

3 July 2026

Challenges at the CMB frontier.

Title of the Talk:

**Unlocking Reionisation with Planck and WMAP low- ℓ
Polarisation: a Unified Likelihood approach**

Based on: [arXiv:2603.22454](https://arxiv.org/abs/2603.22454)

Presenting:

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Giacomo Galloni
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Researcher

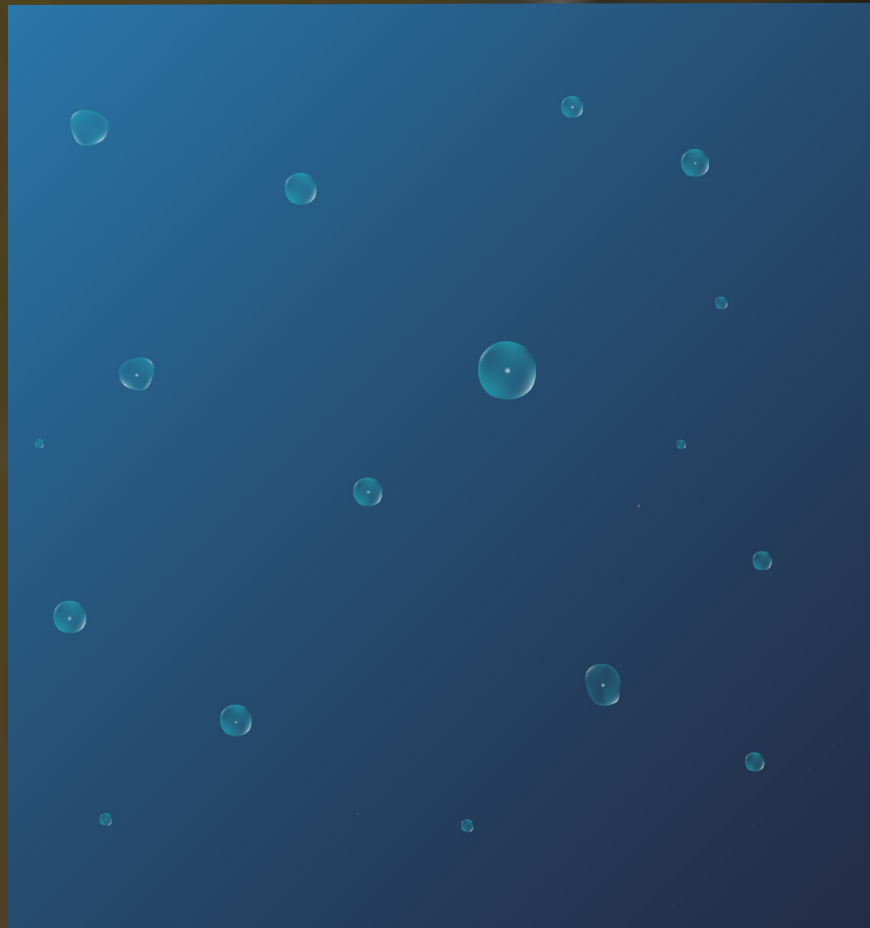


Massimiliano Lattanzi
Researcher

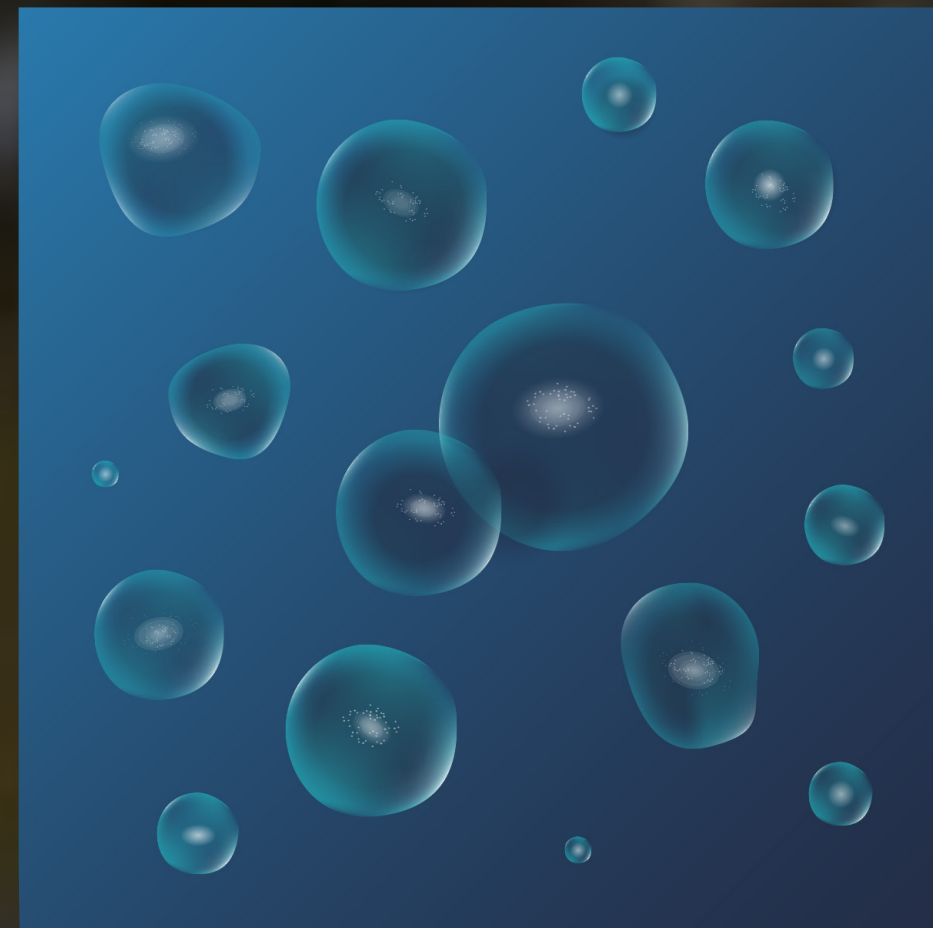
What is cosmic Reionisation?

$z \sim 15 - 20$

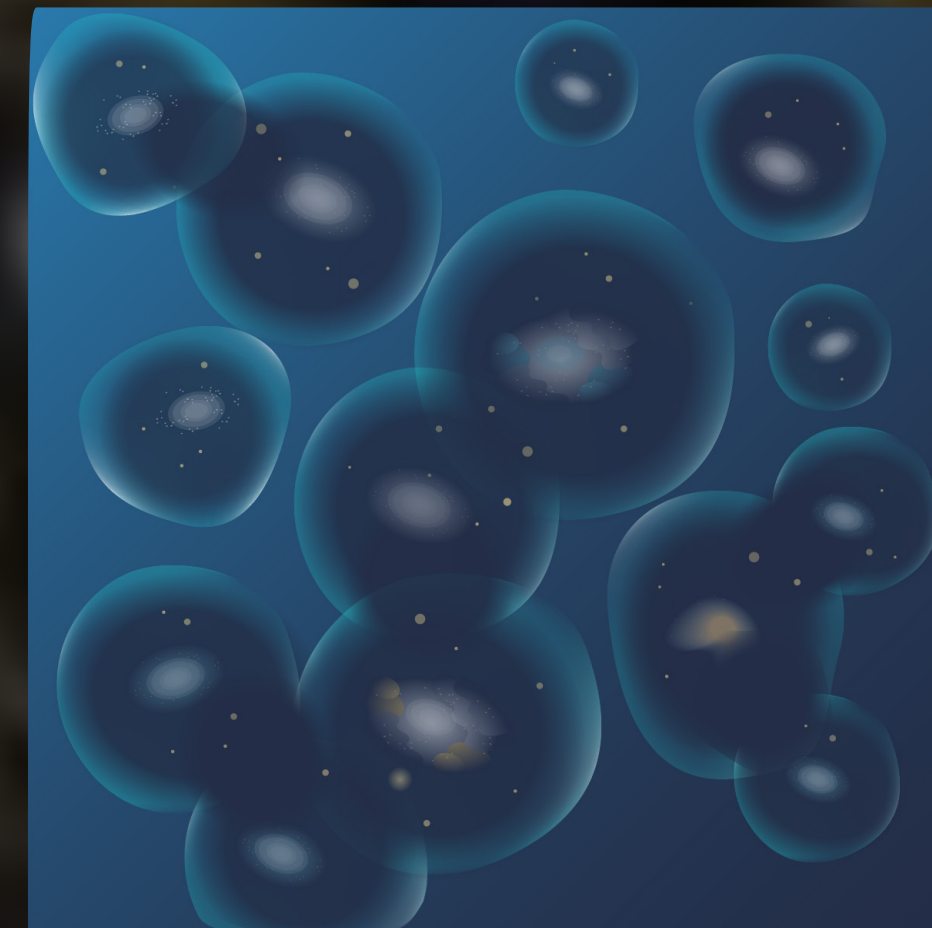
$z \sim 6$



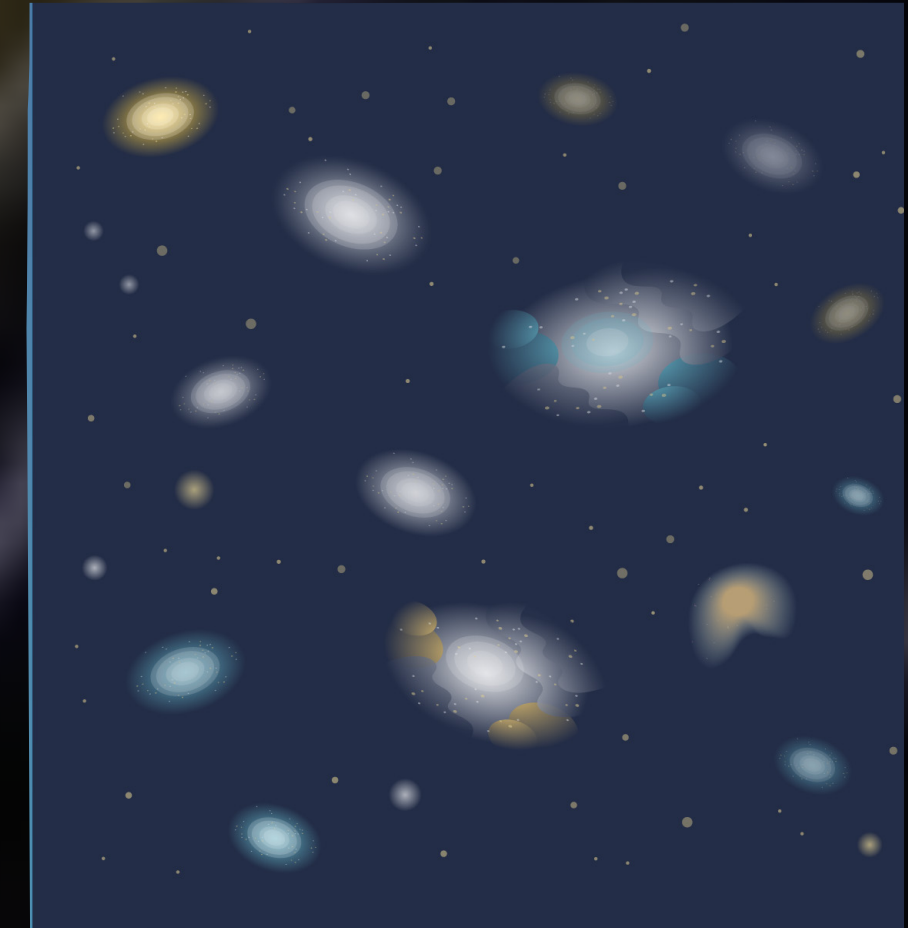
Stars form and
galaxies assemble



Galaxies begin to change
the gas around them



Areas of
transformed gas expand



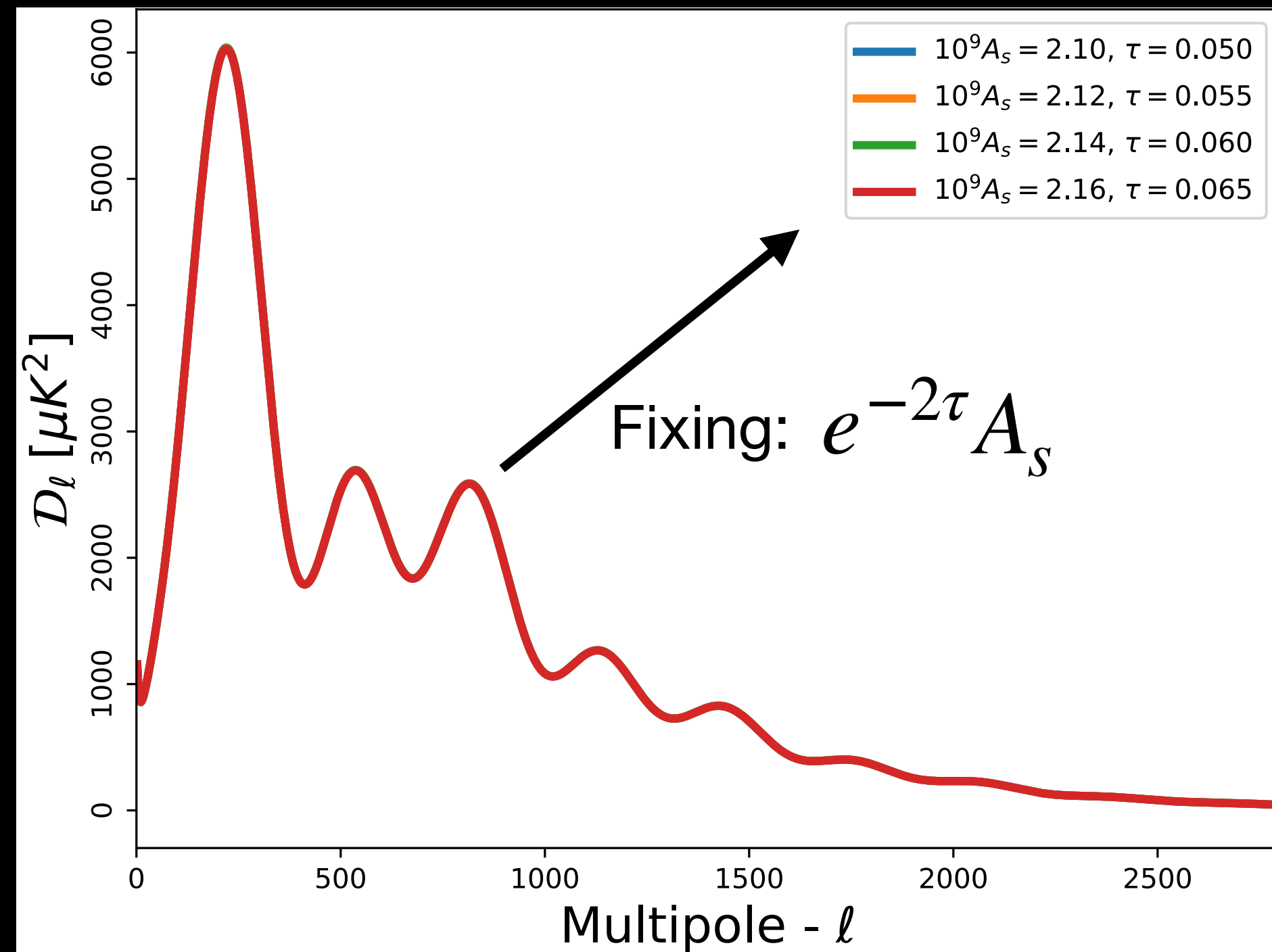
Clear universe,
end of reionization

The most common physical quantity
used to characterise reionisation is
the Thomson scattering optical depth

