redshift



$$x_e = \frac{1 + n_{\mathrm{He}}/n_{\mathrm{H}}}{2}\left[1 + \tanh\left(\frac{y(z_{\mathrm{re}}) - y(z)}{\Delta y}\right)\right]$$

$$y(z) = (1+z)^{3/2}$$

$$\Delta y = \frac{3}{2}(1+z_{\mathrm{re}})^{1/2}\Delta z$$

The optical depth is largely independent on the redshift width in this model (*Lewis-2008*) and it is usually assumed between 0.5 and 1.5
A second hyperbolic tangent is considered a z=3.5 for Helium reionization
The reionization redshift is defined as the redshift at which the ionization fraction is half.

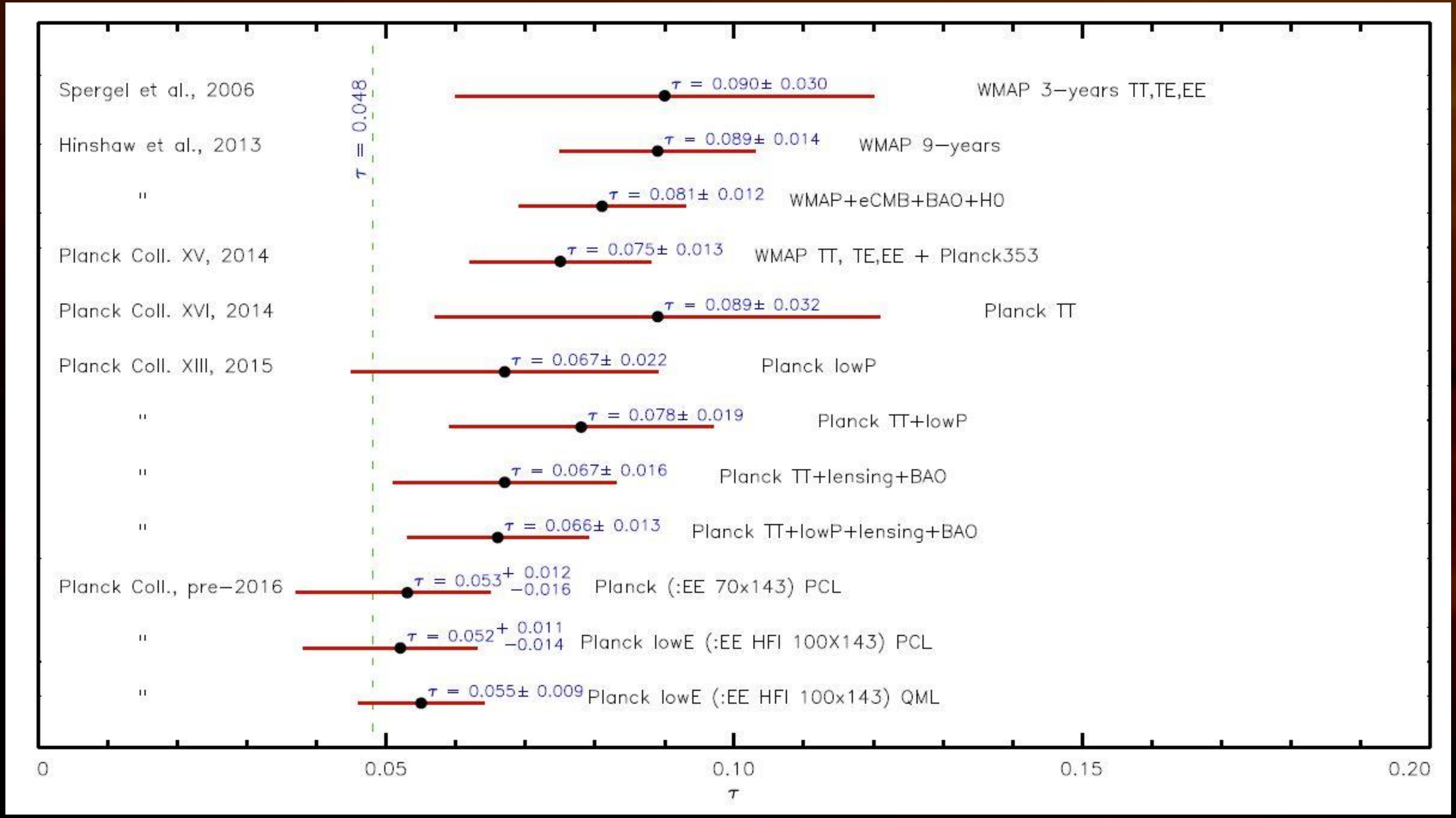
Optical Depth pre-Planck 2018

Prehistory

Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9

WMAP 1year Bennet et al. 2003

History



It has been a long way…
17 years and still the optical depth is the parameter with the worst uncertainty in the standard cosmological model.

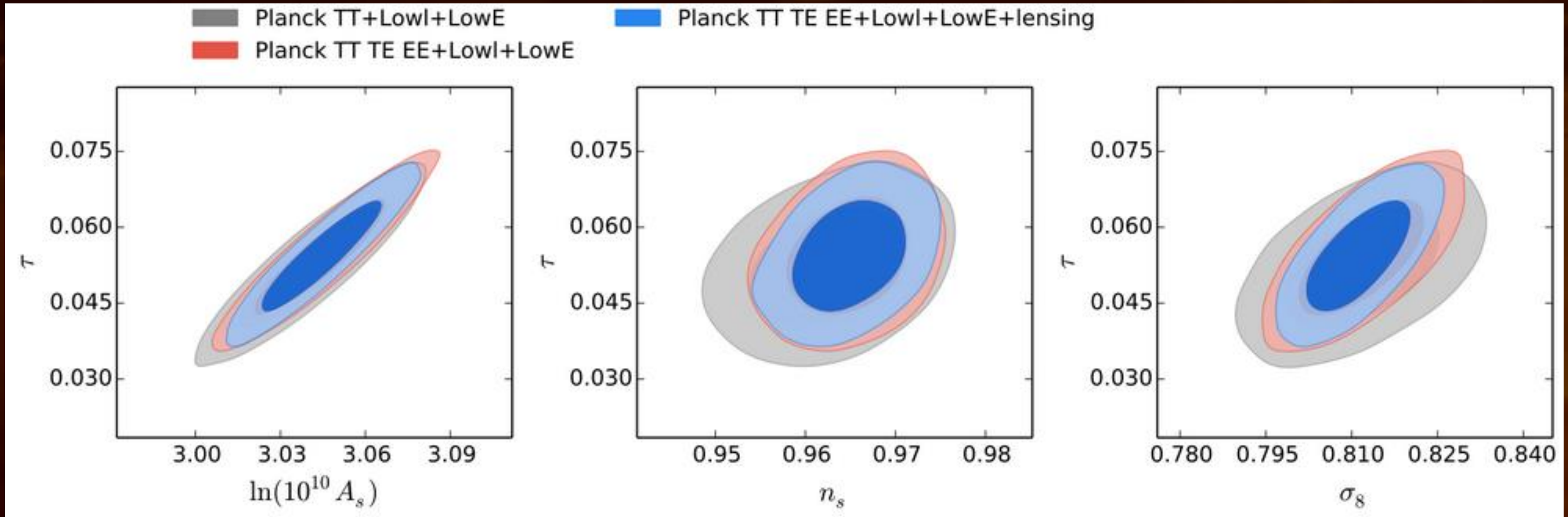
Measuring polarization is complex:

- need large scales – large sky fractions
- need wide frequency coverage for the foreground removal
- need perfect control of systematics since the signal is low in the region of interest

Cosmic Variance limit for a sky coverage a la Planck (70% of the sky) is sigma(optical depth)=0.002

Forecasts show that this limit will be reached by the LiteBIRD mission

Planck 2018- Constraints on the optical depth with an hyperbolic tangent



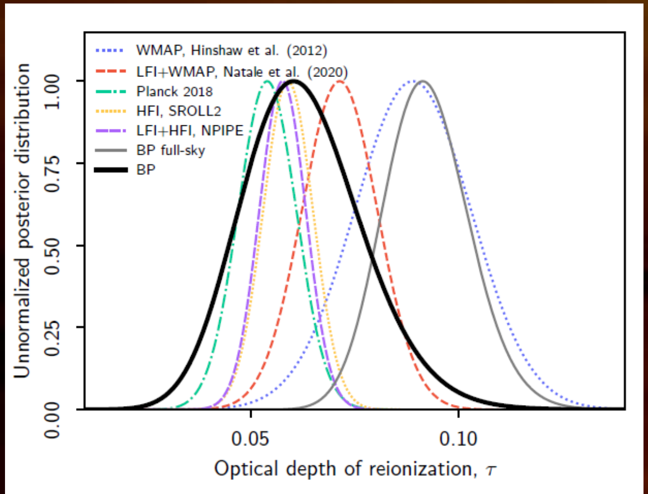
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71

Planck 2018 VI, X

There is so little interest in the optical depth that from the same release we have already 5 different analysis (each to be multiplied by at least 4 different likelihood combo)

Dataset	P2018 BASELINE	P2018 SROLL2	P2018 NPIPE (100x143)	P2018 Planck+WMAP	Beyond Planck	P2015
Optical depth	0.054 ± 0.007	$0.059^{+0.005}_{-0.007}$	0.051 ± 0.006	$0.071^{+0.009}_{-0.010}$	0.067 ± 0.016	0.066 ± 0.016
	P2018 VI	*Pagano+ 2018*	*PIP LVII 2020*	*Natale+ 2020*	*Beyond Planck 2020*	*P2015 XIII*

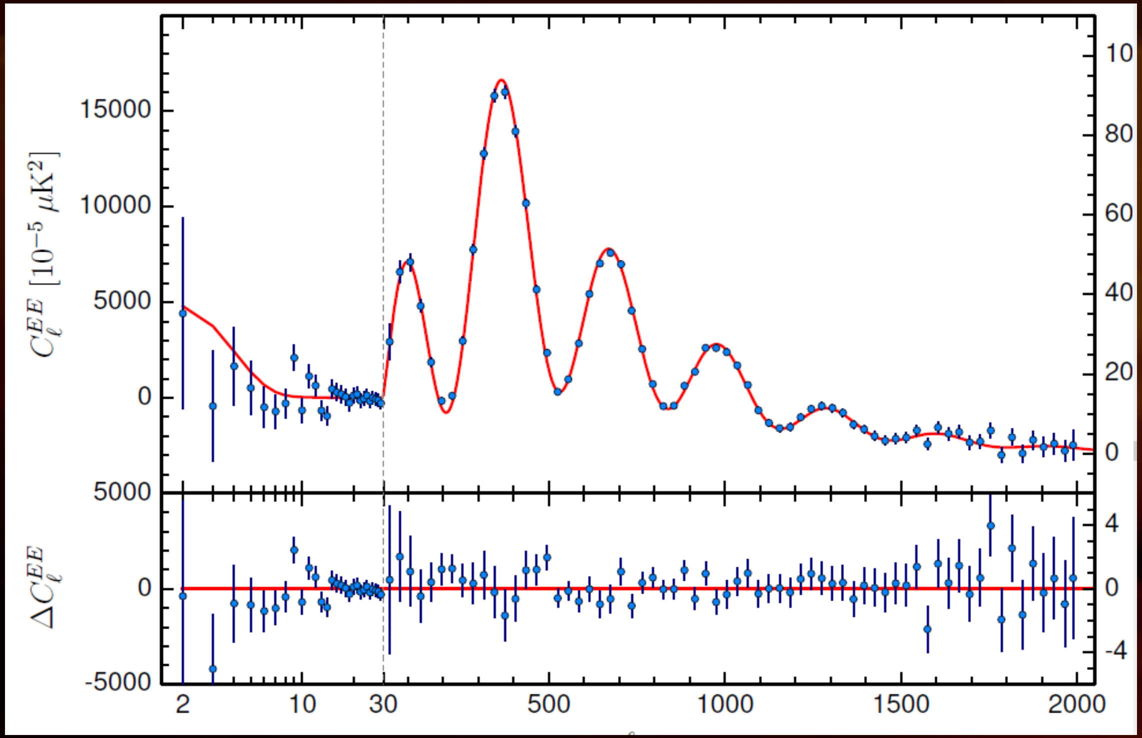
The main driver of the change in the central value and improvement in the error bars wrt Planck 2015 is the use of the HFI cross spectrum 100x143 for the large angular scales polarization likelihood This allows to reduce the errors bars.



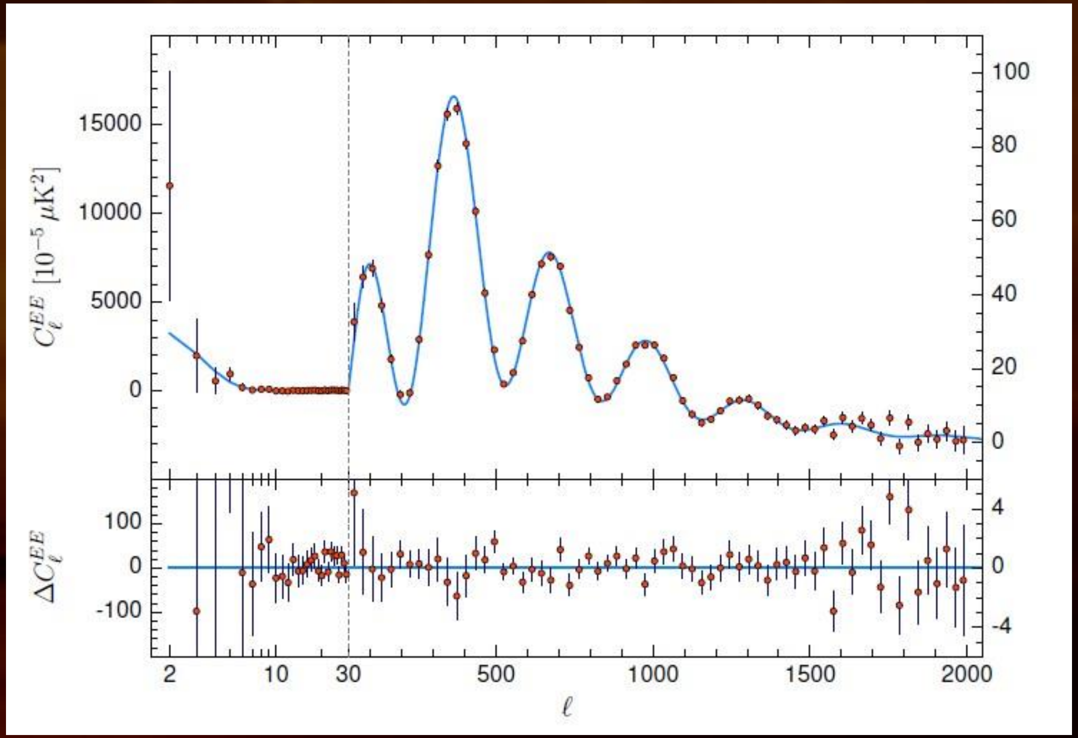
Beyond Planck Coll. 2020

IMPROVEMENT OF DATA WITHIN PLANCK

P2015



P2018



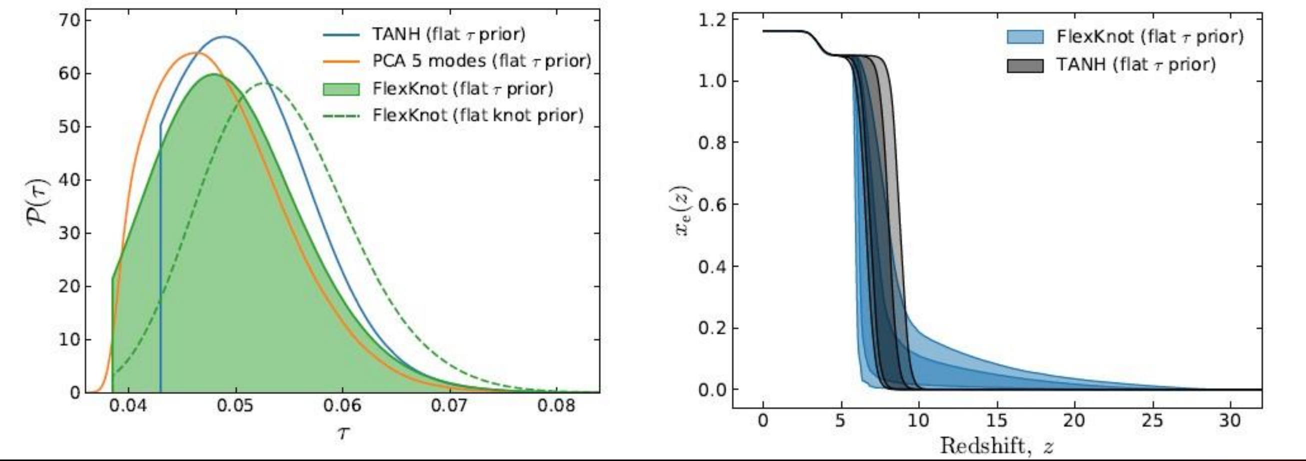
We are already at a point where we can go beyond hyperbolic tangent

PLANCK 2018 OPTICAL DEPTH 2.0

Increasing freedom with respect to the hyperbolic tangent

-PCA: decompose reionization history into eigenmodes that form a complete basis for any observable history (*Hu & Holder 2003*). Its main problem is the physicality, PCA quantities are not directly related to physical quantities creating both a problem of priors (in this case solved using *Millea and Bouchet 2018* results) and it may allow unphysical reionization histories.

-FlexKnot : *Millea & Bouchet 2018* - Physical reconstruction based on interpolation of the ionization fraction between movable knots marginalized over the number of knots (derived from the Poly-Reion by Hazra and Smoot 2017 for the xe fitting, see following slides). Tested both prior on the optical depth and on the knots amplitude and positions.



See also –Hu & Holder 2003,Mortonson & Hu 2008, Douspis+2015, Obied+2018, Heinrich & Hu 2018, Villanueva-Domingo+2018, Millea& Bouchet 2018,
Planck Intermediate XLVII,Trombetti & Burigana 2012,2013 for other extensions and different data analyses

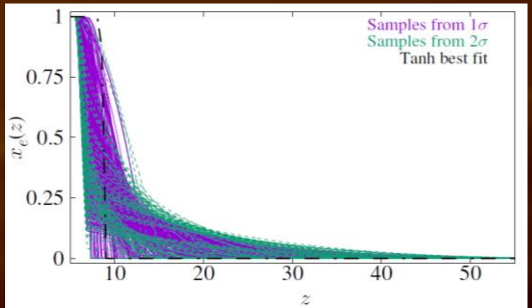
Planck 2018 VI

Poly-Reion Model

Extended model of reionization originally developed by Hazra & Smoot.
Ionization fraction is not anymore modelled but is fitted from the data
This kind of approach allows to have much more freedom as earlier onsets and longer duration of reionization
Free form reconstruction of the ionization fraction with Piecewise Cubic Hermite Interpolating Polynomials (PCHIP)

$$x_e(z) = (1 + F_{\mathrm{He}})f(z)$$

f(z) is the interpolating function



Hazra et al. 2018

PCHIP preserve monotonicity. If the ionized fraction increases with decreasing redshift the monotonicity is preserved but is not an a priori assumptions and can be not guaranteed in the model

Differently from approaches as PCA in our model the Ionization fraction is a physical quantity therefore by construction it can't be negative or greater than 1

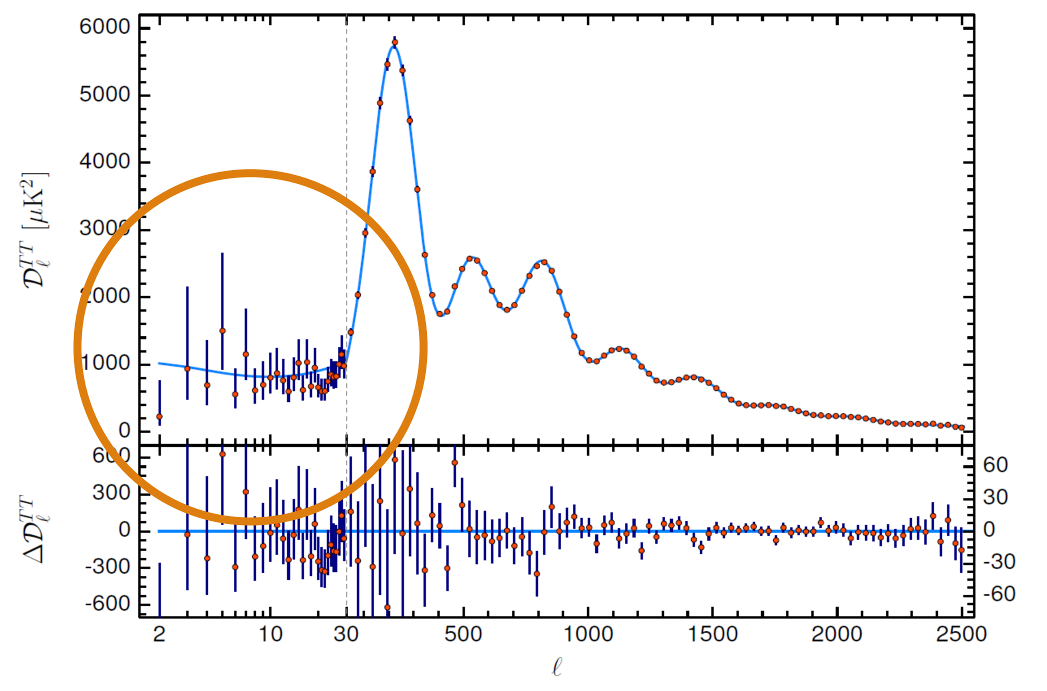
It allows for flexible set up: multiple nodes, flexible nodes etc.

Results on P2015 data have shown the preference for a minimal set up with a single movable knot

CONFUSING THE EARLY UNIVERSE PHYSICS

Before going into details with Planck 2018 latest results we make a step back in time to see an example of how extending reionization can affect your cosmological model constraints

Large scale anomalies as the lack of power and features have been detected with just little below 3 sigma constantly through both WMAP and Planck



A straightforward degeneracy is that if you change the optical depth you change the overall amplitude and you affect for example the lack of power

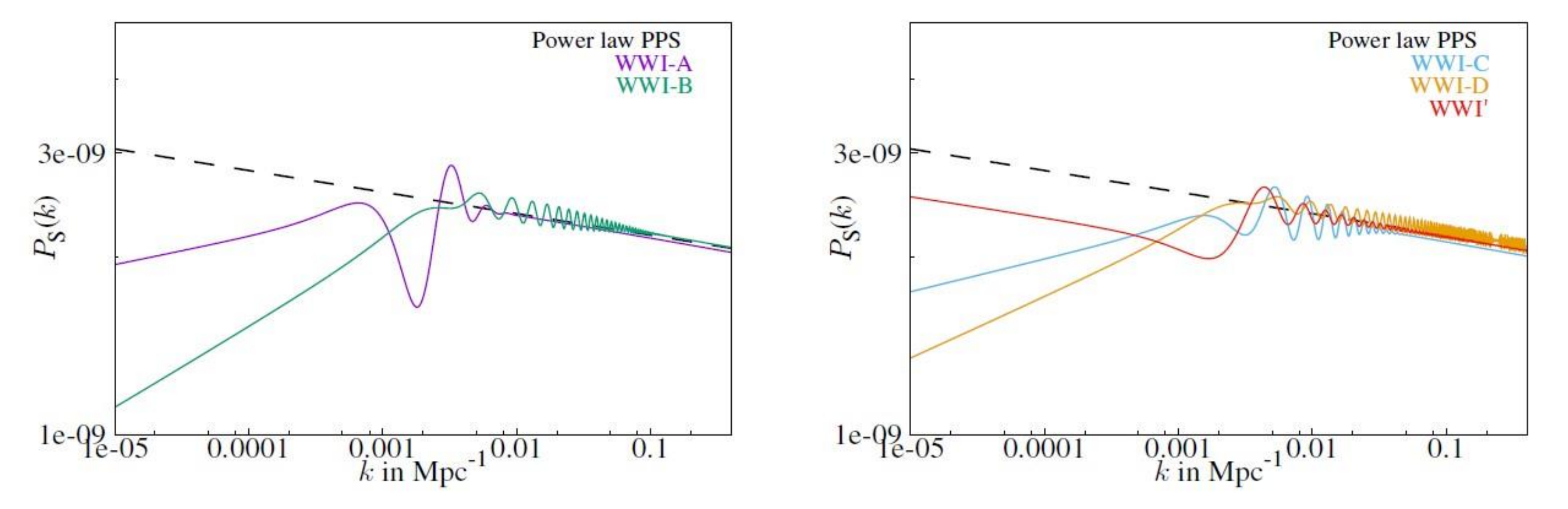
These anomalies may be reproduced by models of inflation which have some form of discontinuity in the inflaton potential
The discontinuity itself generates features, a phase of faster roll before the slow reproduces a lack of power

CONFUSING THE EARLY UNIVERSE PHYSICS - II

The reionization model may affect the statistical significance of these kind of models

We considered the case of Wiggly Whipped Inflation framework which provides a good fit to the large, intermediate and small scale anomalies, with reionization being mostly relevant for the large scales part, with a discontinuity in the inflaton potential or its derivative depending on the model.