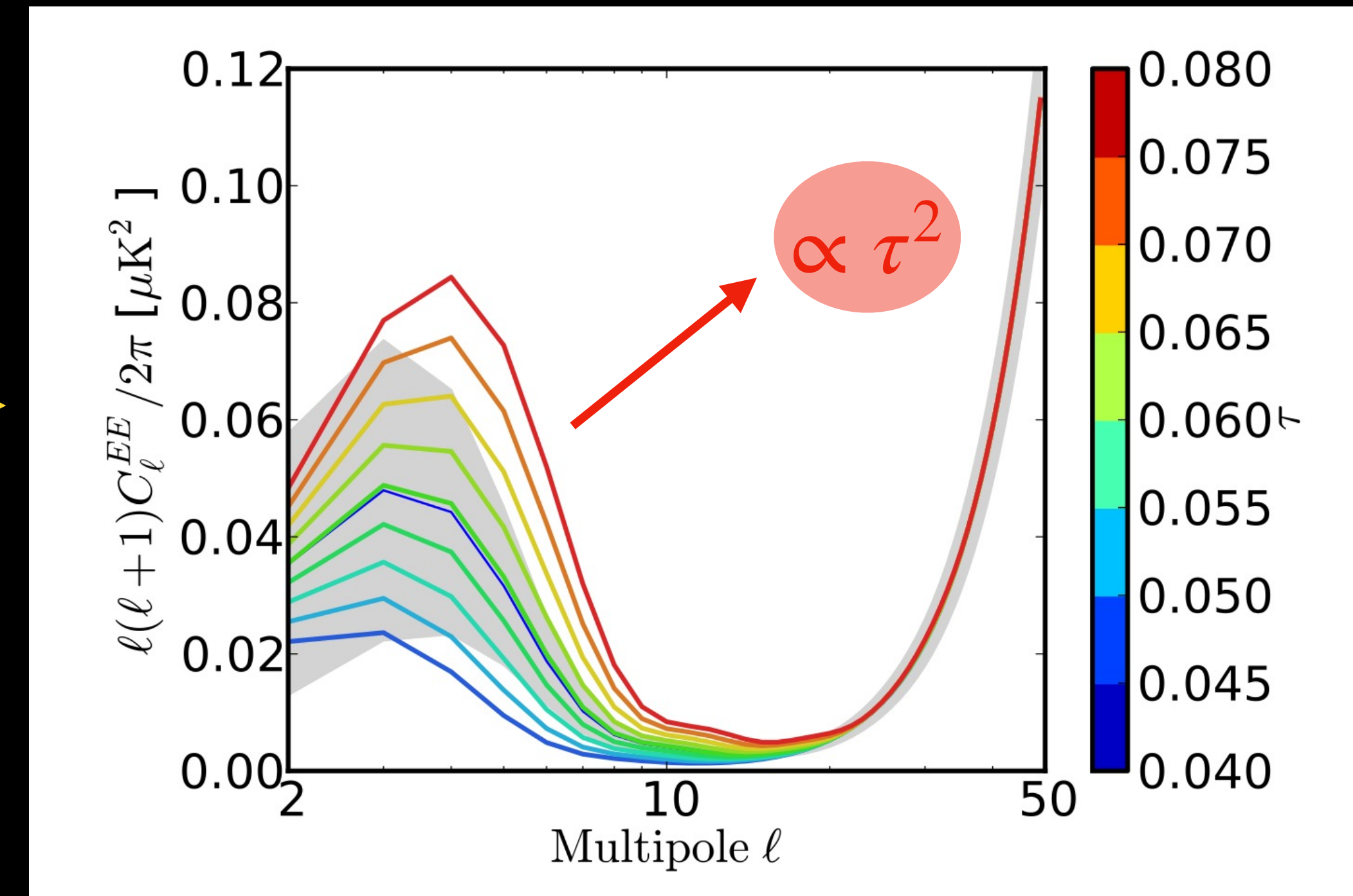
$$\tau = \int_{t(z)}^{t_0} n_e \sigma_T c dt'$$

How does reionisation affect CMB power spectra?

Free electrons during reionisation scatter CMB photons via Thomson scattering, much like what happened during decoupling.



**Breaking
the degeneracy**



Christian L. Reichardt et al. - *Observing the Epoch of Reionization with the Cosmic Microwave Background* (2016).

Is τ higher than we thought?

Recent James Webb Space Telescope observations have revealed unexpectedly massive and evolved galaxies at $z > 10$.

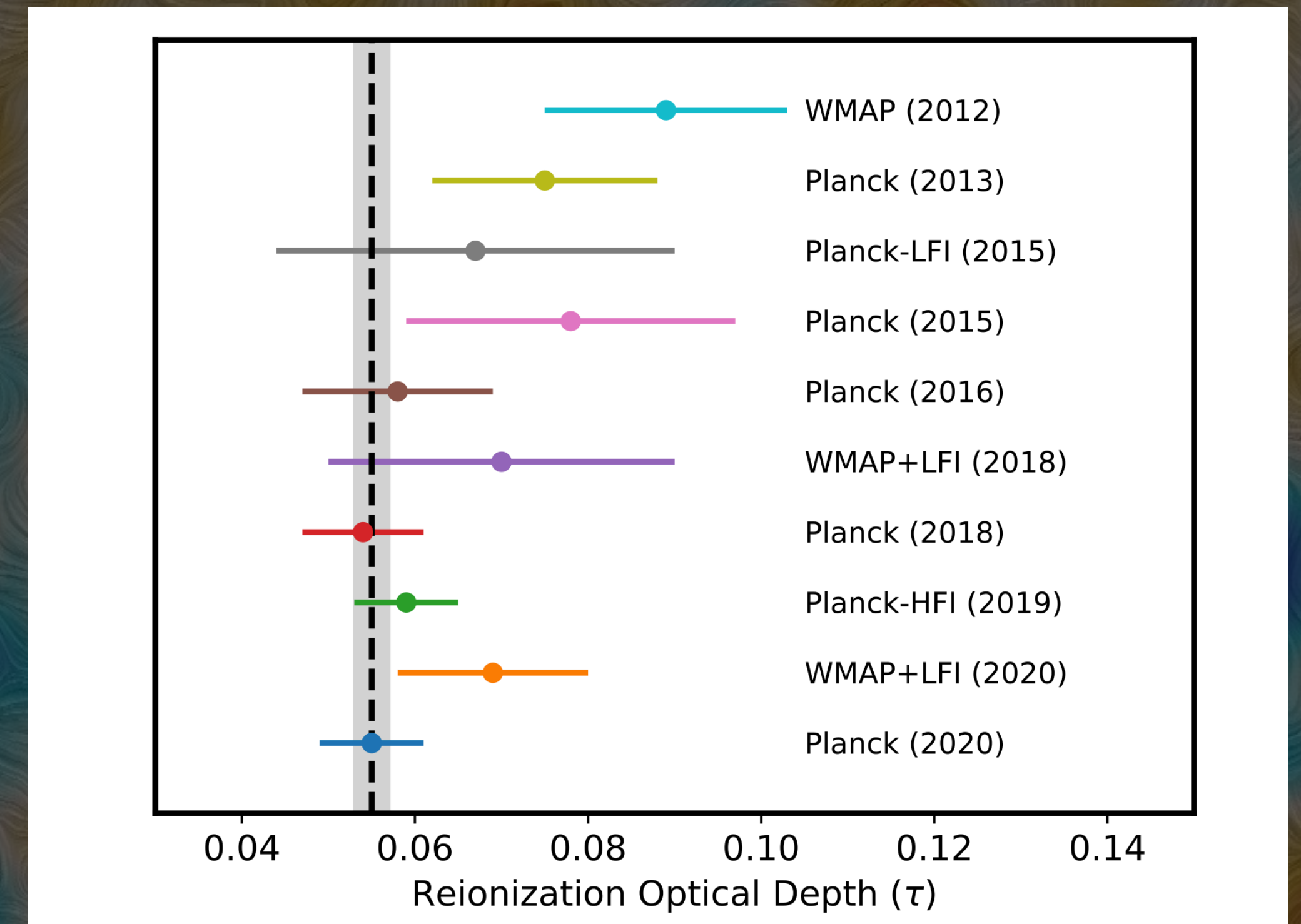
Muñoz et al.-Reionization after JWST: a photon budget crisis? (2024)

$$\tau \sim 0.09$$

Independent analyses of DESI DR2 suggest a framework with an increased τ in a non-dynamical dark energy scenario.

Sailer et al.-Addressing Tensions in Cosmology by an Increase in the Optical Depth to Reionization (2026)

CMB polarisation data rule out higher values for the optical depth



LiteBIRD collaboration. Probing cosmic inflation with the litebirdcosmic microwave background polarization survey (2022).

$$\tau \sim 0.06$$

U. Natale et al.-A novel CMB polarization likelihood package for large angular scales built from combined WMAP and Planck LFI legacy maps (2020).

Planck HFI



Unmatched sensitivity



Poor noise characterisation

Harmonic based
(Cross-spectrum only)

L. Pagano et al.-Reionization optical depth determination from Planck HFI data with ten percent accuracy (2019)



WMAP + LFI

Robust noise characterisation



Lower resolution compared to HFI

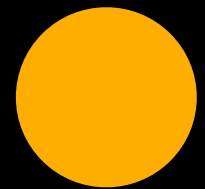
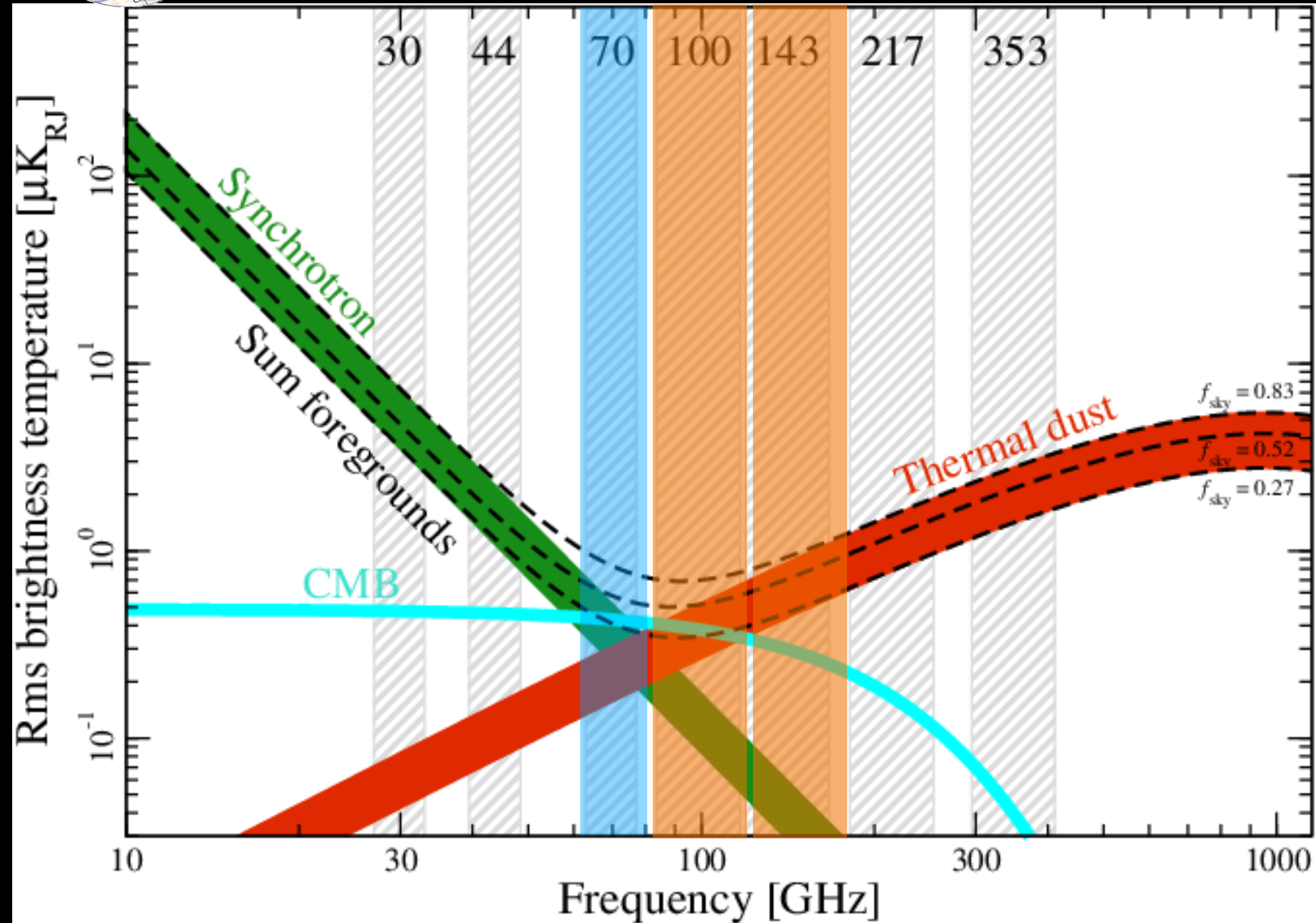