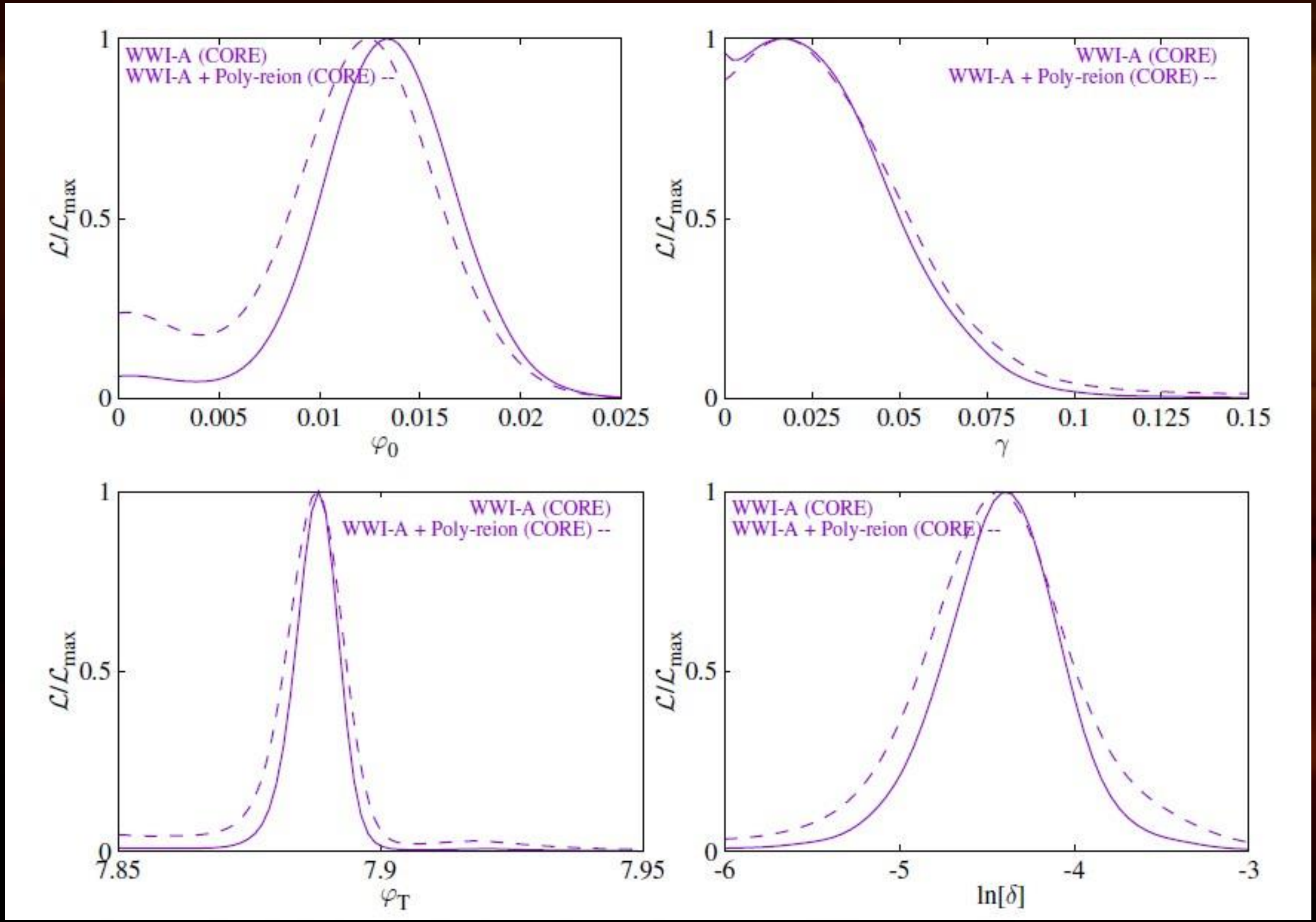
$$V(\phi) = V_0 \left[\left(1 - \left(\frac{\phi}{\mu} \right)^p \right) + \Theta(\phi_{\mathrm{T}} - \phi) \left(\gamma (\phi_{\mathrm{T}} - \phi)^q + \phi_0^q \right) \right]$$



Hazra, Paoletti, Finelli, Ballardini, Shafieloo, Smoot, Starobinsky 2018

CONFUSING THE EARLY UNIVERSE PHYSICS - III

If we use an hyperbolic tangent the forecasts for future CMB mission a la COrE (analogous consideration should apply for a LiteBIRD like experiment) we have a likely possibility to detect such models with a good significance



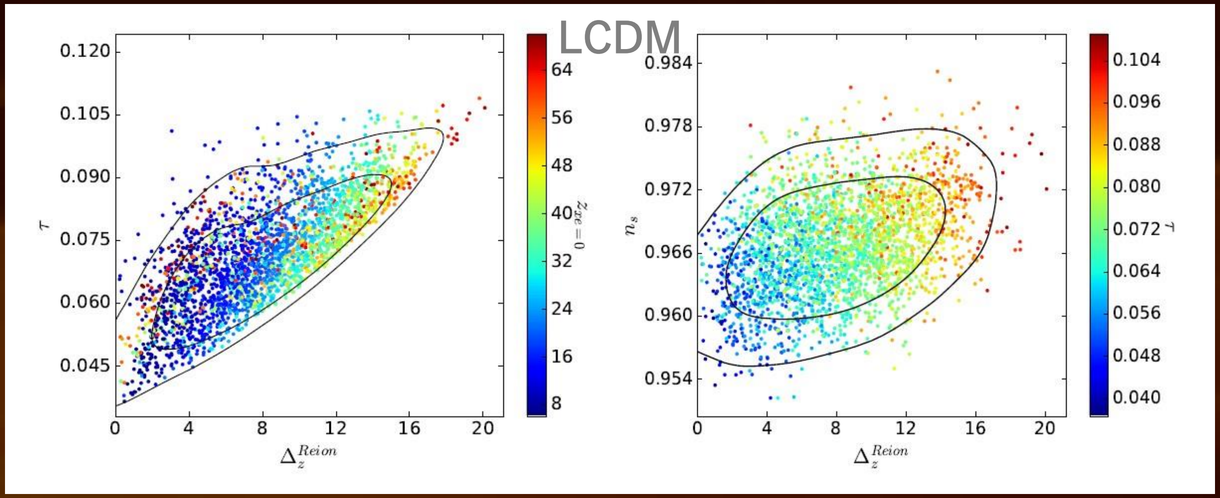
When we instead assume a more free model of reionization as the Poly-Reion the significance of the detection is decreased by more than one sigma especially for the suppression-like model.

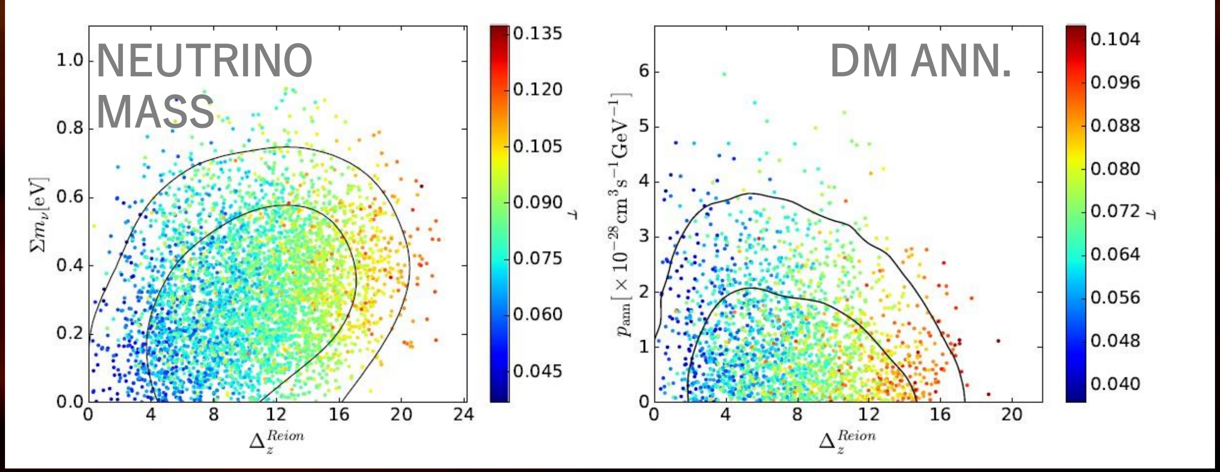
Hazra, Paoletti, Finelli, Ballardini, Shafieloo, Smoot, Starobinsky 2018

Planck 2015 – Opening up degeneracies

Hazra, Paoletti, Finelli, Smoot 2018

With a sensitivity like the one of Planck 2015 the adoption of an extended cosmological model opened up strong degeneracies also for both the standard cosmological model and its basic extensions as neutrino mass e dark matter annihilation





Planck 2018 and Poly-Reion Still degeneracies?

Paoletti, Hazra, Finelli, Smoot 2018

We assume a Poly-Reion model for reionization with four nodes:
-z=0 and z=5.5 we assume the reionization is over. This is a conservative approach that considers the possibility to still have residual reionization between 6 and 5.5
-z_int an intermediate node with flexible position between z=5.5 and 30 and ionization fraction value
-z_xe=0 the node where reionization begins which has xe=0

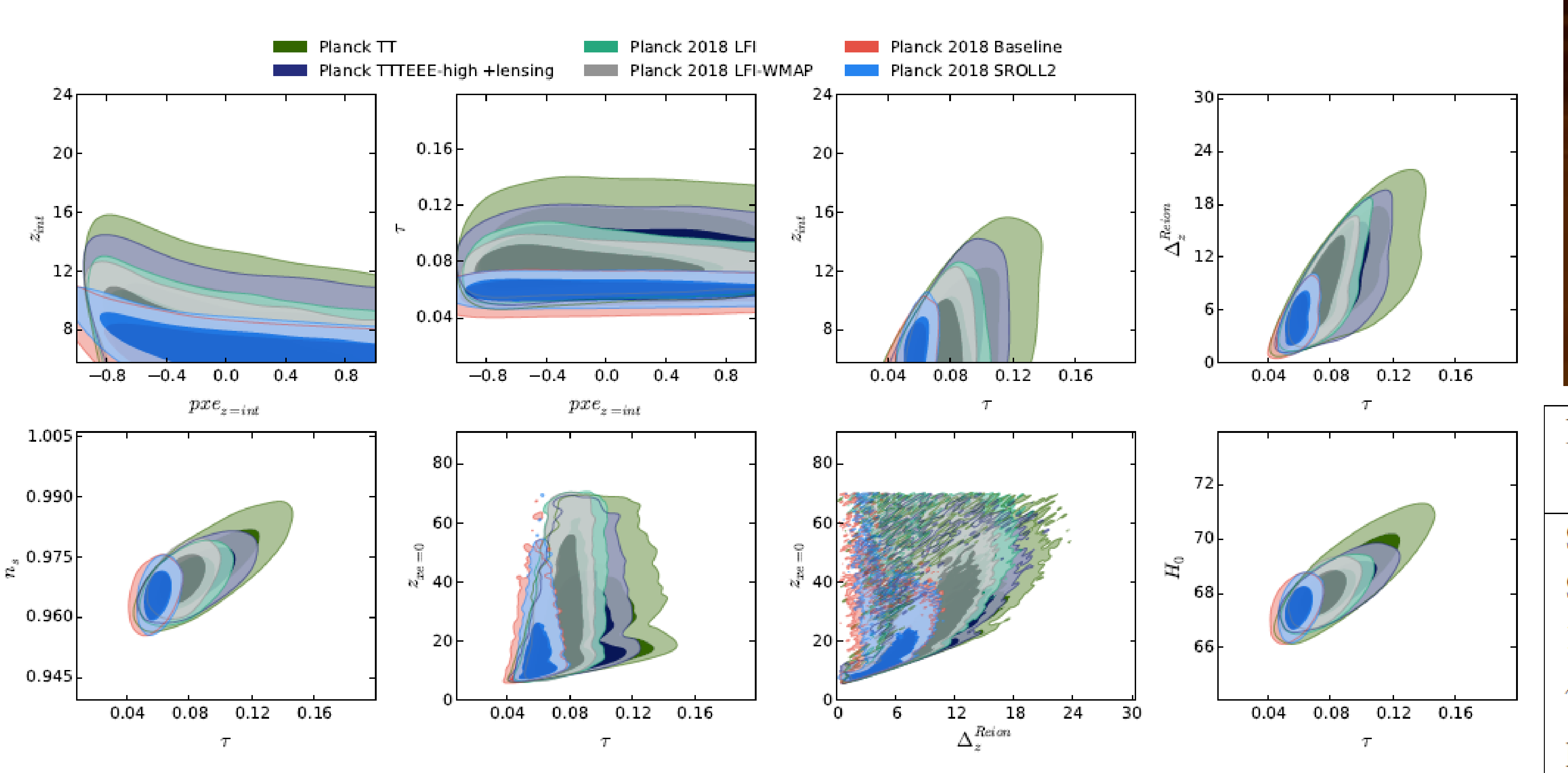
The three parameters which are varied together with the standard cosmological parameters are
-position of z_int
-value of xe in z_int between 0 and 1
-optical depth

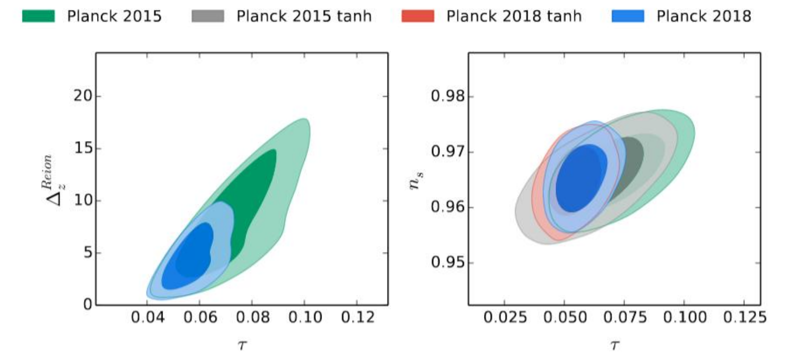
Given z_int and xe(z_int) we solve for the beginning of reionization z(xe=0) integrating for the optical depth between z_int and z=70

Having a single flexible node by construction we are allowing only for monotonic histories of reionization on the basis of previous results.