Pixel based

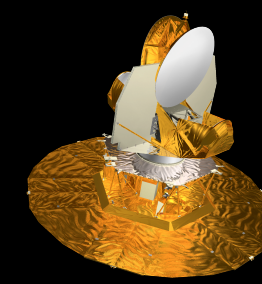


Planck

Planck collaboration-Planck 2018 results.
I. Overview and the cosmological legacy of
Planck (2019)

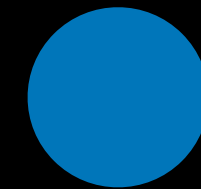
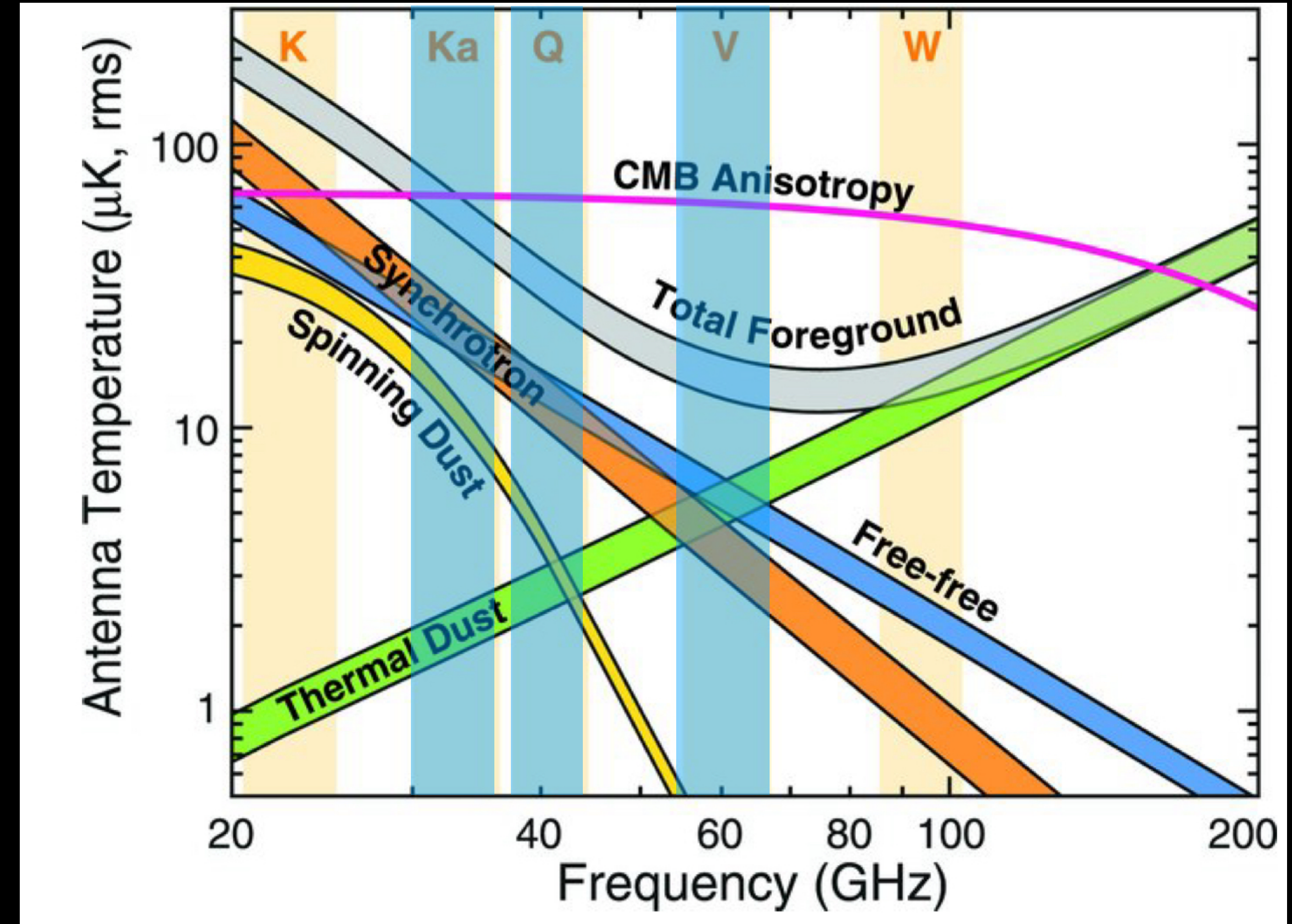


L. Pagano et al.-Reionization optical depth determination from
Planck HFI data with ten percent accuracy (2019)



WMAP

WMAP collaboration- Nine-year wilkinson microwave
anisotropy probe (wmap) observations: Final maps
and results. (2013)



U. Natale et al.-A novel CMB polarization likelihood package for large
angular scales built from combined WMAP and Planck LFI legacy
maps (2020).

This dataset will be referred to as 'WL'.

How are foregrounds removed?

In the previous analysis the starting point of this method is the **assumption** that all the maps employed can be modelled as a linear combination of CMB, Dust and Synchrotron. The foreground-cleaned map is provided by:

Band	Synchrotron	$10^2 \times \alpha$	Dust	$10^2 \times \beta$
Ka band	K band	32.15 ± 0.39	353 GHz	0.346 ± 0.061
Q band	K band	16.51 ± 0.39	353 GHz	0.369 ± 0.063
V band	K band	5.27 ± 0.27	353 GHz	0.744 ± 0.043
70 GHz	30 GHz	6.41 ± 0.46	353 GHz	0.966 ± 0.041
100 GHz	K band	0.95 ± 0.07	353 GHz	1.86 ± 0.015
143 GHz	Ka band	1.63 ± 0.21	353 GHz	3.94 ± 0.014

Results from:

- U. Natale et al.-A novel CMB polarization likelihood package for large angular scales built from combined WMAP and Planck LFI legacy maps (2020).
- L. Pagano et al.-Reionization optical depth determination from Planck HFI data with ten percent accuracy (2019)

$$\tilde{\mathbf{m}}_{\nu}^{P,fc} = \frac{\mathbf{m}_{\nu}^P - \alpha_{\nu} \mathbf{t}_s - \beta_{\nu} \mathbf{t}_d}{1 - \alpha_{\nu} - \beta_{\nu}}$$

Thermal dust scaling
coefficient

Synchrotron scaling
coefficient

U. Natale et al.-A novel CMB polarization likelihood package for large angular scales built from combined WMAP and Planck LFI legacy maps (2020).

Planck HFI



Unmatched sensitivity



Poor noise characterisation

Harmonic based
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L. Pagano et al.-Reionization optical depth determination from Planck HFI data with ten percent accuracy (2019)

ELiCA

WMAP + LFI

Robust noise characterisation



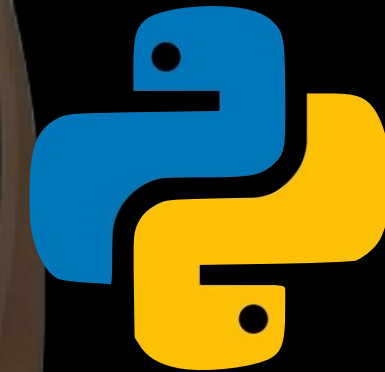
Lower resolution compared to HFI



Pixel based

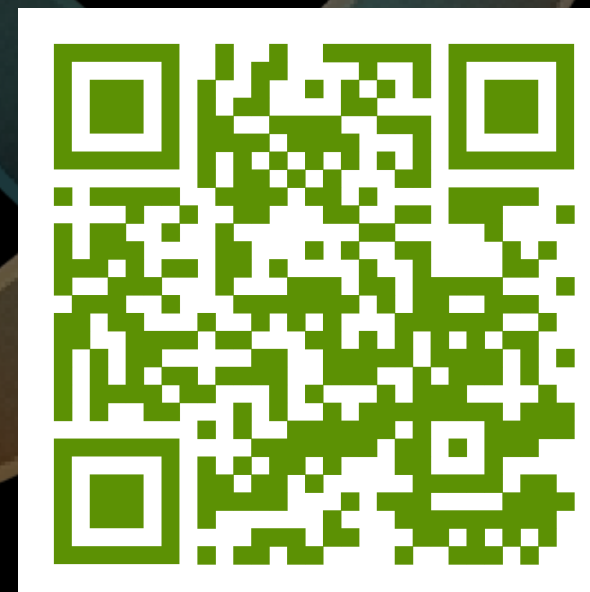
Planck HFI

WMAP + LFI

ELiCA 

E-mode Likelihood for Cross-Analysis

a multi-frequency, harmonic-space likelihood spanning multipoles $\ell = 2 - 29$



- Pip-installable
- Cobaya compatible

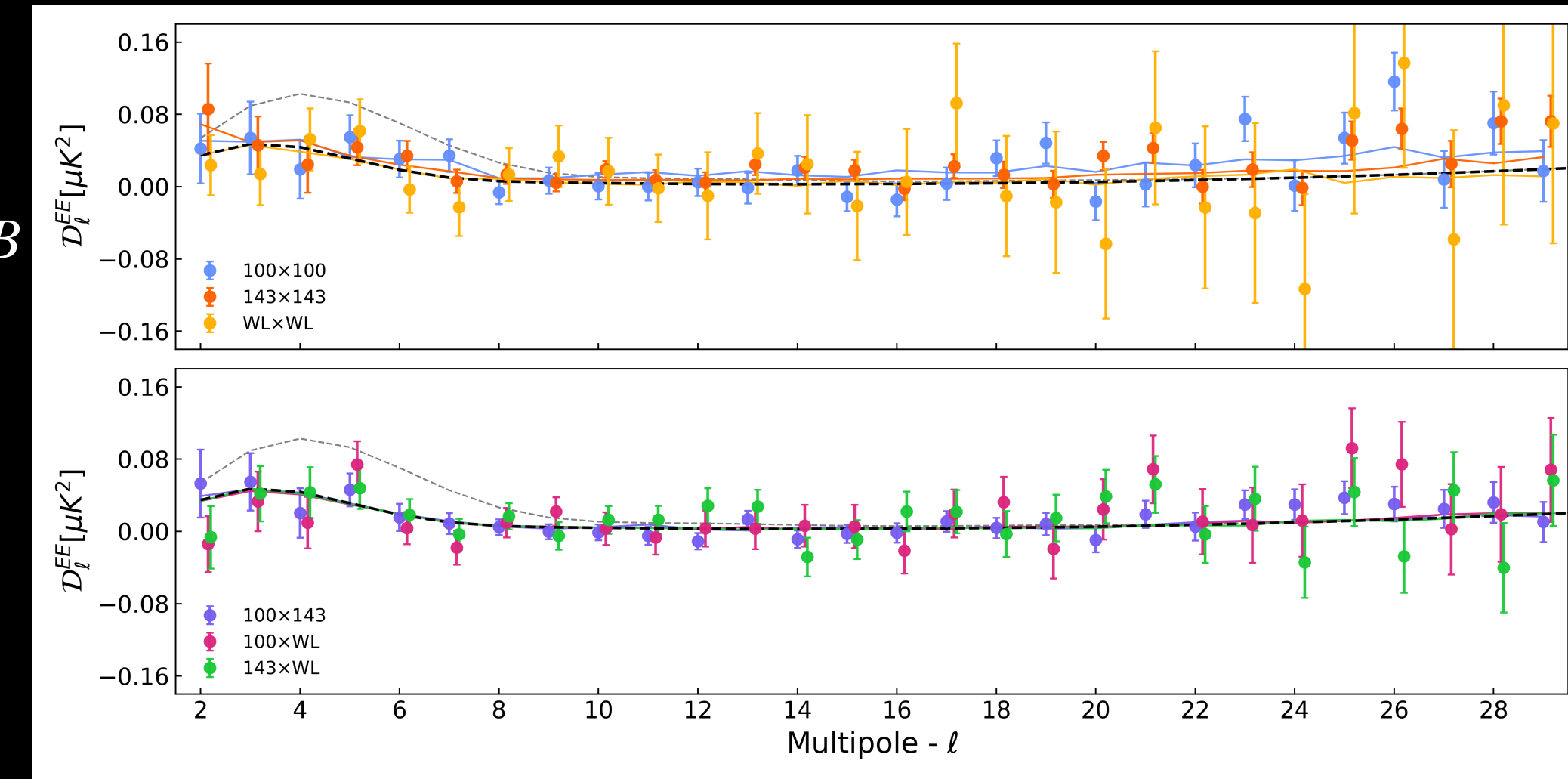
Check: Genesini et al.-Cross-spectra likelihood for robust τ constraints from all satellite polarisation data (2026)