Regarding Helium I and Helium II reionization we use the same approach as Planck Baseline
standard hyperbolic tangent form with the first helium reionization at the same
time as the hydrogen and the second at redshift of 3.5 as in Planck baseline.

LCDM – Testing the power and consistency of Planck 2018





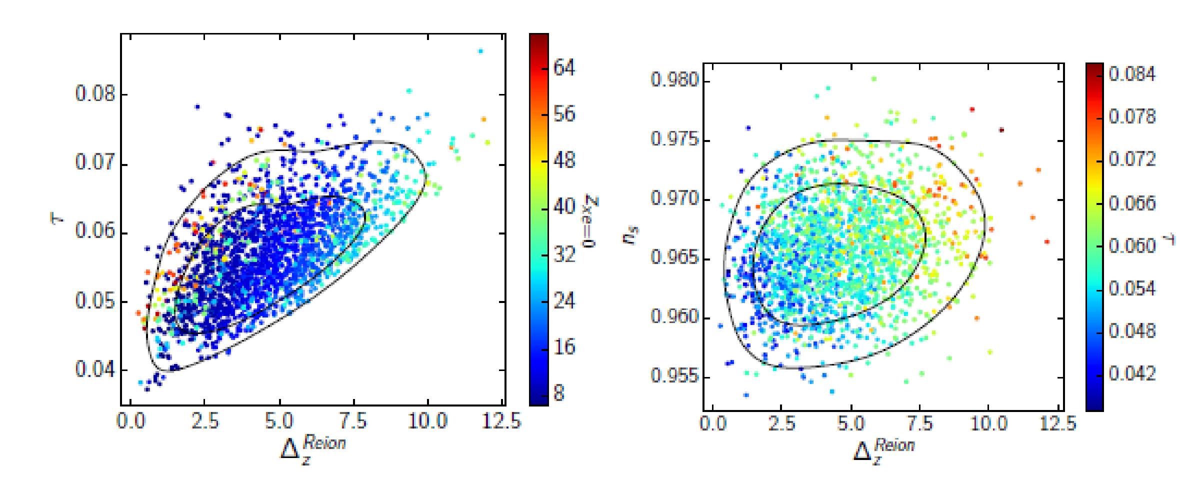
Parameter/Data	Planck TTTEEE + lowE + lensing
Ω_b	0.0224 ± 0.0001
Ω_c	0.120 ± 0.001
$100\theta_{MC}$	1.0409 ± 0.0003
τ	$0.0572^{+0.0064}_{-0.0075}$
$\ln(10^{10} A_s)$	3.05 ± 0.01
n_s	0.9656 ± 0.0041
H_0	67.46 ± 0.54
$z_{\rm re}$	$7.24^{+0.74}_{-1.11}$
$z_{xe=0}$	$18.18^{+1.61}_{-10.89}$
$\Delta_z^{\rm Reion}$	$4.59^{+1.67}_{-2.45}$

Back to the jungle!

We have analysed several different data combinations based on Planck 2018 in the Poly-Reion model

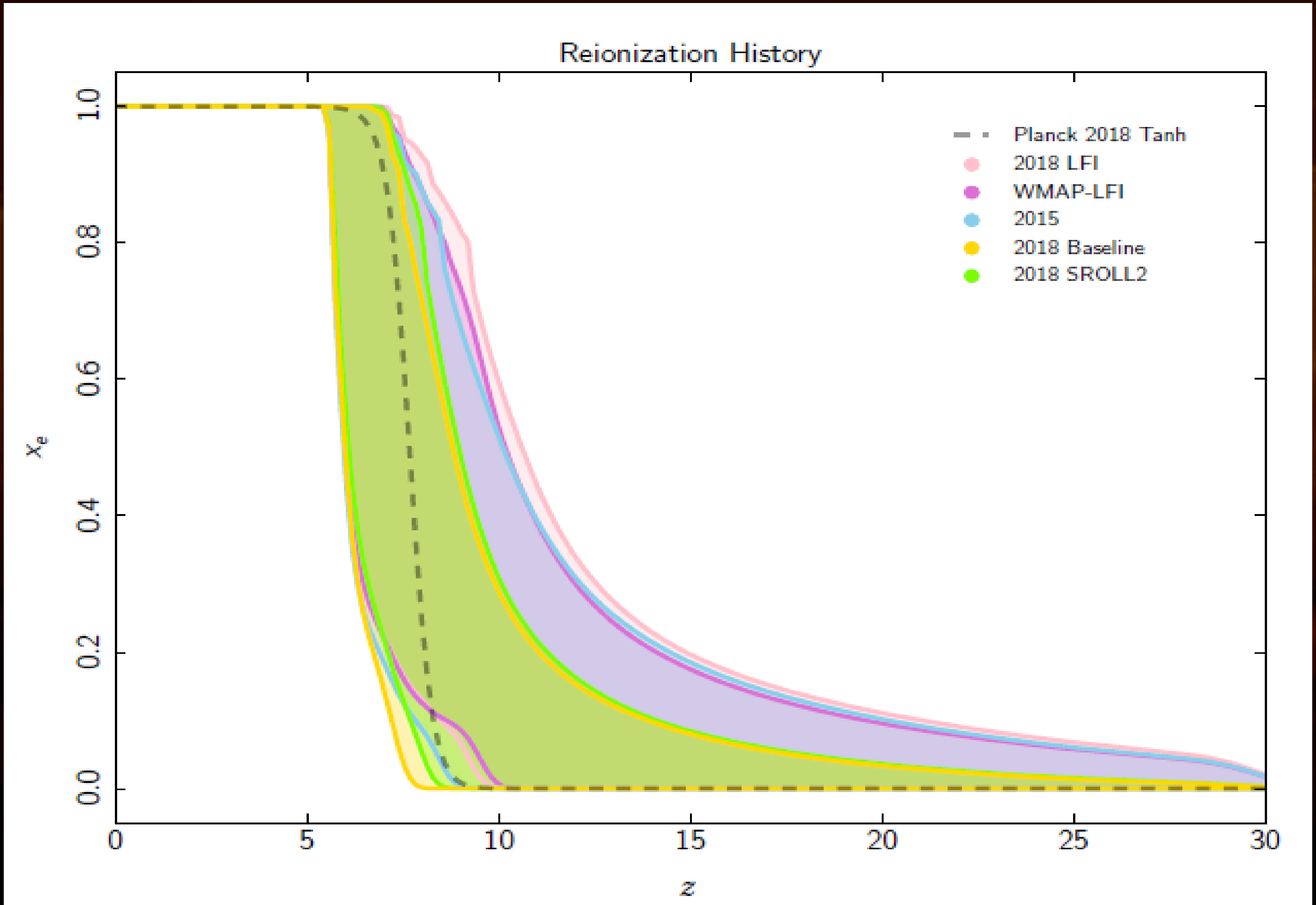
Dataset	P2018 BASELINE	P2018 SROLL2	P2018 LFI	P2018 Planck+WMAP
Optical depth	$0.057^{+0.006}_{-0.008}$	$0.060^{+0.005}_{-0.006}$	0.078 ± 0.012	0.076 ± 0.009
Duration of reion.	$4.59^{+1.67}_{-2.45}$	$5.09^{+1.77}_{-2.29}$	$9.21^{+3.62}_{-4.24}$	$8.85^{+3.36}_{-3.52}$

We have an overall consistency of the different branch and reanalises of Planck 2018 data



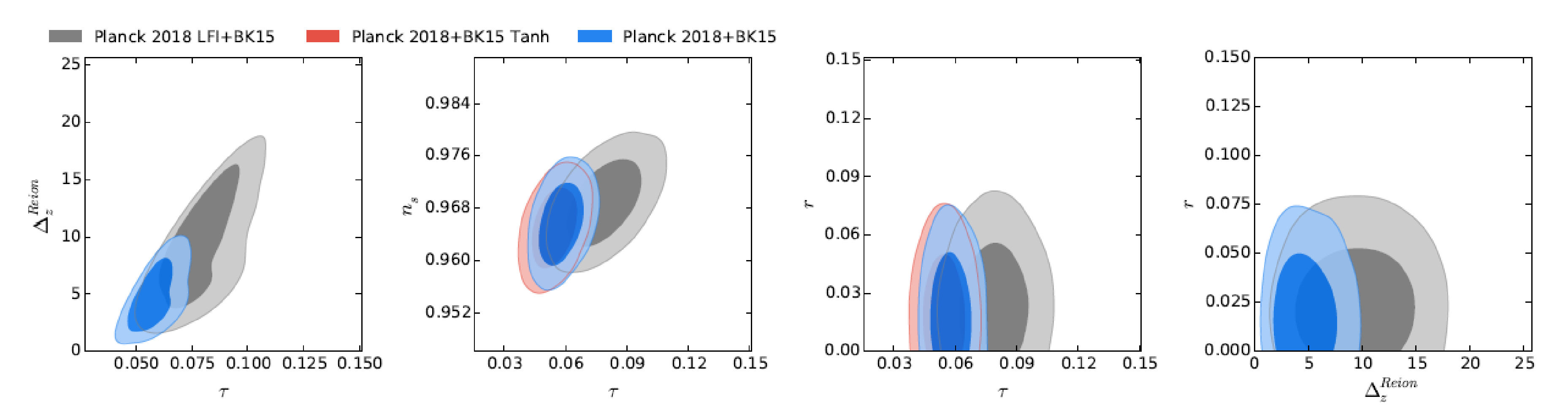
Polyreion consistently prefer higher values of the optical depth with respect to the hyperbolic tangent.
This is due to the freedom in the duration of the reionization

The longer the reionization/ the earlier the onset the larger is the optical depth

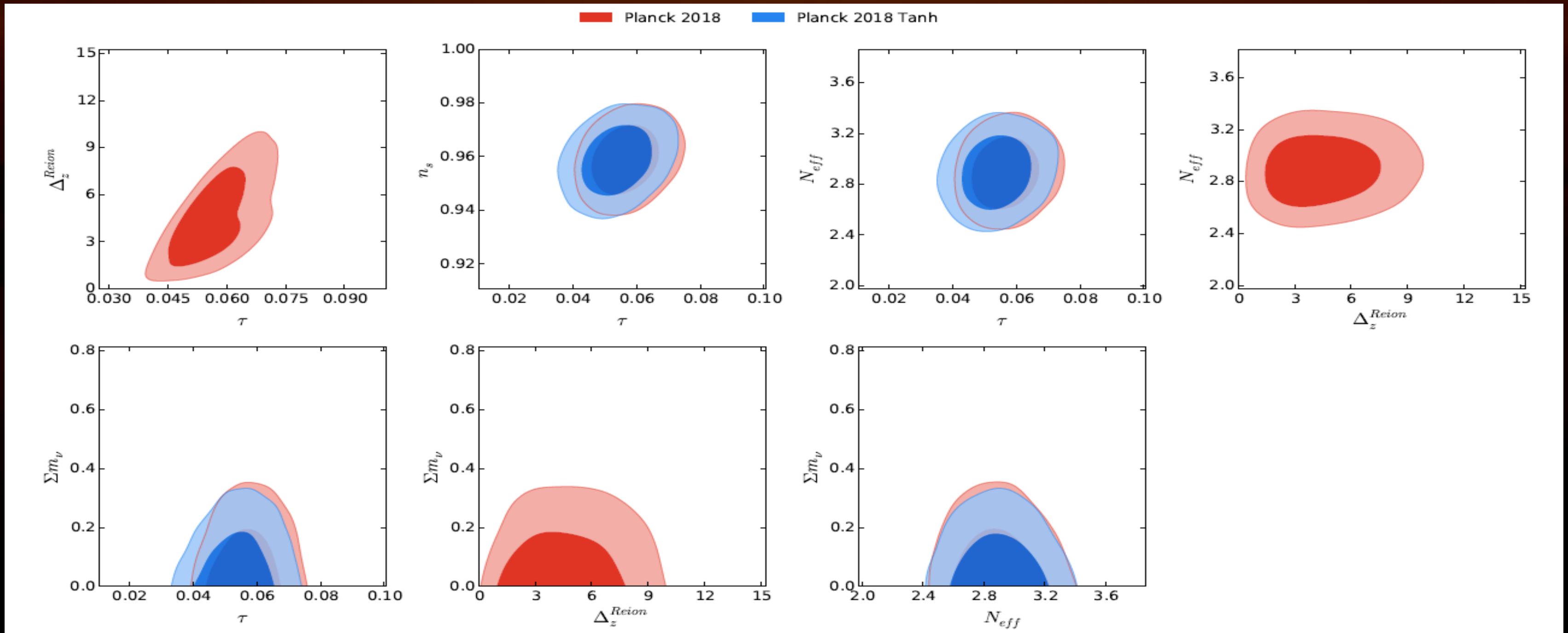

Reionization History
Planck 2018 Tanh
2018 LFI
WMAP-LFI
2015
2018 Baseline
2018 SROLL2
x_e
z
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
30