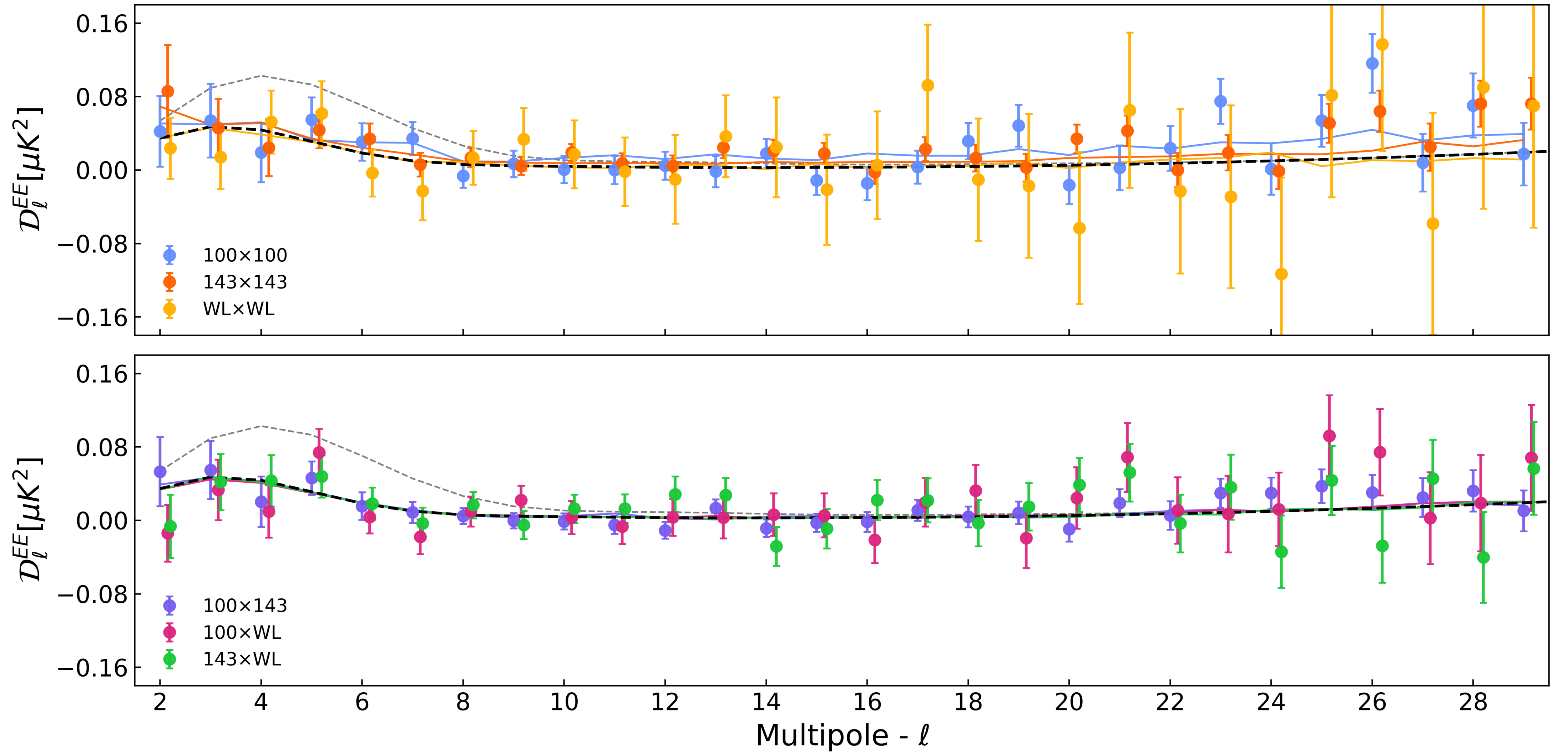
How can we recover the CMB spectrum from maps?

One algorithm that allows for moving back to the harmonic space is the Quadratic Maximum Likelihood Estimator (QML), which provides a method for reconstructing the CMB power spectrum with minimal error bars.

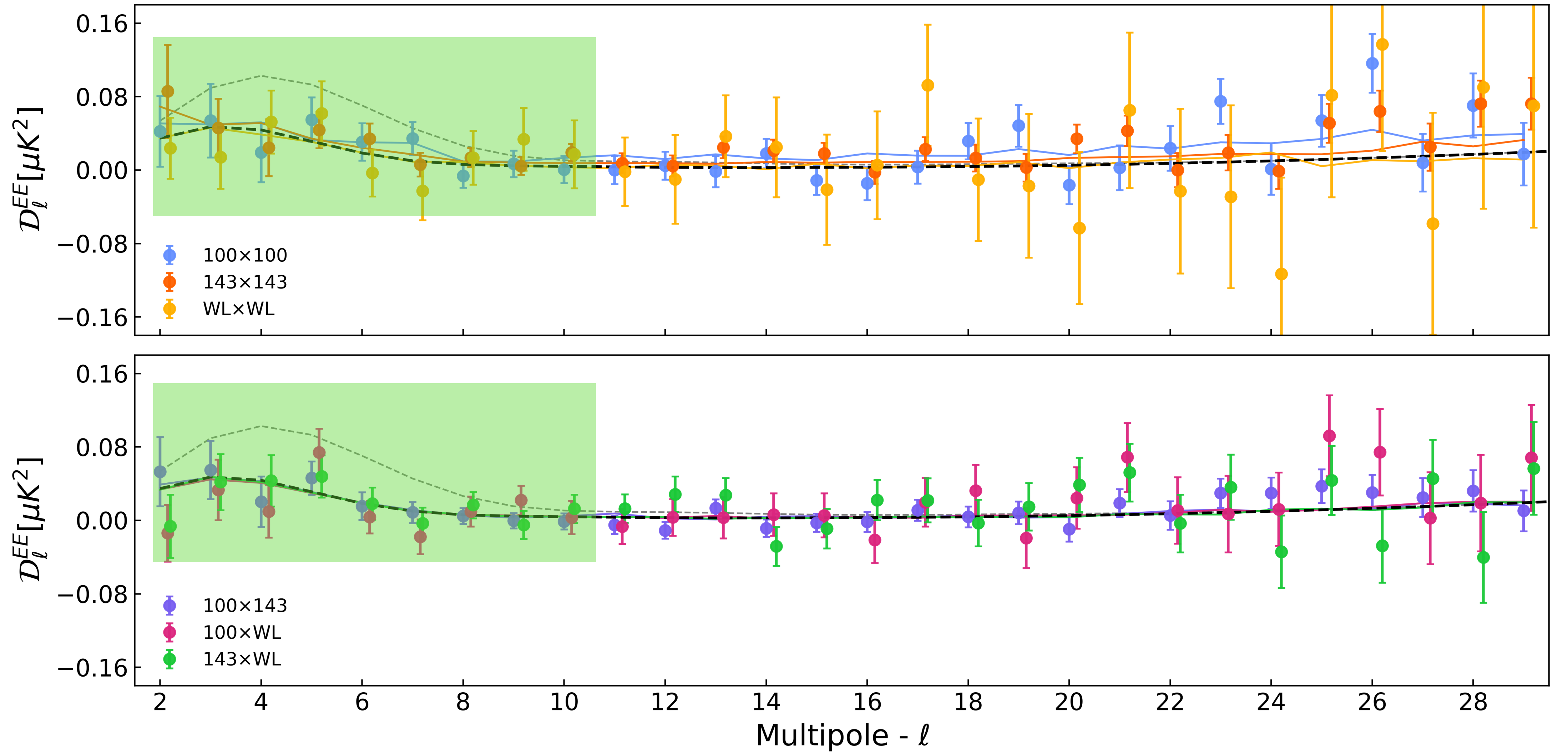
$$\hat{y}_\ell^{AB} = \mathbf{d}^{AT} \mathbf{E}_\ell \mathbf{d}^B - b_\ell^{AB}$$

$$\hat{C}_\ell \equiv \sum_{\ell'} [W^{-1}]_{\ell\ell'} \hat{y}_{\ell'}^{AB}$$

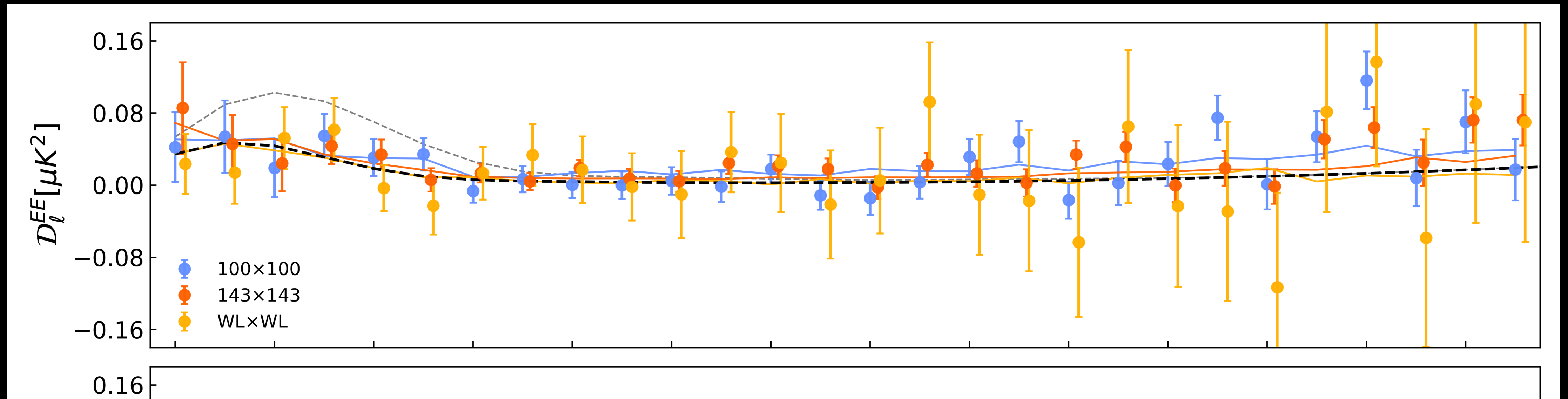




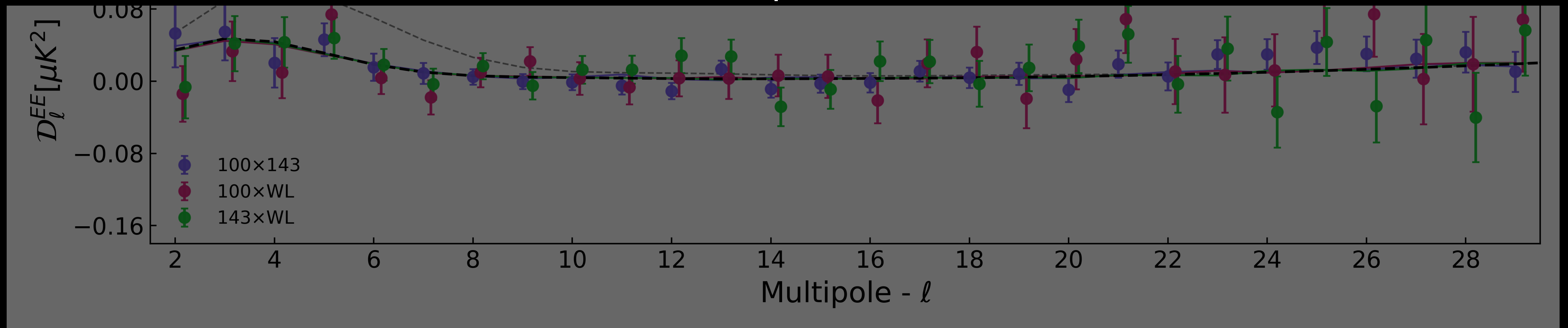
The six power spectra are compared with the fiducial power spectrum at large scales.
Tanh parametrisation is assumed for the history of Reionisation.



The six power spectra are compared with the fiducial power spectrum at large scales.