EXTENSIONS – I

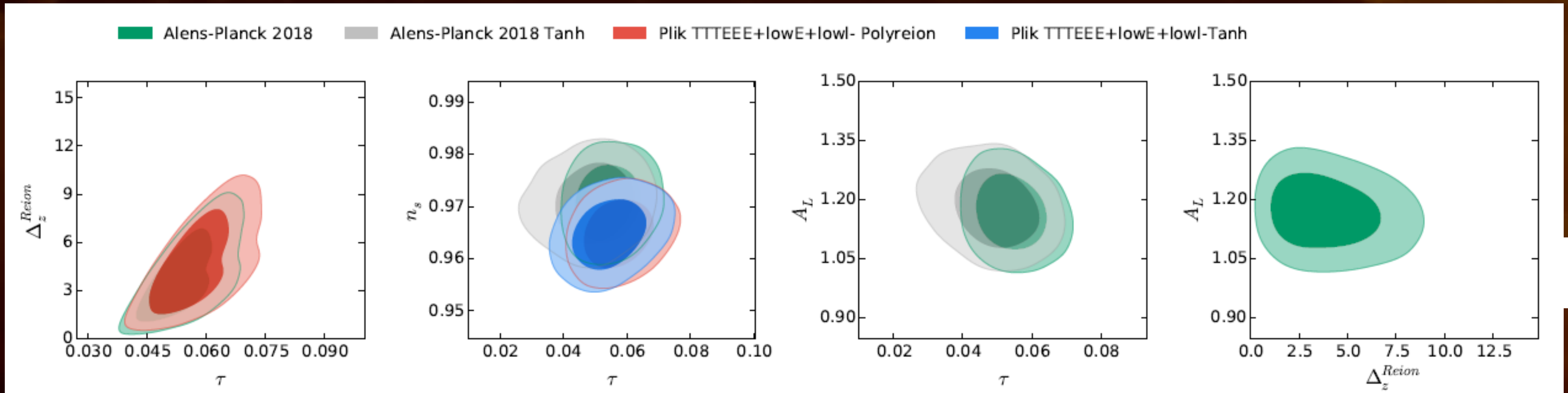
LCDM+TENSORS



NEUTRINO PHYSICS



The accuracy of Planck 2018 large scale polarization data seem to remove the degeneracies of the extended reionization model with the standard extensions of the LCDM
So, have we already managed to disentangle the reionization model from the cosmological model?
If we have cured the main extensions indeed some degeneracies remain with the most complex models

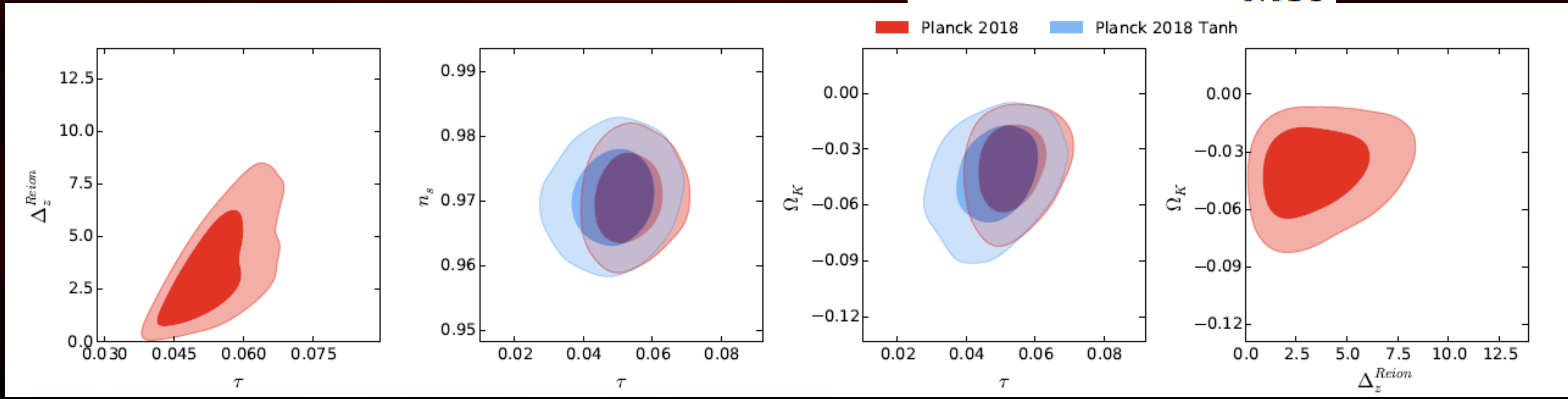


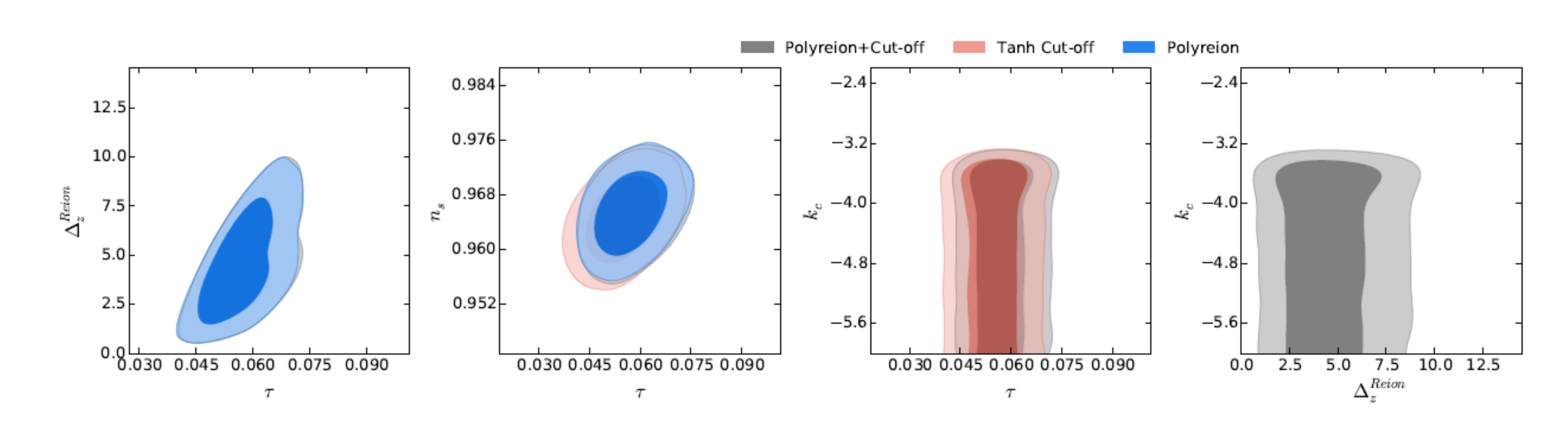
Alens and spatial curvature

$$A_L = 1.17^{+0.06}_{-0.07}$$

$$\Omega_K = -0.040^{+0.017}_{-0.014}$$

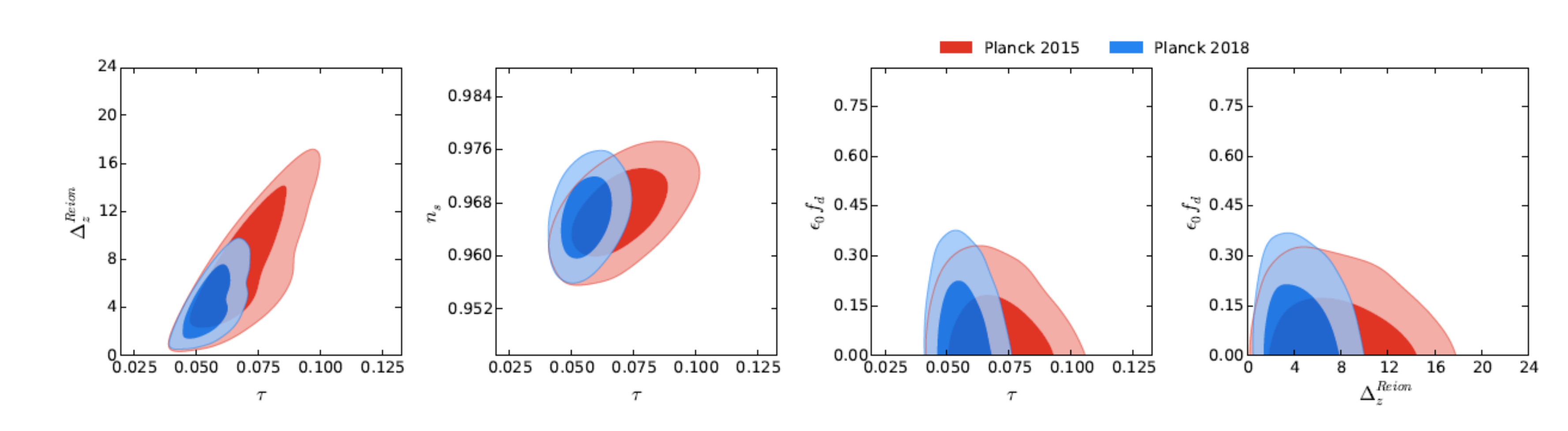
Poly-Reion tendency to increase the optical depth counteracts the pull of these models towards lower values somehow reducing the deviations from the LCDM





Large Scale Cut Off

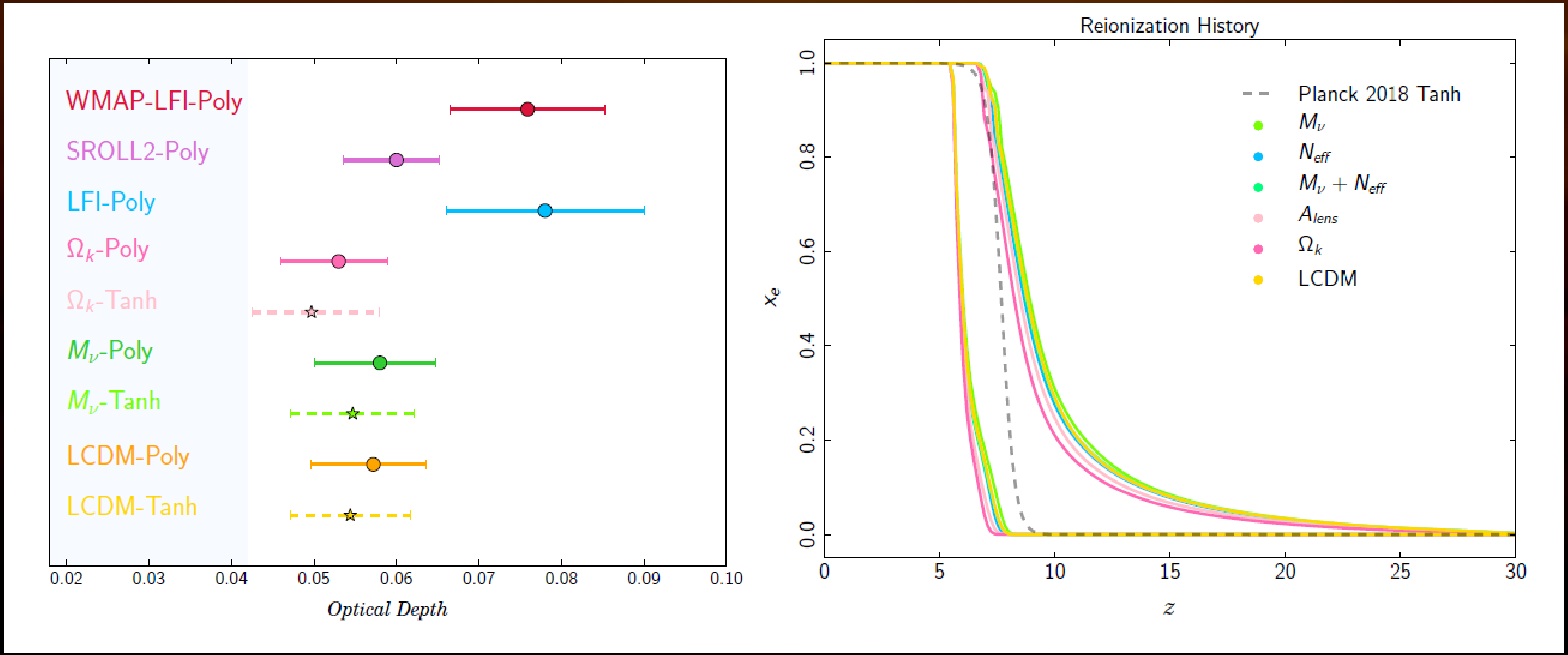
$$P(k) = P_0(k)\left[1 - \exp - \left(\frac{k}{k_c}\right)^{\lambda_c}\right],$$



DM annihilation

Reionization represents one of the greatest uncertainty in cosmology. The precision of current polarization data has allowed the removal of many degeneracies with the main extensions of the cosmological model **but some related to crucial models as spatial curvature still remain and uncertainties with complex models as primordial features will not be solved even by future generations as COrE-like experiments.**

It is therefore crucial in the future to test the extensions of the standard cosmological model against extended reionization




After the dawn

THE BEST OF BOTH WORLDS

We can gather information on EoR from two astrophysical observables (among many others):
QSO with Ly-alpha absorption or damping wing profiles
UV emission from Galaxies which represents one of the main contributors to the EoR

While these astrophysical probes provide insights on the end of Reionization (especially quasars because absorption requires minimal HI fractions), the CMB is instead affected by the whole history integrated.

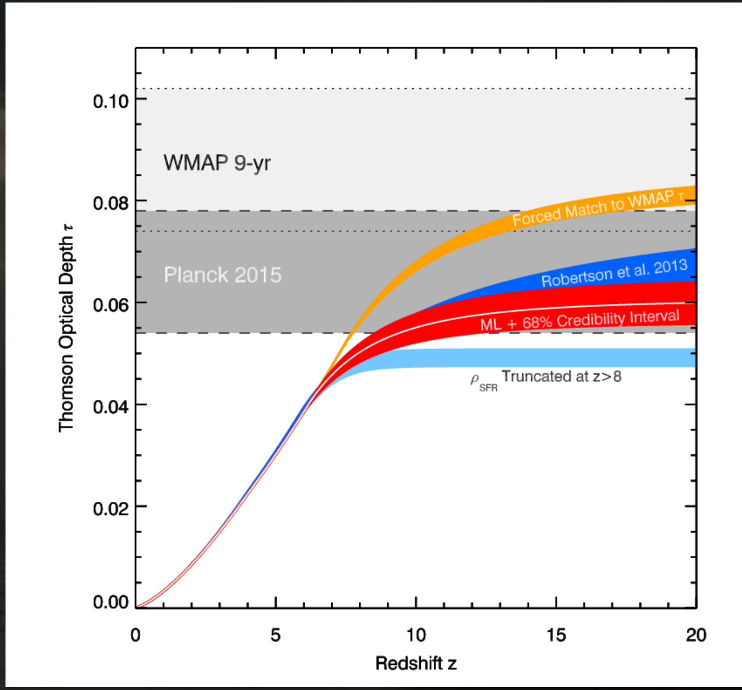
The two classes of probes are sort of complementary -the CMB is sensitive to the timing of EoR whereas astrophysical probes map its end.-

The reduced optical depth of Planck 2018 data to 0.0544 points to a later reionization in overlaps with the astrophysical probes.

Planck has indeed reconciled the value of the optical depth from CMB with the values predicetd by astrophysical sources!

Combining the two sets may represent a win win solution.
CMB constraints that region in redshift which will never be covered by astrophysical data and astrophysical data can provide a transversal probe that helps removing degeneracies with the cosmological model assumed.

We can therefore jointly constrain Cosmology and EoR by taking the best of both worlds



Robertson+2015

ASTROPHYSICAL OBSERVATIONS

Shape of UV luminosity densities

Hubble Frontier Fields (HFF): galaxies at high redshifts (z ~ 6–10), mainly with recent six cluster observations (Abell 2744, MACSJ0416, MACSJ0717, MACSJ1149, AbellS1063, and Abell370) *– Coe+2015, Lotz+ 2017, Livermore+ 2017-*

Remaining Neutral Hydrogen Measurements in IGM

Quasars: Gunn-Peterson optical depth *–Fan+2006,Fan+2006-*, ionized near the zone around high redshift quasars *–Mortlock+2011,Bolton+2011* -, dark gaps in quasar spectra *-McGreer+ 2015-*, damping wings of gamma-ray burst 050904 *–Totani+2006,McQuinn+2008-* and quasars *-Schroeder+2013, Greig+2017-*, Lyman-α emitters *-Davies+2018,McQuinn+2007,Ouchi+2012-* , and Lyman-α emission from galaxies *-Ono+2012,Caruana+2014,Schenker+2014,Tilvi+2014,Pentericci+2014,Sobacchi&Mesinger 2015,Mason+2018,Mason+2019-*

In order to combine CMB and Astrophysical data we cannot anymore fit for the ionization fraction because it would not be suitable for UV data.

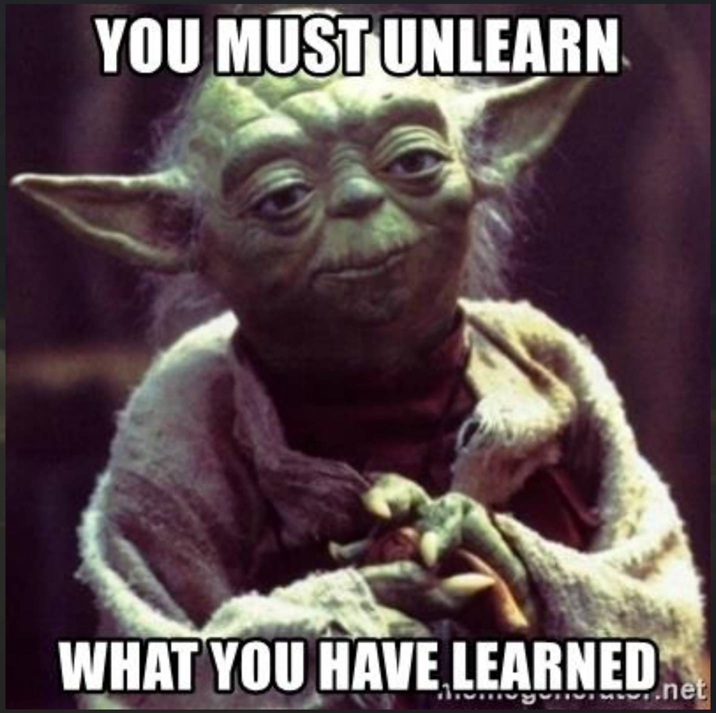
The only way is change the paradigm

We do not try to reconstruct directly the ionization fraction but we solve directly for the volume filling equations

We do not fit the results but we fit its sources through a non parametric reconstruction of the reionization history

The use of CMB allows to co-vary all the cosmological model accounting for all the possible correlations and to investigate possbile degeneracies

See –Ishigaki+2018,,2015,Mitra+ 2012,2015,2018 ;Ishigaki+2015,2018; Gorce+2018,Price+2016,Bouwens+2015,Robertson+2010,2015,Greig & Mesinger2018-etc. for analyses with fixed cosmology-



FREE FORM RECONSTRUCTION

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Combine CMB+UV+Neutral fraction

Solve for the volume filling equations.

The reionization process proceeds through the unbalance between the ionization source and the recombination time

$$\frac{dQ_{\rm HII}}{dt} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H}\rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}}$$

These are the quantities we are going to fit with the data

SOURCE TERM

The source term $\dot{n}_{\rm ion}$ is the ionizing photon production rate and is the product of:

- $\rho_{\rm UV}$ the UV luminosity density
- $\xi_{\rm ion}$ the photon production efficiency
- $f_{\rm esc}$ the escape fraction

As a first analysis we fix $\log_{10}\langle f_{\rm esc}\xi_{\rm ion}\rangle = 24.85$

According *to Ishigaki et al. 2014 and 2018, Price et al 2016, Madau et al 2017*.

CMB has not power to constrain the escape fraction and therefore the parameter if left free to vary is generally uncostrained

RECOMBINATION TERM

$$t_{\rm rec} = 1/\left[C_{\rm HII}\alpha_{\rm B}(T)(1+Y_p/(4X_p))\langle n_{\rm H}\rangle(1+z)^3\right]$$

- $C_{\rm HII}$ Clumpiness factor accounts for the higher probability of recombination in a denser environment
- $\alpha_{\rm B}(T)$ Recombination coefficient
- $\langle n_{\rm H}\rangle$ Density of Hydrogen

Our approach consists in varying as free parameters the UV luminosity density and the recombination time.
The optical depth for this kind of treatment is a derived parameters which is computed from:

$$\tau = \int_0^{z_{\rm begin}} \frac{c(1+z)^2}{H(z)} Q_{\rm HII}(z)\sigma_{\rm Thomson}\langle n_{\rm H}\rangle(1+\frac{Y_p}{4X_p})$$

SET UP

The UV and recombination time are fitted in different nodes connected by PCHIP polynomials.

Each node has three variables:

1. Redshift
2. UV luminosity density
3. Recombination time –sampled on the ratio $(1/t_{\rm rec})/(\dot{n}_{\rm ion}/\langle n_{\rm H}\rangle)$

Again we have fixed nodes at the beginning and end of reionization at z=30 and z=5.5 and z=0. In these nodes the values of source and recombination terms are fixed to be consistent to best fit logarithmic double power law from *Ishigaki et al 2014* and consistent with *Becker et al 2013*

DATA

-UV luminosity z=6-11 *Ishigaki+2018* –full 6 clusters HFF-. The density is obtained by integrating the UV luminosity function by fitting the Schechter function until a truncation magnitude of −17. This is a conservative assumption to avoid the flattening of the UV LF at the faint end

-Remaining neutral fraction *McGreer+ 2015,Totani+2006, McQuinn+2008, Schroeder+2013, Greig+2017, Davies+2018, McQuinn+2007, Ouchi+2012, Schenker+2014,Tilvi+2014, Mason+2018, Mason+2019-*

CONFIGURATIONS:

- B0 –minimal case, single node with fixed recombination time $\dot{n}_{\rm ion} t_{\rm rec} = \langle n_{\rm H} \rangle$.
  - It represents monotonic power law histories
- B1 –single node case
  - It represents the possibility to have a step-like history
- B2 –two nodes
  - Possibility of non monotonic histories
- B3 – three nodes
  - Possibilities of non-monotonic histories

To ensure the consistency of the approach the range in redshift of the different nodes are conditional one to the other in order to maximize the impact of the data

- B0 and B1 the node is free to vary between z=5.5 and z=30
- B2 the first node varies between z=5.5 and z=12 in order to incorporate the UV data and be sensitive to them. The second node varies between z=12 and z=30 to explore the CMB dominated tail
- B3 the first two nodes vary between z=5.5-8 and z=8-12 and are designed to capture any suppression or break in the power of the luminosity densities. The third node is for the CMB z=12-30.

CONSTRAINTS

With our setup we run the constraints on the reionization history together with the parameters of the standard cosmological model and the nuisance and foreground parameters included in the Planck likelihood.

Model and data		P18	P18 + UV17	P18 + UV17 + QHII
*B*0	$\chi^2_{\rm eff}$	2779.9	2783.4	2792
	$\ln B$	0	0	0
	τ	$0.051^{+0.006}_{-0.009}$	0.05 ± 0.001	0.051 ± 0.001
	$\Delta_z^{\rm reion}$	$3^{+0.79+2.0}_{-1.2-1.8}$	$2.8^{+0.11+0.27}_{-0.15-0.25}$	$2.9^{+0.12+0.29}_{-0.16-0.26}$
*B*1 1 node	$\chi^2_{\rm eff}$	2780.5	2782	2790.3
	$\ln B$	−0.4	−0.1	0
	τ	$0.052^{+0.006}_{-0.009}$	0.05 ± 0.001	0.051 ± 0.001
	$\Delta_z^{\rm reion}$	$3.08^{+0.77+2.1}_{-1.3-2.0}$	$2.8^{+0.11+0.31}_{-0.15-0.24}$	$2.9^{+0.12+0.29}_{-0.16-0.26}$
*B*2 2 nodes	$\chi^2_{\rm eff}$	2778.8	2782	2789
	$\ln B$	−2.2	−3.5	−3.2
	τ	0.05 ± 0.008	$0.049^{+0.007}_{-0.006}$	$0.052^{+0.0008}_{-0.002}$
	$\Delta_z^{\rm reion}$	$3.3^{+0.03+7}_{-2.7-3}$	$2.7^{+0.2+1.3}_{-0.32-0.8}$	$3.05^{+0.08+1.2}_{-0.53-0.7}$
*B*3 3 nodes	$\chi^2_{\rm eff}$	…	2781.8	2786.5
	$\ln B$	…	−6.6	−8.2
	τ	…	0.05 ± 0.005	$0.052^{+0.0006}_{-0.003}$
	$\Delta_z^{\rm reion}$	…	$2.9^{+0.086+4.3}_{-0.82-2.1}$	$2.86^{+0.07+1.5}_{-0.6-0.86}$

Bayes factor derived from the chains with MCEvidence *–Heavens+ 2017-*

The case B3 with only CMB does not provide constraints having two nodes too weakly coupled to the CMB range