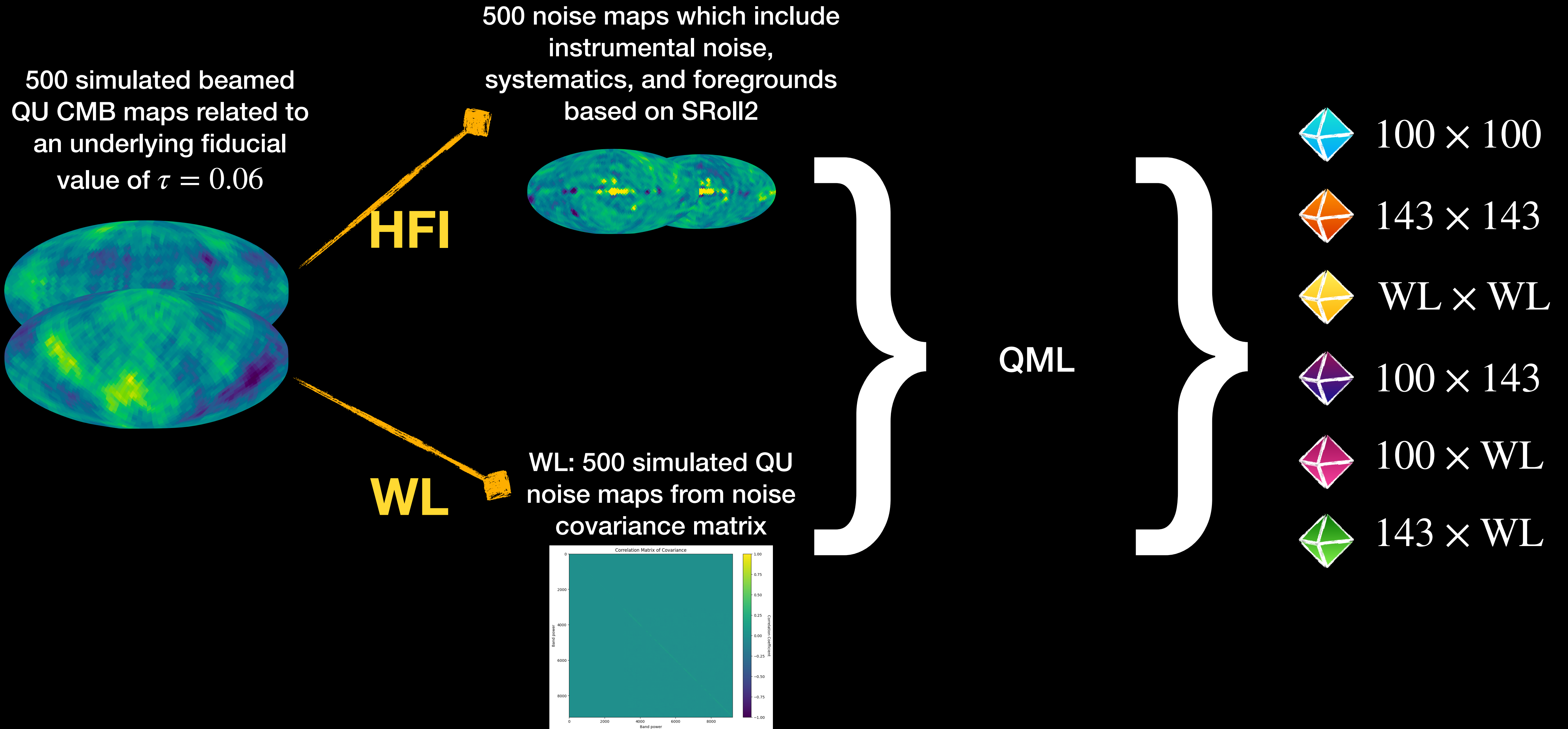


HFI auto-spectra seem biased



The six power spectra are compared with the fiducial power spectrum at large scales.

How do we generate mock CMB observations?



ELiCA algorithm: E-mode Likelihood for Cross-Analysis

Based on: G. Galloni et al.-Accurate and efficient likelihood modeling for large-scale CMB data (2025) (Monday poster session)

First step:

$$-2 \ln \mathcal{L}(\hat{C}_\ell | C_\ell) = \sum_{\ell \ell'} \mathbf{X}_\ell^T \left(M_{\ell \ell'}^{-1} \right)_{\text{fid}} \mathbf{X}_{\ell'}$$

- C_ℓ : True power spectra
- $\hat{C}_\ell$: Estimate
- $M_{\ell \ell'}$: Simulation-based covariance matrix

Based on:

S. Hamimeche, A. Lewis - Likelihood Analysis of CMB Temperature and Polarization Power Spectra



How do we get X_ℓ ?

ELiCA algorithm: E-mode Likelihood for Cross-Analysis

$$-2 \ln \mathcal{L}(\hat{C}_\ell | C_\ell) = \sum_{\ell \ell'} \mathbf{X}_\ell^T (M_{\ell \ell'}^{-1})_{\text{fid}} \mathbf{X}_{\ell'}$$

We start by building this object: $C_\ell^{-\frac{1}{2}} \hat{C}_\ell C_\ell^{-\frac{1}{2}}$.

Evaluating its eigenvalues and eigenvectors $\begin{cases} D_\ell & \text{:diagonal matrix of eigenvalues} \\ U_\ell & \text{:diagonalization matrix} \end{cases}$

$$C_{\mathbf{g}\ell} = C_{f\ell}^{1/2} U_\ell g(D_\ell) U_\ell^T C_{f\ell}^{1/2}.$$

$$[g(\mathbf{D}_\ell)]_{ij} = g(D_\ell^{ii}) \delta_{ij} = \text{sign}(D_\ell^{ii} - 1) \sqrt{2(D_\ell^{ii} - \ln D_\ell^{ii} - 1)} \delta_{ij}$$

The independent elements of the matrix $C_{\mathbf{g}\ell}$ are indeed our $\mathbf{X}_\ell$.

ELiCA algorithm: E-mode Likelihood for Cross-Analysis

How do we handle the noise bias?

Based on: G. Galloni et al.-Accurate and efficient likelihood modeling for large-scale CMB data (2025)

$$C_\ell = \begin{bmatrix} C_\ell^{100 \times 100} + N_\ell^{100} & C_\ell^{100 \times 143} & C_\ell^{100 \times WL} \\ C_\ell^{100 \times 143} & C_\ell^{143 \times 143} + N_\ell^{143} & C_\ell^{143 \times WL} \\ C_\ell^{100 \times WL} & C_\ell^{143 \times WL} & C_\ell^{WL \times WL} + N_\ell^{WL} \end{bmatrix}$$

In the case of auto-spectra, we also account for the **noise bias**, whereas for cross-spectra the noise is assumed to be uncorrelated.

We do not have a reliable noise estimate for the HFI auto-spectra, we instead marginalize over them, obtaining:

$$X_\ell = \left[X_\ell^{100 \times 100}, X_\ell^{100 \times 143}, X_\ell^{100 \times WL}, X_\ell^{143 \times 143}, X_\ell^{143 \times WL}, X_\ell^{WL \times WL} \right]$$

ELiCA algorithm: E-mode Likelihood for Cross-Analysis

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$$C_\ell = \begin{bmatrix} C_\ell^{100 \times 100} + N_\ell^{100} & C_\ell^{100 \times 143} & C_\ell^{100 \times WL} \\ C_\ell^{100 \times 143} & C_\ell^{143 \times 143} + N_\ell^{143} & C_\ell^{143 \times WL} \\ C_\ell^{100 \times WL} & C_\ell^{143 \times WL} & C_\ell^{WL \times WL} + N_\ell^{WL} \end{bmatrix}$$

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$$X_\ell = [X_\ell^{100 \times 143}, X_\ell^{100 \times WL}, X_\ell^{143 \times WL}, X_\ell^{WL \times WL}]$$



ELiCA algorithm: E-mode Likelihood for Cross-Analysis

How do we handle the incomplete sky coverage?

Based on: G. Galloni et al. -Accurate and efficient likelihood modeling for large-scale CMB data (2025)

Although auto-spectra are positive definite on the full-sky, masking induces the matrix $\mathbf{C}_\ell^{-1/2} \hat{\mathbf{C}}_\ell \mathbf{C}_\ell^{-1/2}$ to develop negative eigenvalues.

$$\mathbf{C}_\ell = \begin{bmatrix} \mathbf{C}_\ell^{100 \times 100} + \mathbf{N}_\ell^{100} + \mathbf{O}_\ell^{100 \times 100} & \mathbf{C}_\ell^{100 \times 143} & \mathbf{C}_\ell^{100 \times WL} \\ \mathbf{C}_\ell^{100 \times 143} & \mathbf{C}_\ell^{143 \times 143} + \mathbf{N}_\ell^{143} + \mathbf{O}_\ell^{143 \times 143} & \mathbf{C}_\ell^{143 \times WL} \\ \mathbf{C}_\ell^{100 \times WL} & \mathbf{C}_\ell^{143 \times WL} & \mathbf{C}_\ell^{WL \times WL} + \mathbf{N}_\ell^{WL} + \mathbf{O}_\ell^{WL \times WL} \end{bmatrix}$$

The offset idea is first introduced in: A. Mangilli-Large-scale CMB temperature and polarization cross-spectra likelihoods (2015)

ELiCA algorithm: E-mode Likelihood for Cross-Analysis

One last step:

$$-2 \ln \mathcal{L}(\hat{C}_\ell | C_\ell) = \sum_{\ell\ell'} X_\ell^T (M_{\ell\ell'}^{-1})_{\text{fid}} X_{\ell'}$$

Based on: E. Sellentin, A. Heavens-Parameter inference with estimated covariance matrices (2015)

↓

We must take into account that the covariance matrix is simulation-based.

Since we are limited by the number of simulations, we marginalize over the true covariance matrix, obtaining:

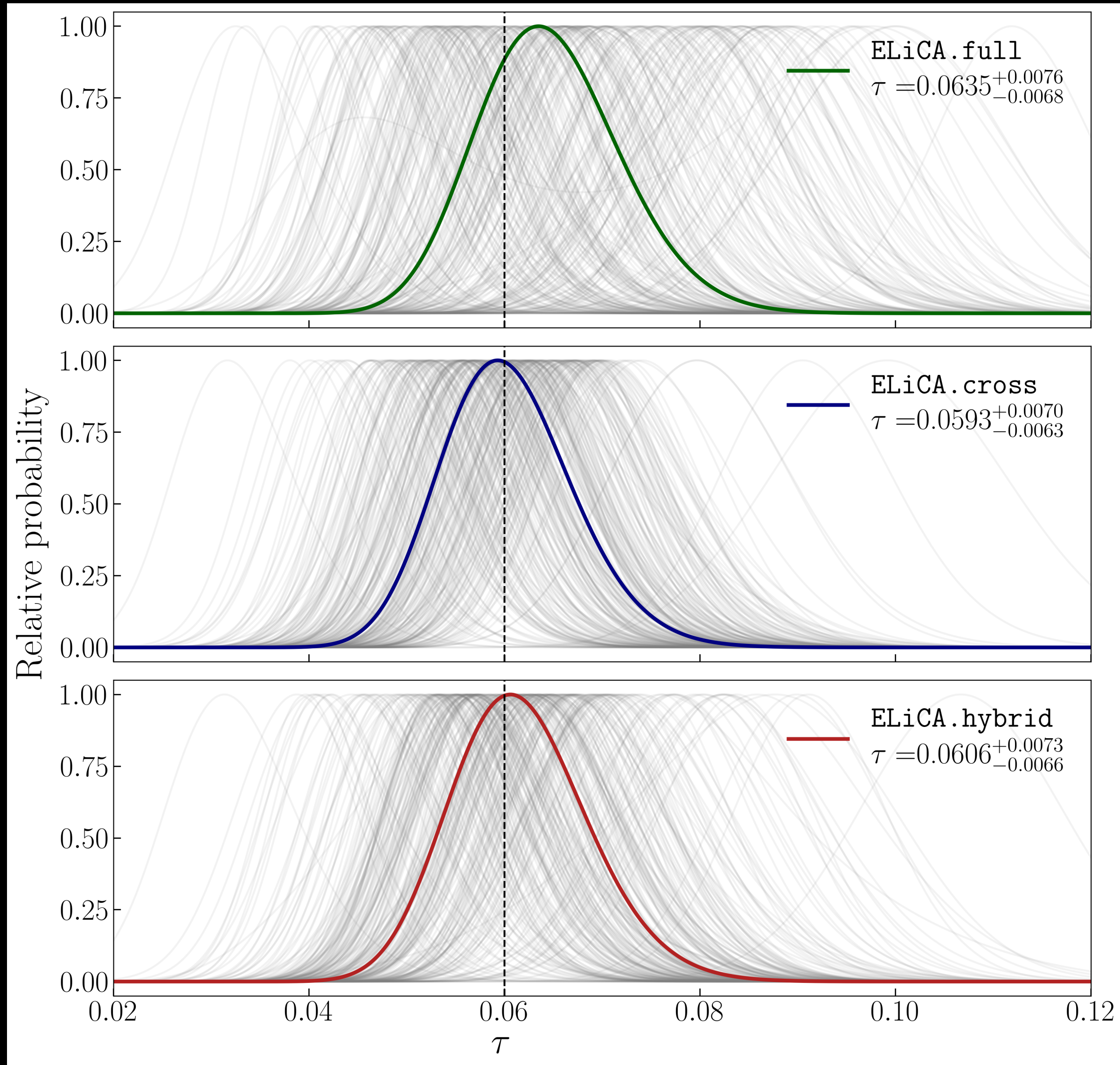
$$-2 \ln \mathcal{L}(\hat{C}_\ell | C_\ell) = N \ln \left[1 + \frac{\sum_{\ell\ell'} X_\ell^T (M_{\ell\ell'}^{-1})_{\text{fid}} X_{\ell'}}{N - 1} \right]$$

↙ ↘

The number of simulations in my work is N=500

Fiducial $\tau = 0.06$

How do we validate ELiCA:



all auto- and cross-spectra are included.