There is very good agreement between the recovered values of the optical depth with also the results of P2018 demonstrating the very good agreement of CMB and astrophysical data.
Although improving the chisqr complex models of reionization are disfavoured by the Bayesian evidence

Consistency check by varying the escape fraction provides almost unchanged optical depth $\tau = 0.052 \pm 0.002$ 95% CL
Less conservative approach whcih varies the escape fraction and integrates to fainter objects the UV LF provides a slighlty higher tau value due to the pick up of faint sources contribution $\tau = 0.054 \pm 0.003$ 95% CL

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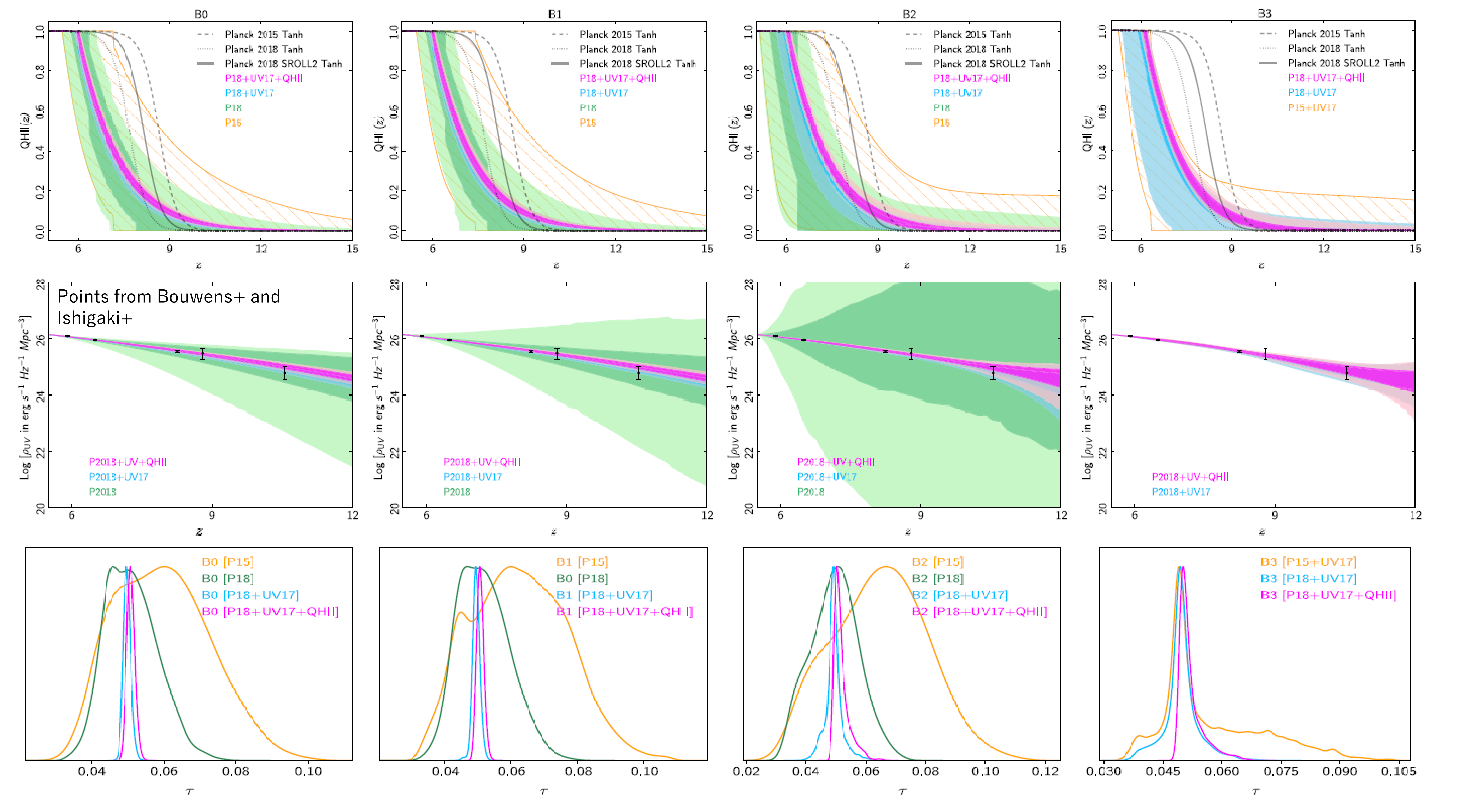

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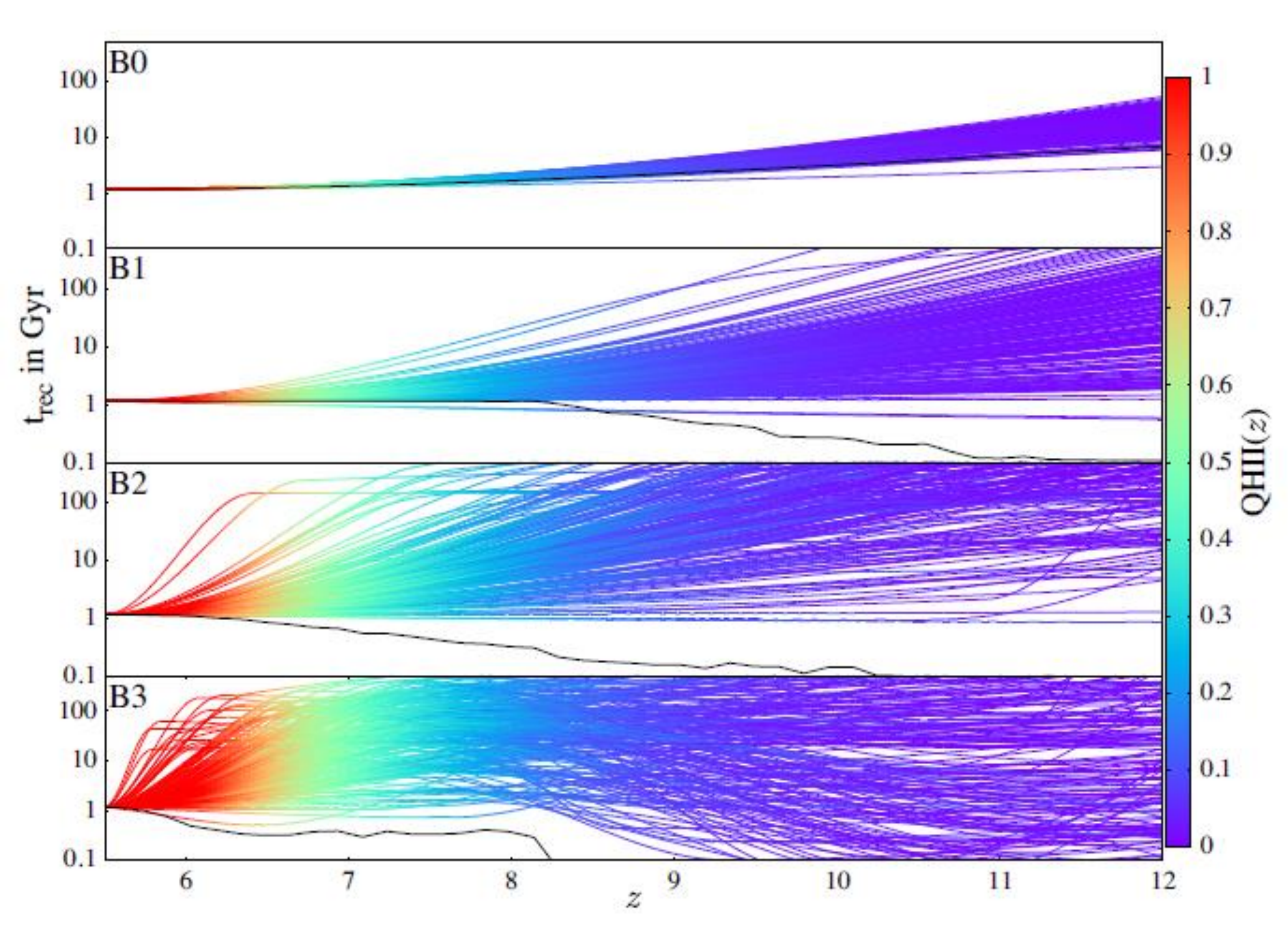

Black line is the 95%CL lower bound fromP2018+UV17+QHII

From the recombination time by assuming an IGM temperature we can reconstruct also the clumping factor at differen redshifts. Assuming T_IGM=20000 K, we find CHII ≲ 3 within 6<z< 8 and monotonically increasing with decreasing redshift. This result is completely consistent with

$$C_{\rm HII} = 2.9 \left[\frac{1+z}{6}\right]^{-1.1}$$

As fitted from sims Shull+2012

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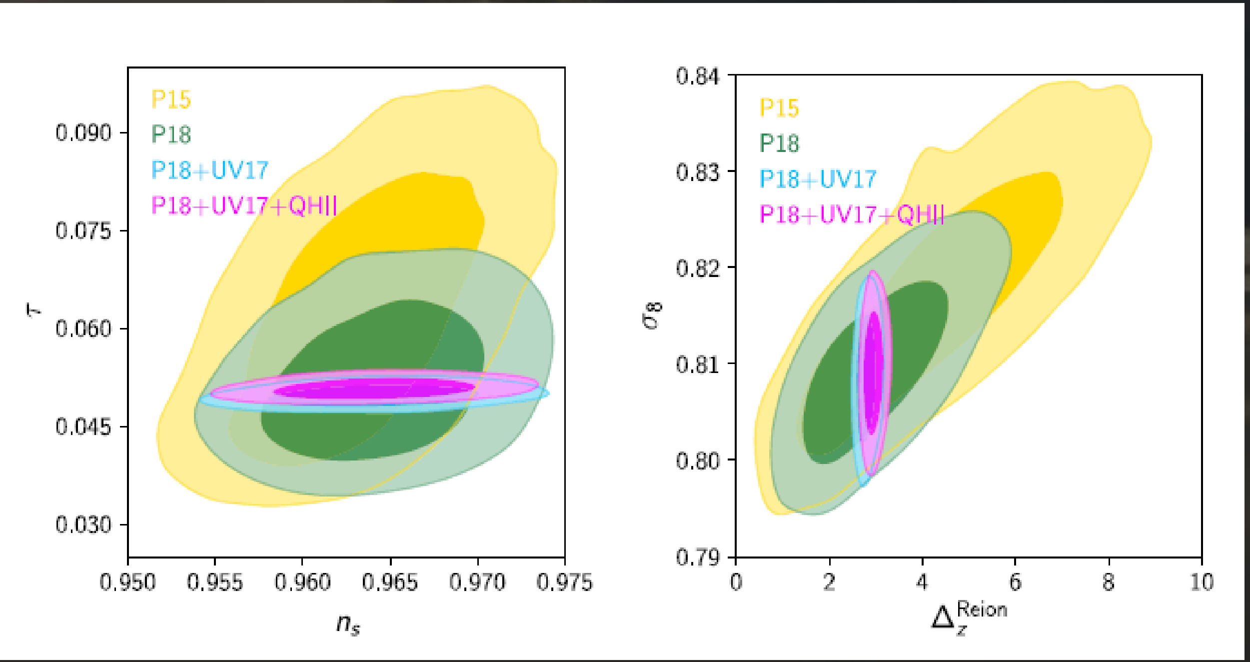
The combination of the improved data from Planck 2018 and the astrophysical data allows to remove almost all degeneracies of standard cosmological parameters with the reconstructed reionization history