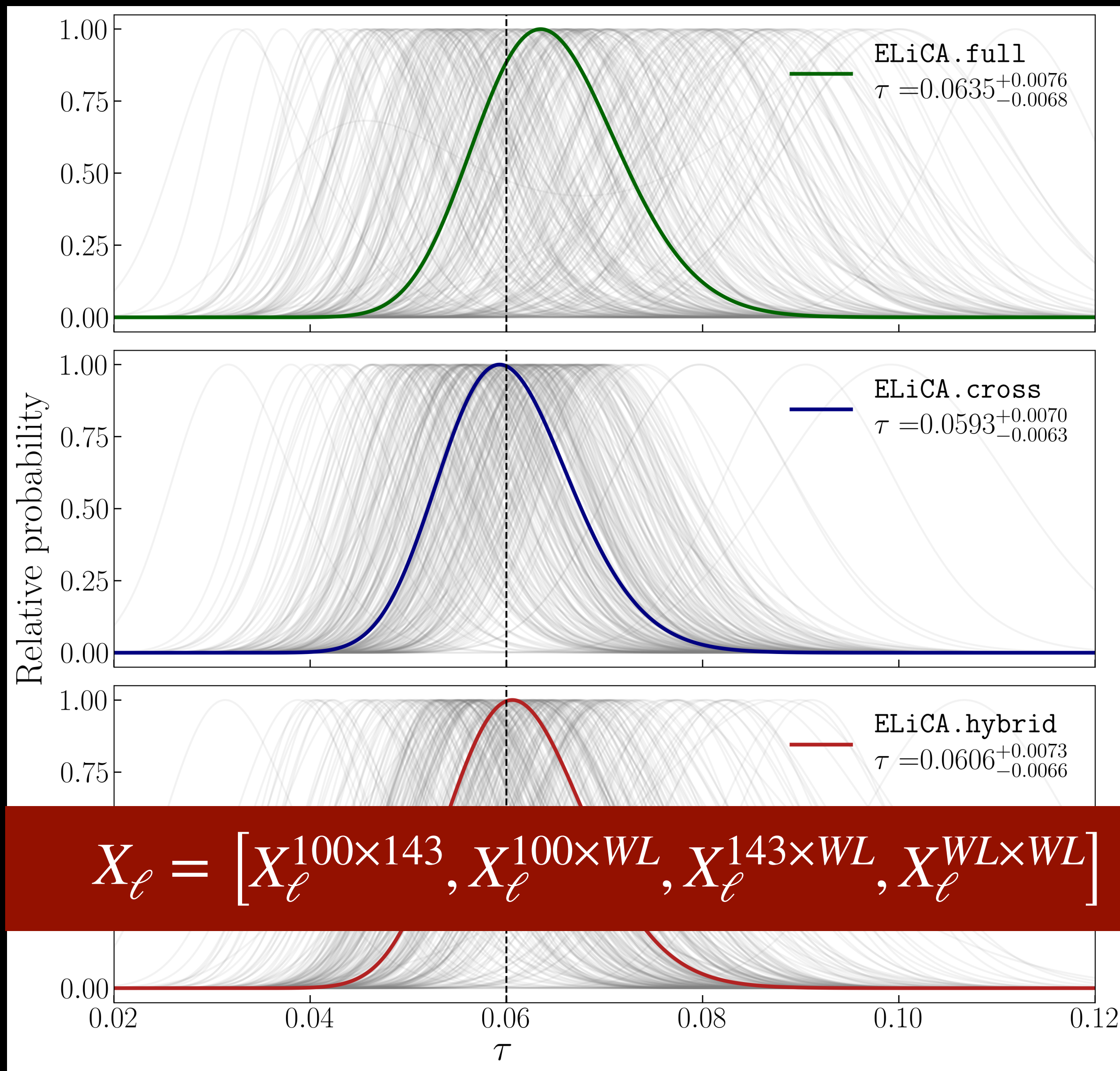
Bias: $7.55\hat{\sigma}$

all auto spectra are marginalised over.

Bias: $-1.63\hat{\sigma}$

all HFI auto spectra are marginalised over.

Bias: $1.34\hat{\sigma}$



$$X_\ell = [X_\ell^{100 \times 143}, X_\ell^{100 \times WL}, X_\ell^{143 \times WL}, X_\ell^{WL \times WL}]$$

ELiCA.hybrid is our baseline configuration

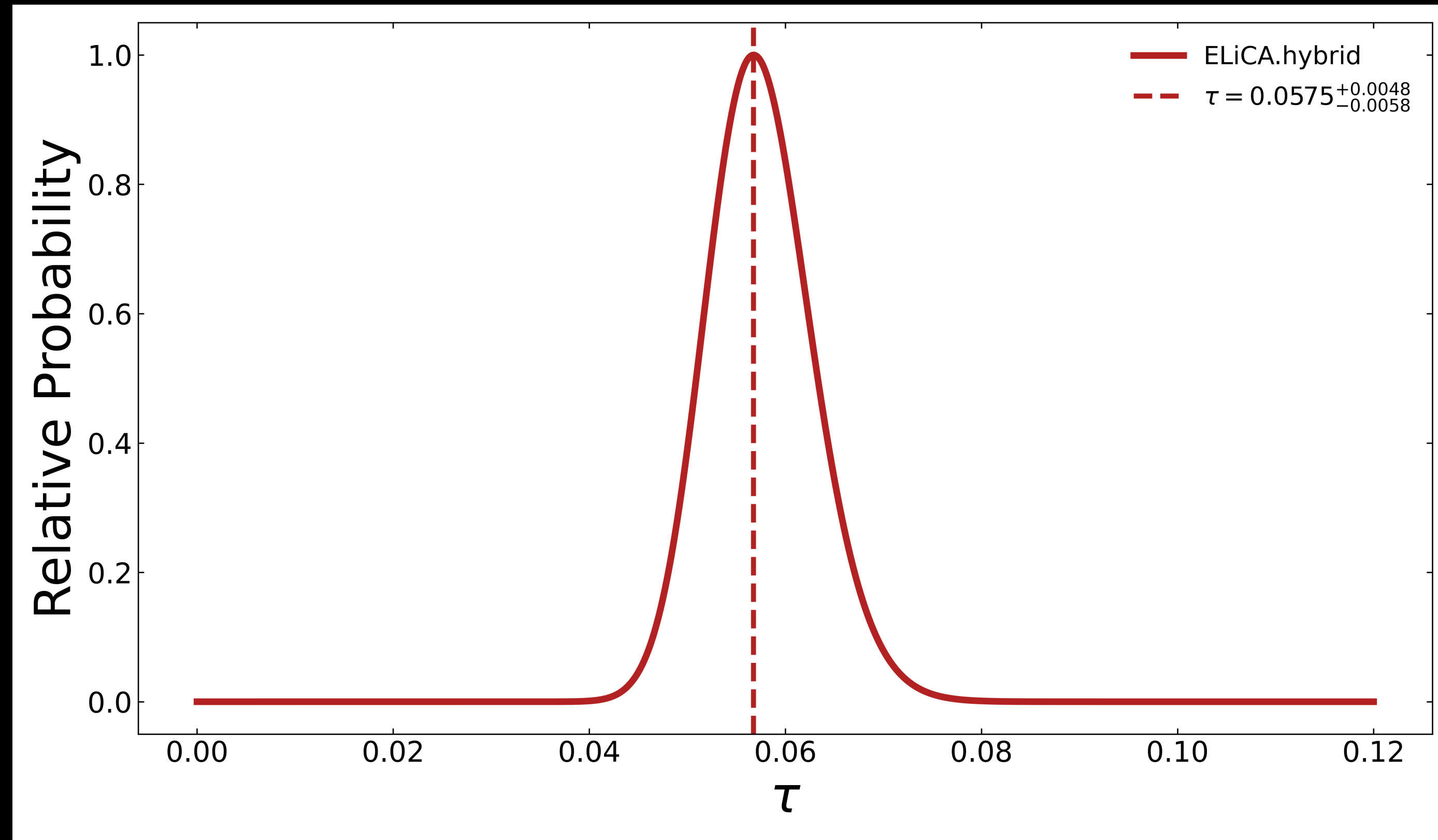
all HFI auto spectra are marginalised over.

Bias: $1.34\hat{\sigma}$

Results:



What can ELiCA.hybrid reveal about low- ℓ modes?



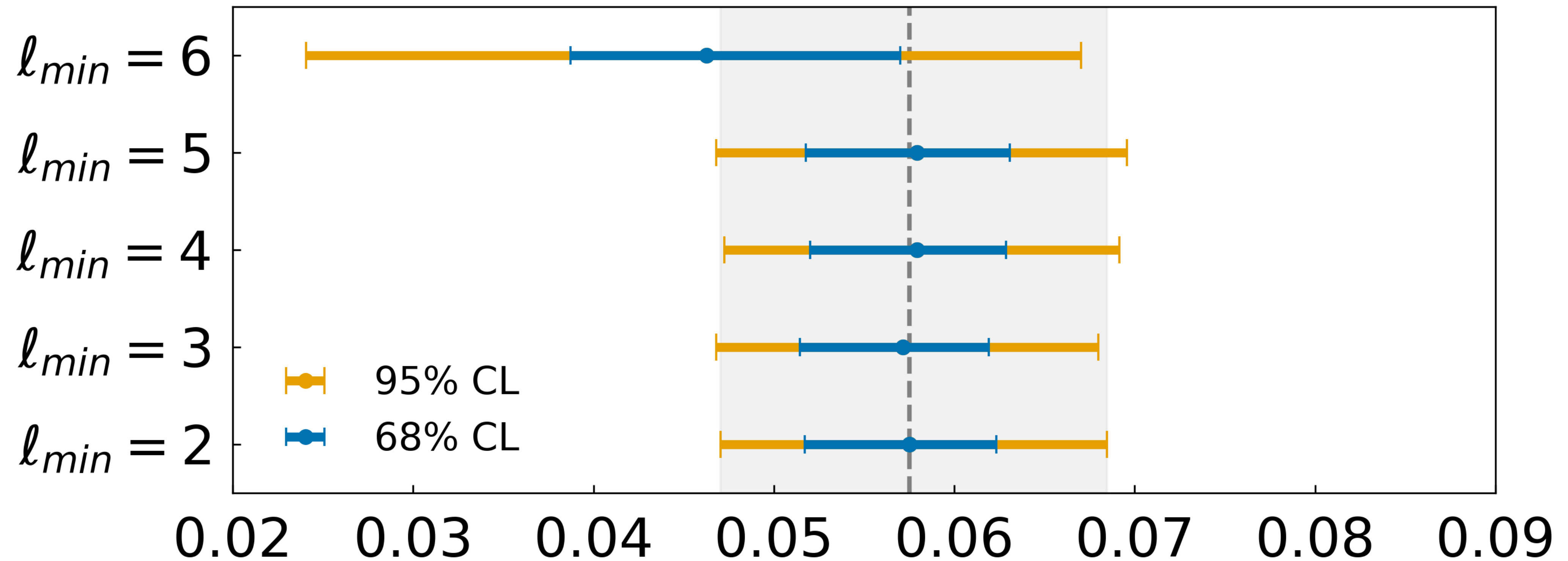
The mean value and the 68% confidence level bounds on the optical depth derived from the data:

$$\tau = 0.0575^{+0.0048}_{-0.0058}$$

Tightest
constraint on τ
from CMB

What can ELiCA.hybrid reveal about low- ℓ modes?

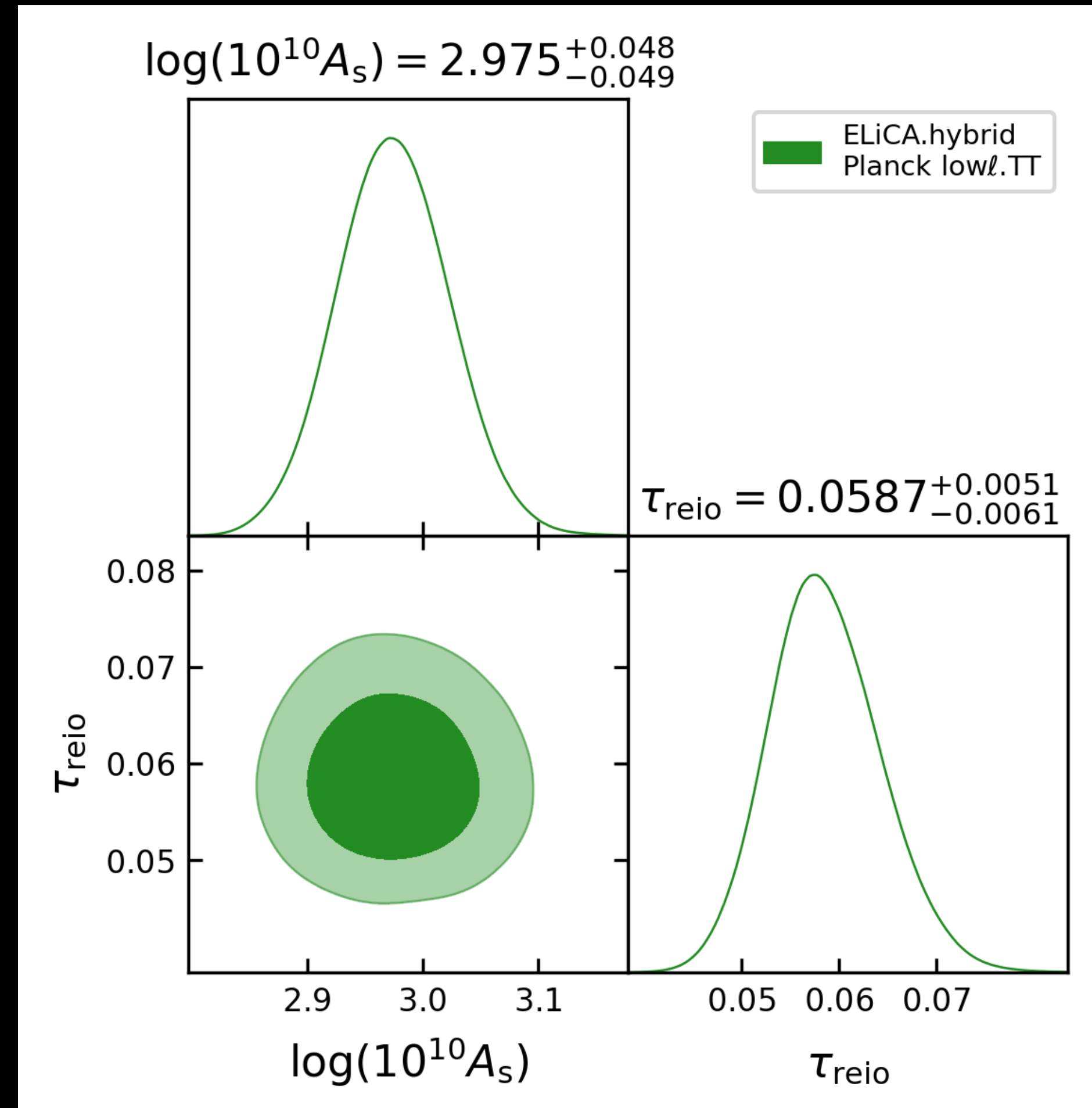
Robustness check:



What Do TT+EE Large scales results show?