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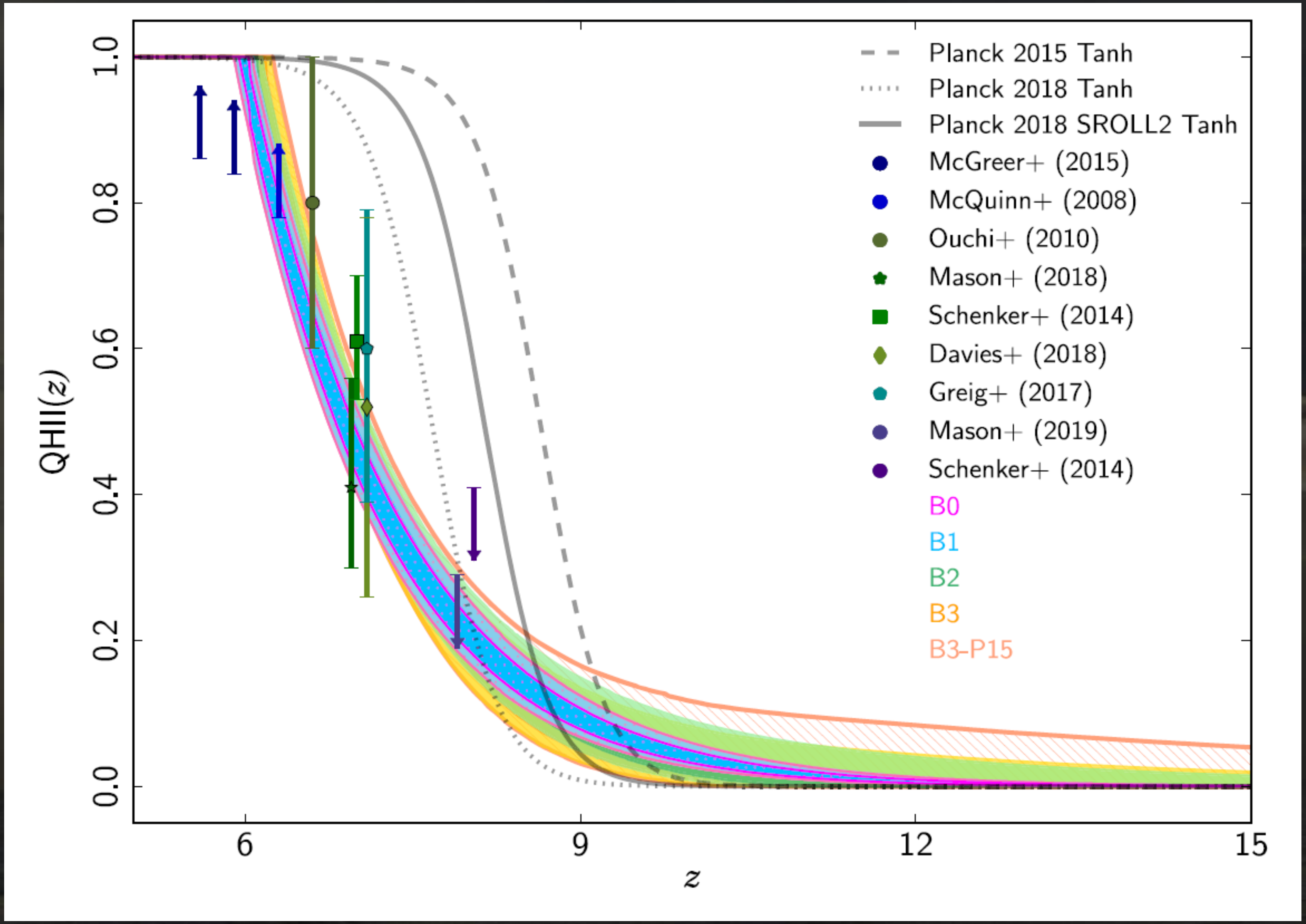

The results disfavour reionization histories beyond the simple monotonic case which is favoured by Bayesian evidence.

Sharp reionizations as the hyperbolic tangent model (Δ_z^{reion}= 1.7)tends to be disfavoured with a duration of reionization in the minimal case $2.6 < \Delta_z^{reion} < 3.2$

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CONCLUSIONS

Planck has been a game changer for reionization in cosmology. The most recent data have finally reconciled the optical depth value to the ones predicted by studying astrophysical observations.

After 17 years from the first determination by WMAP of 0.17 we now have a much lower value but still the optical depth is the parameter with the largest uncertainty in the CMB standard cosmological model. This is also remarked by the recent series of reanalyses of the Planck 2018 data that estimate slightly different values albeit consistent with each other within the error bars

The study of more physical models of reionization, beyond the conventional and unphysical tanh with fixed width, either with parametrized forms or reconstruction approach to the ionization fraction or to its evolution equation has been already explored for many of the available likelihoods, always finding that monotonous smooth ionization history are statistically preferred by CMB data.

CMB can be complemented by astrophysical probes of reionization, as happens with low redshift probes of structure formation, as BAO for instance. This additional handle is useful to break remaining degeneracies and can push the uncertainty in tau below the CMB cosmic variance measurements.

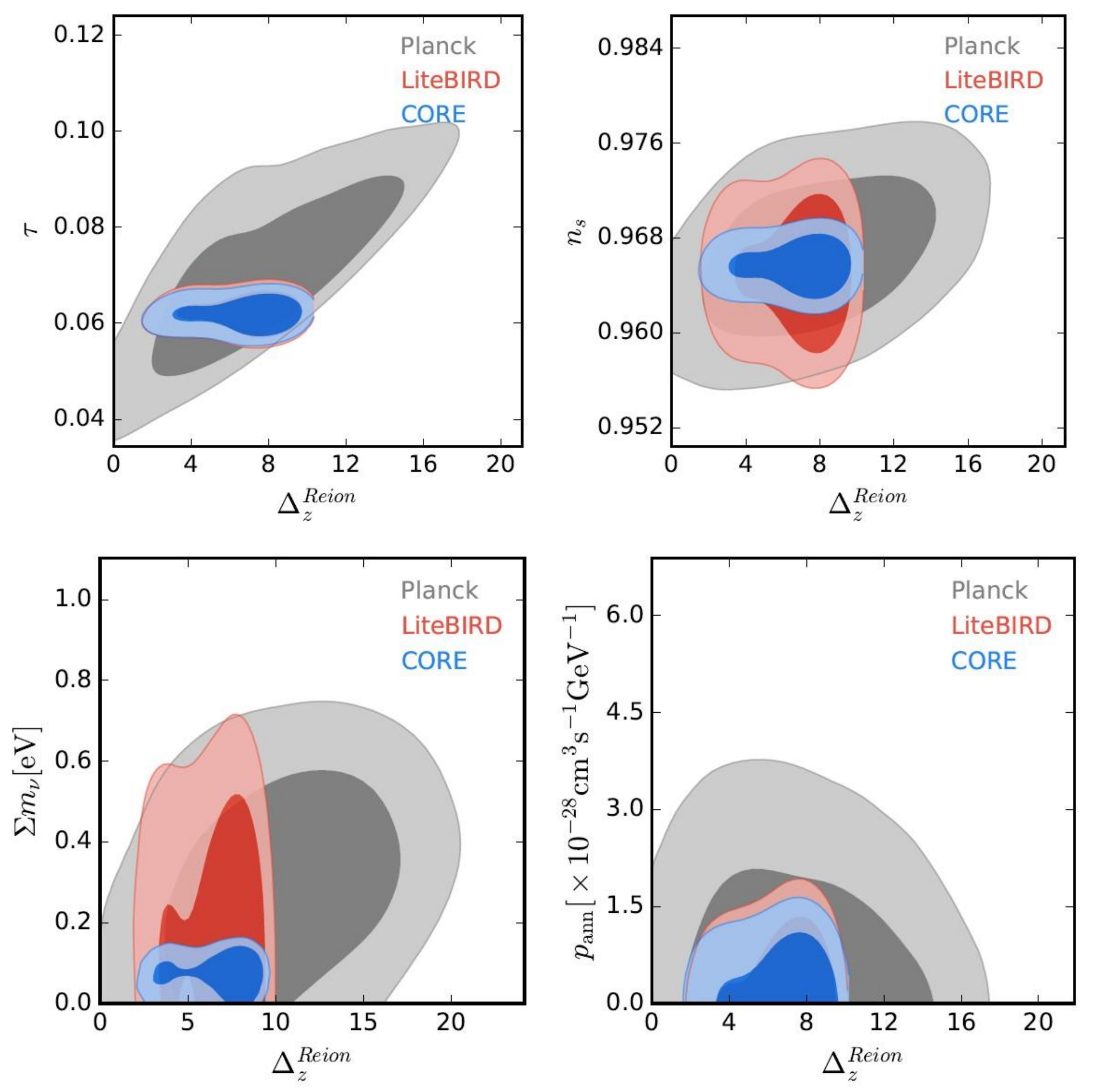
FUTURE PERSPECTIVES

With the future CMB experiments as LiteBIRD and Simons Observatory completely dedicated to the polarization of the CMB it will be crucial to consider reionization as an active part in the play when using the data to constrain cosmological models
Account for the effects of a non totally trivial history of reionization may decrease the significance of detection of deviations of the standard cosmological model and in this preparation times we will investigate its impact on more and more complex cosmological models.

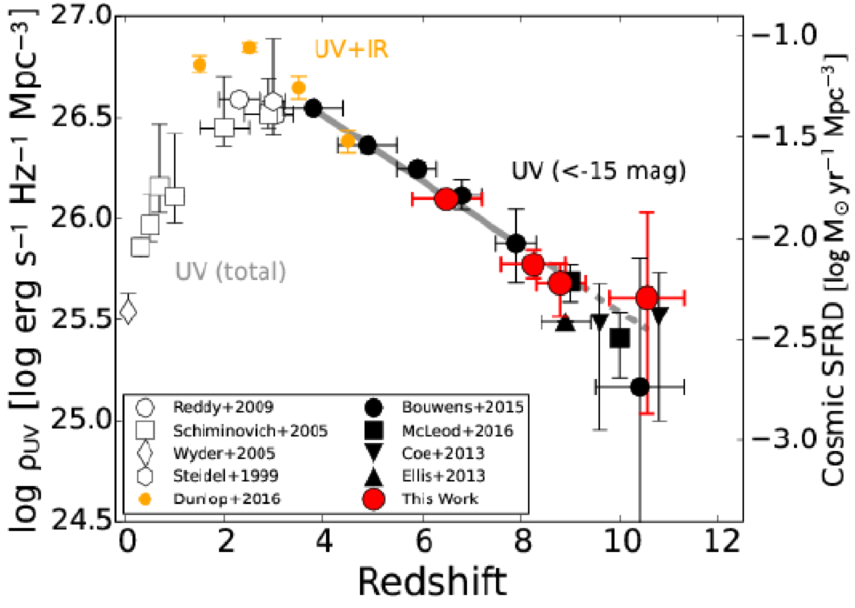
At the same time we are setting up the path for the future data to combine with CMB to reconstruct the reionization history jointly with cosmology.
Examples are the future data on UV luminosity density by JWST that will allow to populate the fainter region of the UV luminosity function determining possible shape changes which can affect the reionization history.
At the same time future data as the one by Theseus can allow to set more realistic priors and possibly provide joint constraints on the escape fraction increasing the robustness of these kind of analyses.

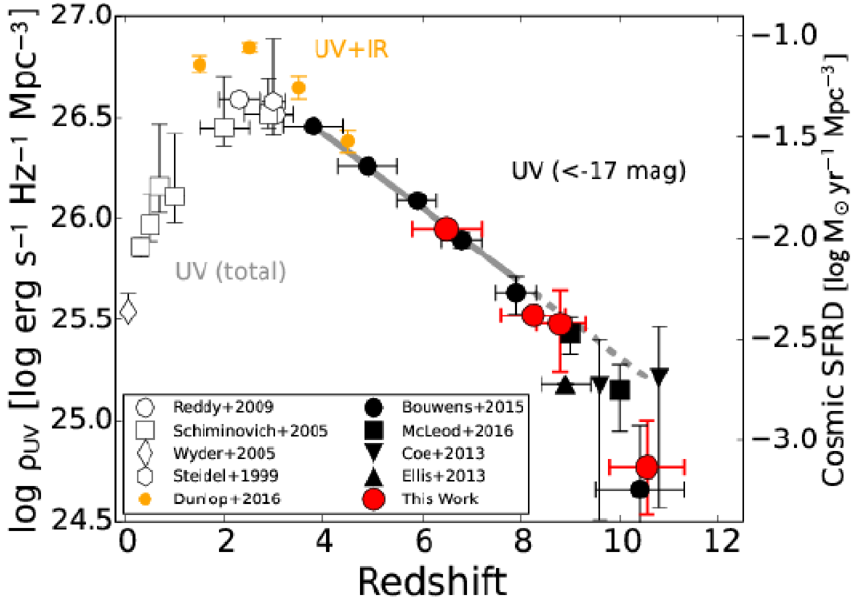
Stay tuned

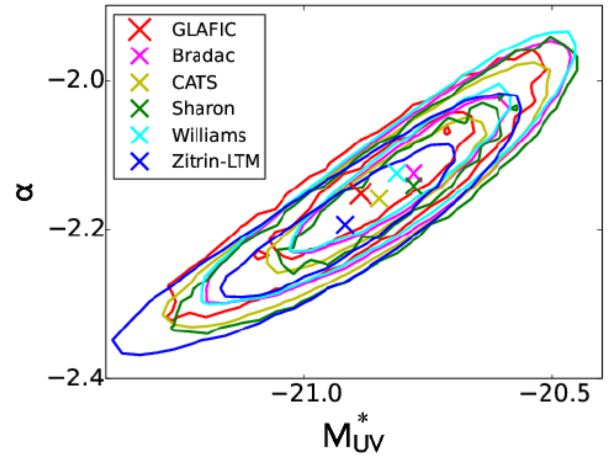
Backup slides



Planck
LiteBIRD
CORE
τ
0.12
0.10
0.08
0.06
0.04
0.984
0.976
0.968
0.960
0.952
n_s
0
4
8
12
16
20
Δ_z^{Reion}
$\Sigma m_\nu[\mathrm{eV}]$
1.0
0.8
0.6
0.4
0.2
0.0
5
10
15
$p_{\mathrm{ann}}[\times 10^{-28}\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{GeV}^{-1}]$
6.0
4.5
3.0
1.5







Ishigaki+ 2018