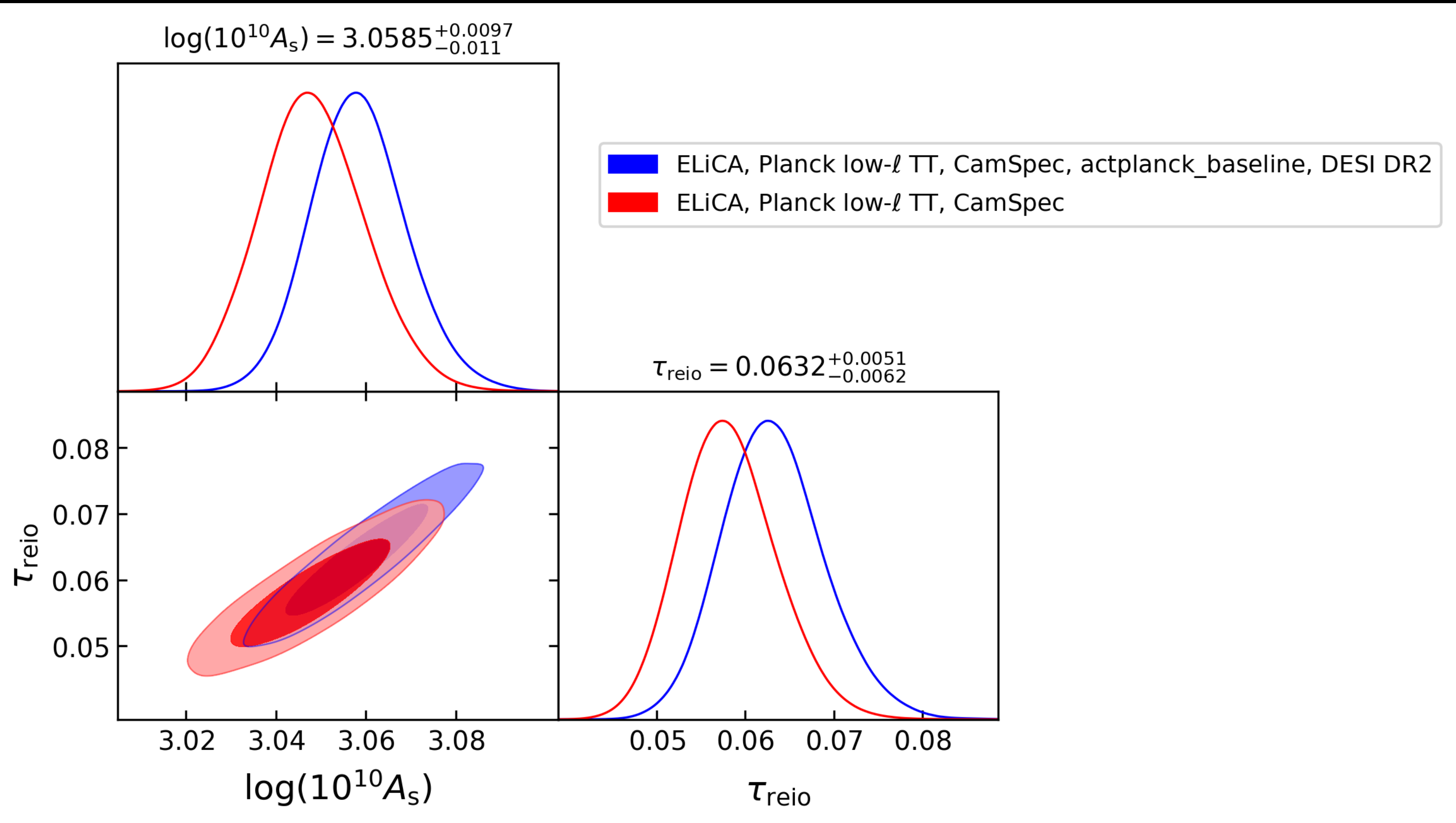
After passing validation, we explore the impact of ELiCA.hybrid on the parameters of the Λ Cold Dark Matter model by combining the likelihood with other CMB data.

To explore this, we perform a series of Markov Chain Monte Carlo (MCMC) analyses using the Cobaya framework, with theoretical power spectra computed using camb.



Check: Genesini et al. -Cross-spectra likelihood for robust τ constraints from all satellite polarisation data (2026)

What Do ELiCA.hybrid Λ CDM Results Show?

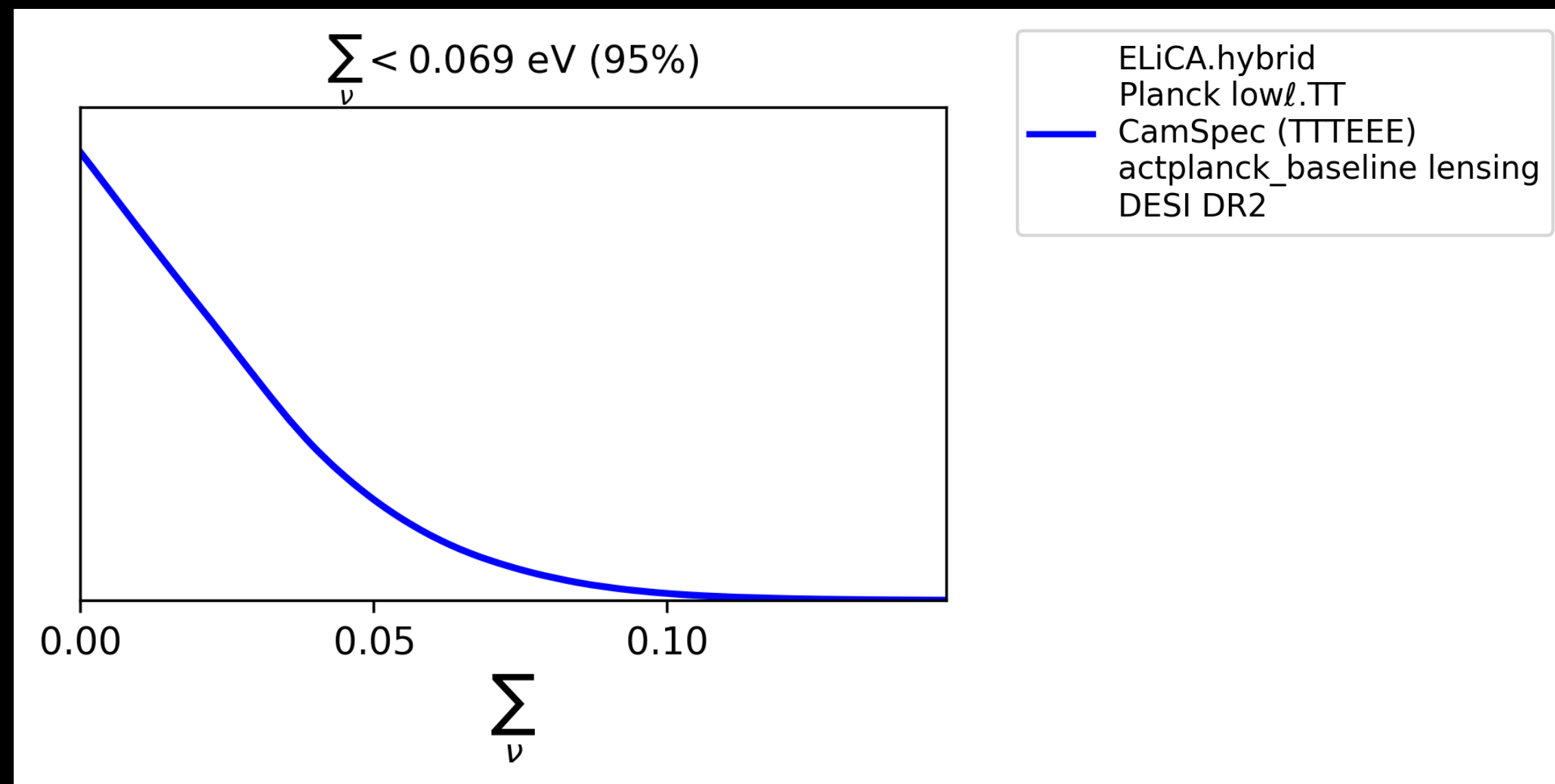


Check: Genesini et al. -Cross-spectra likelihood for robust τ constraints from all satellite polarisation data (2026)

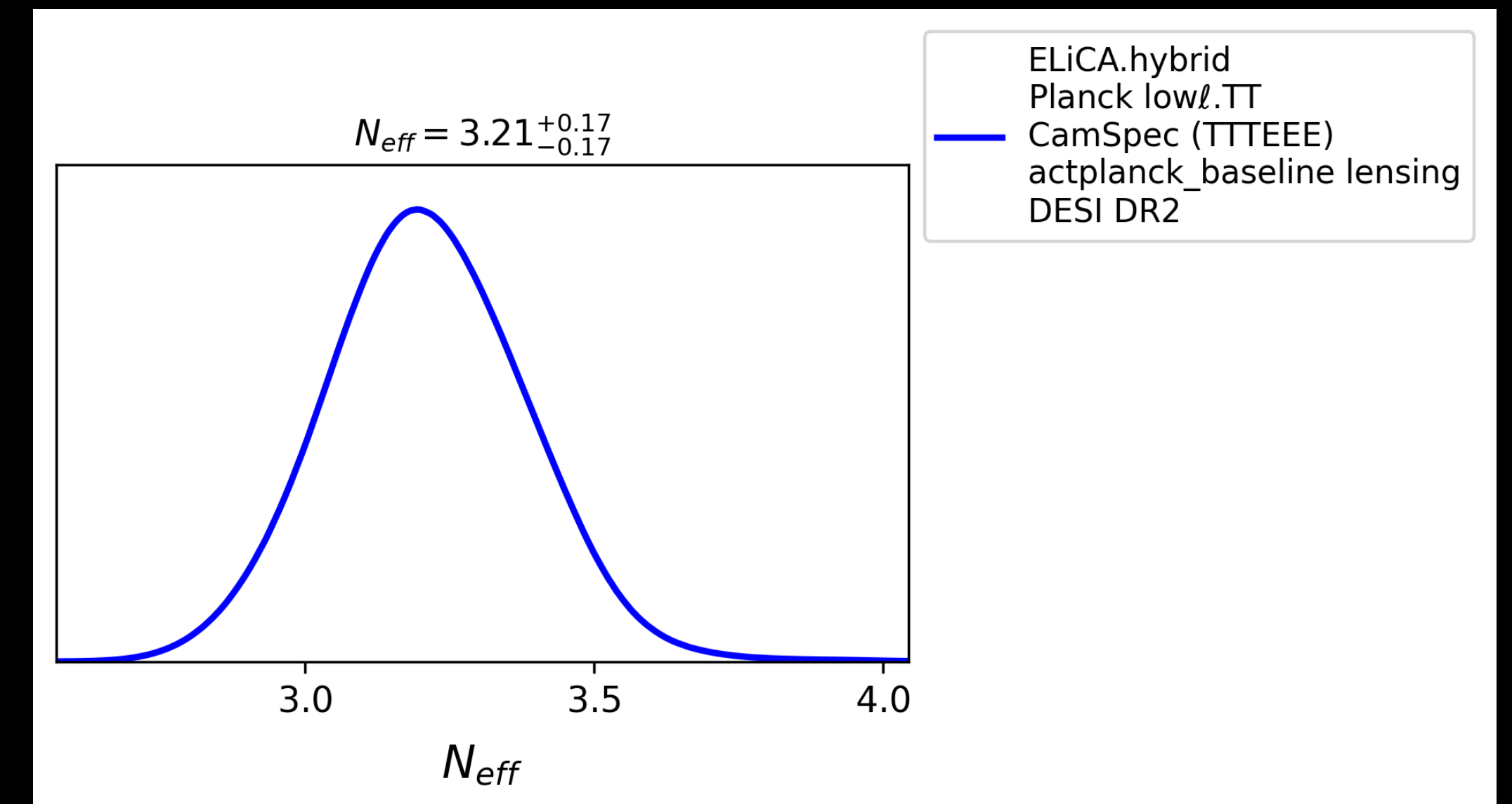
Can ELiCA.hybrid constrain neutrino masses?

Given the new bound on A_s , we explored the impact of this constraint on extensions to the Λ -CDM model, particularly in the neutrino sector:

$$\Lambda\text{CDM} + \sum m_\nu$$



$$\Lambda\text{CDM} + N_{\text{eff}}$$

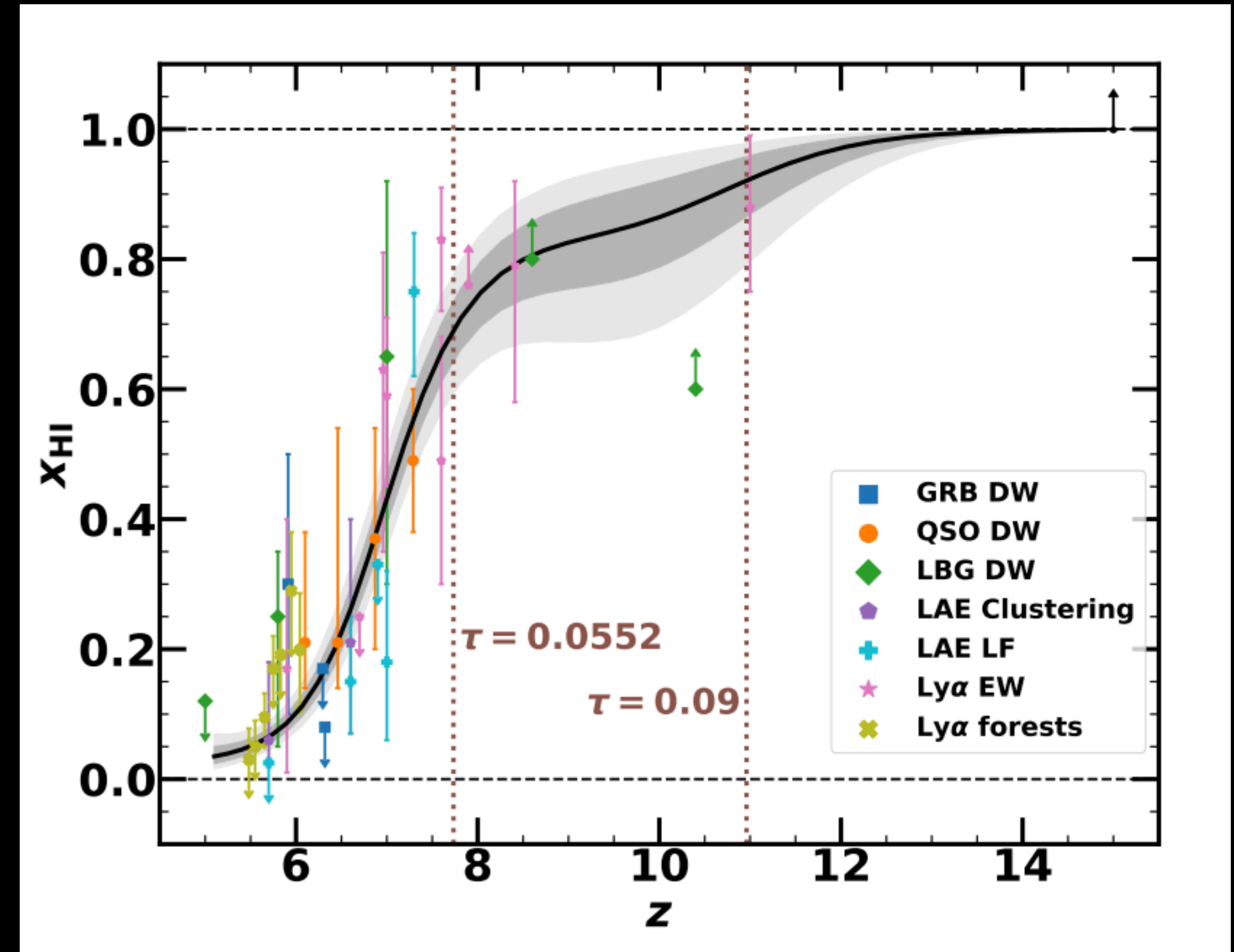




With no new large-scale CMB polarization data before LiteBIRD, any significant improvement on τ must rely on complementary datasets.

With astrophysics we have different probes:

- Ly α damping-wing absorption of QSOs
- Fraction of dark pixels in the Lyman-series forests
- Ly α damping-wing absorption of GRBs
- Ly α damping-wing absorption of LBGs
- Evolution of the Ly α luminosity function
- Dark gaps in the Ly β forest



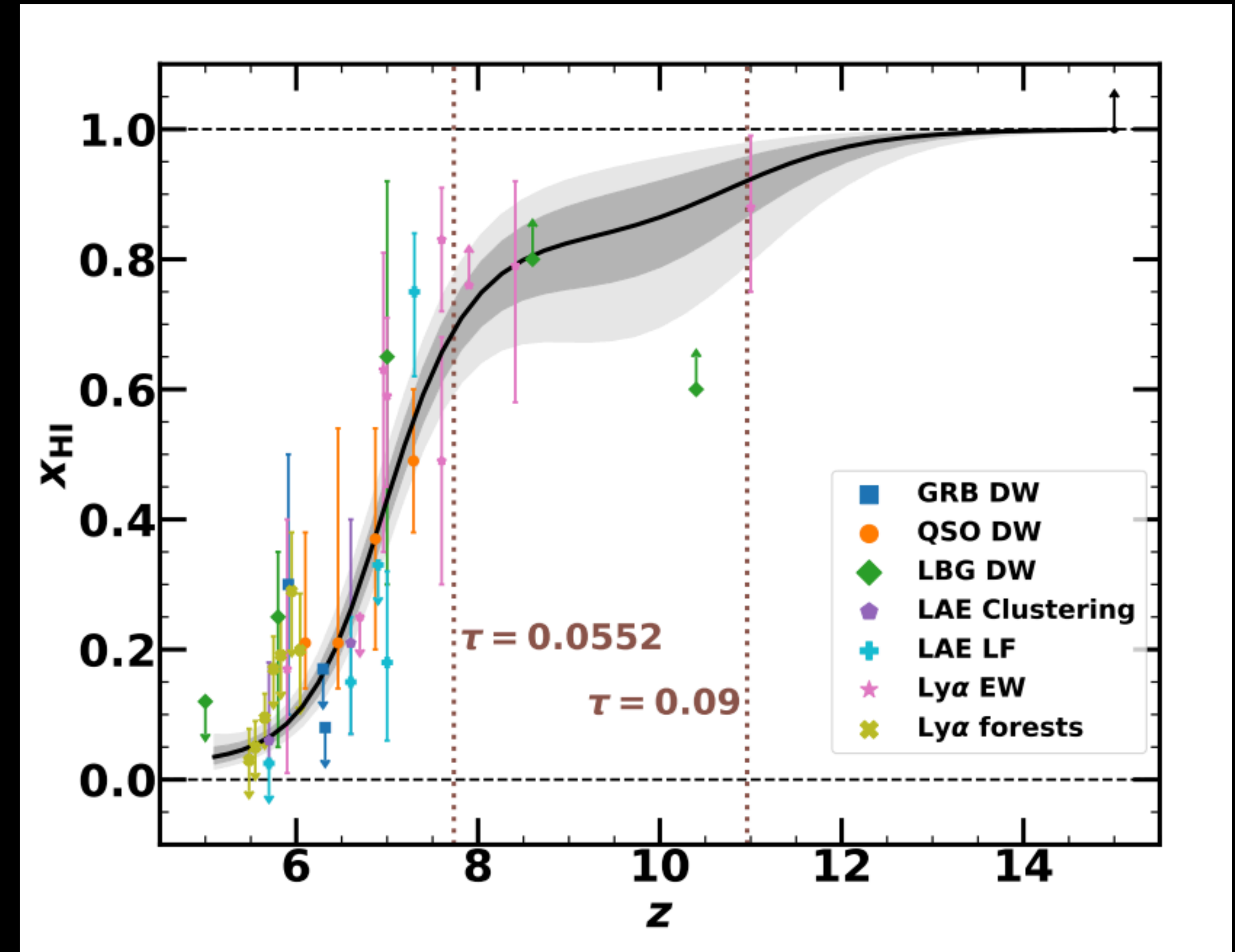
Credits: Y. Kageura-A New Constraint on the Optical Depth from the Reionization History Independent of CMB Large-Scale E-Mode Polarization

With astrophysics we have different probes:

Combining $x_{HI}(z)$ with the Planck CMB power spectra, **excluding the large-scale E-mode polarisation** the result is:

$$\tau = 0.0552^{+0.0075}_{-0.0049}$$

(accounting for systematics in the absorption modeling, with neutral hydrogen fixed to 0 at $z=15$)

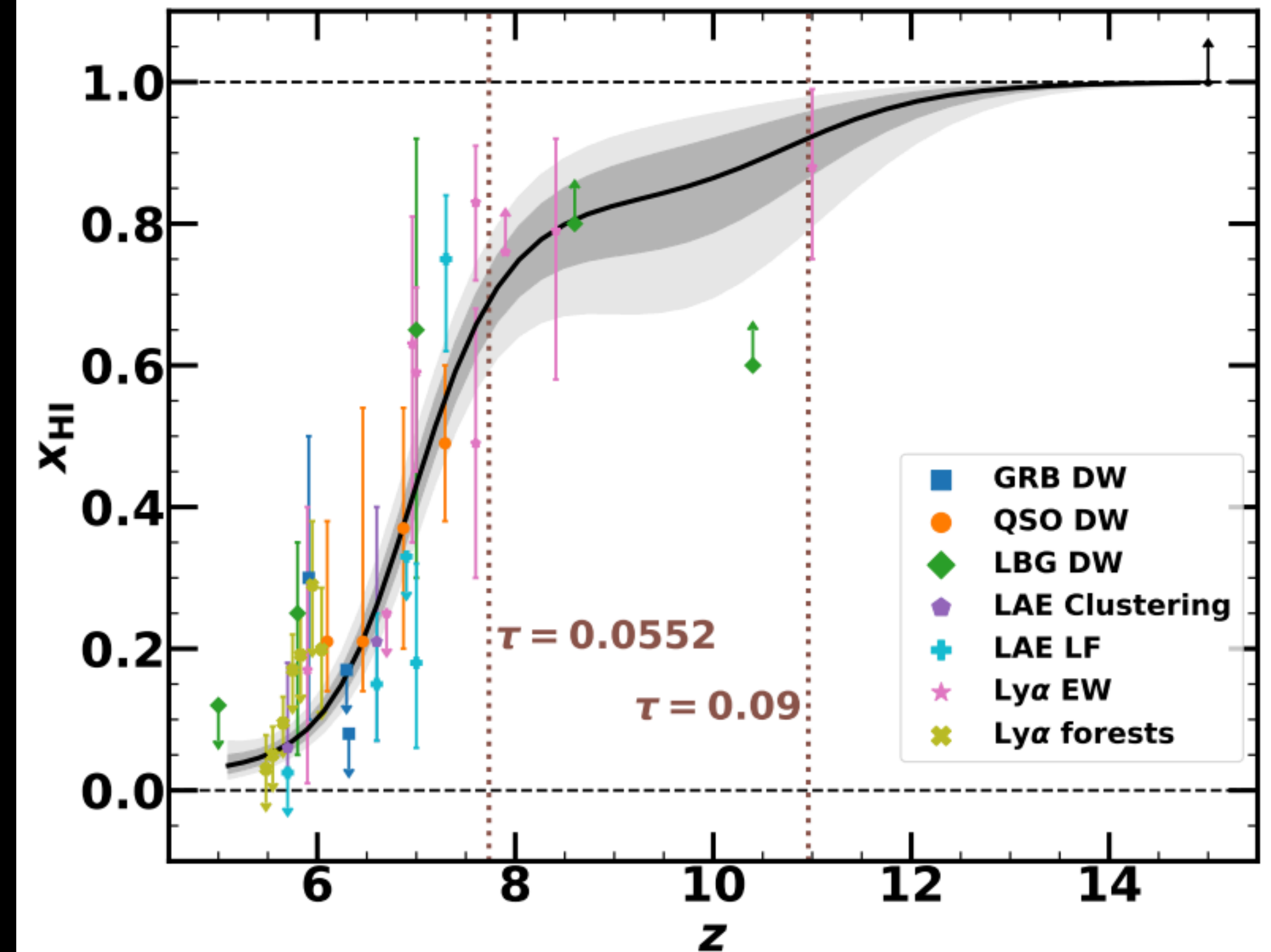
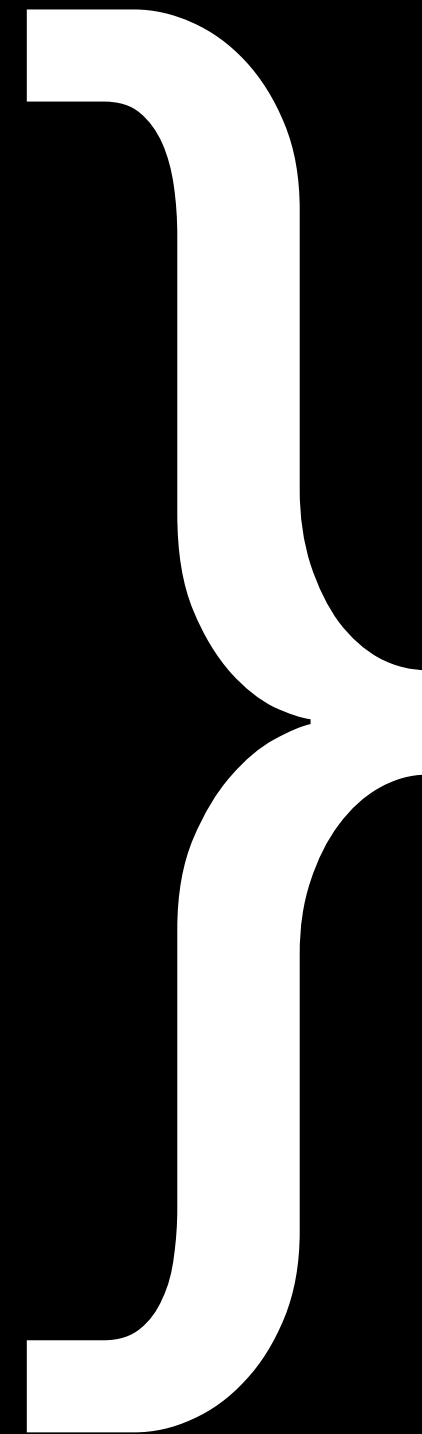


Credits: Y. Kageura-A New Constraint on the Optical Depth from the Reionization History Independent of CMB Large-Scale E-Mode Polarization

Astrophysics is capturing more details on the evolution of the EoR



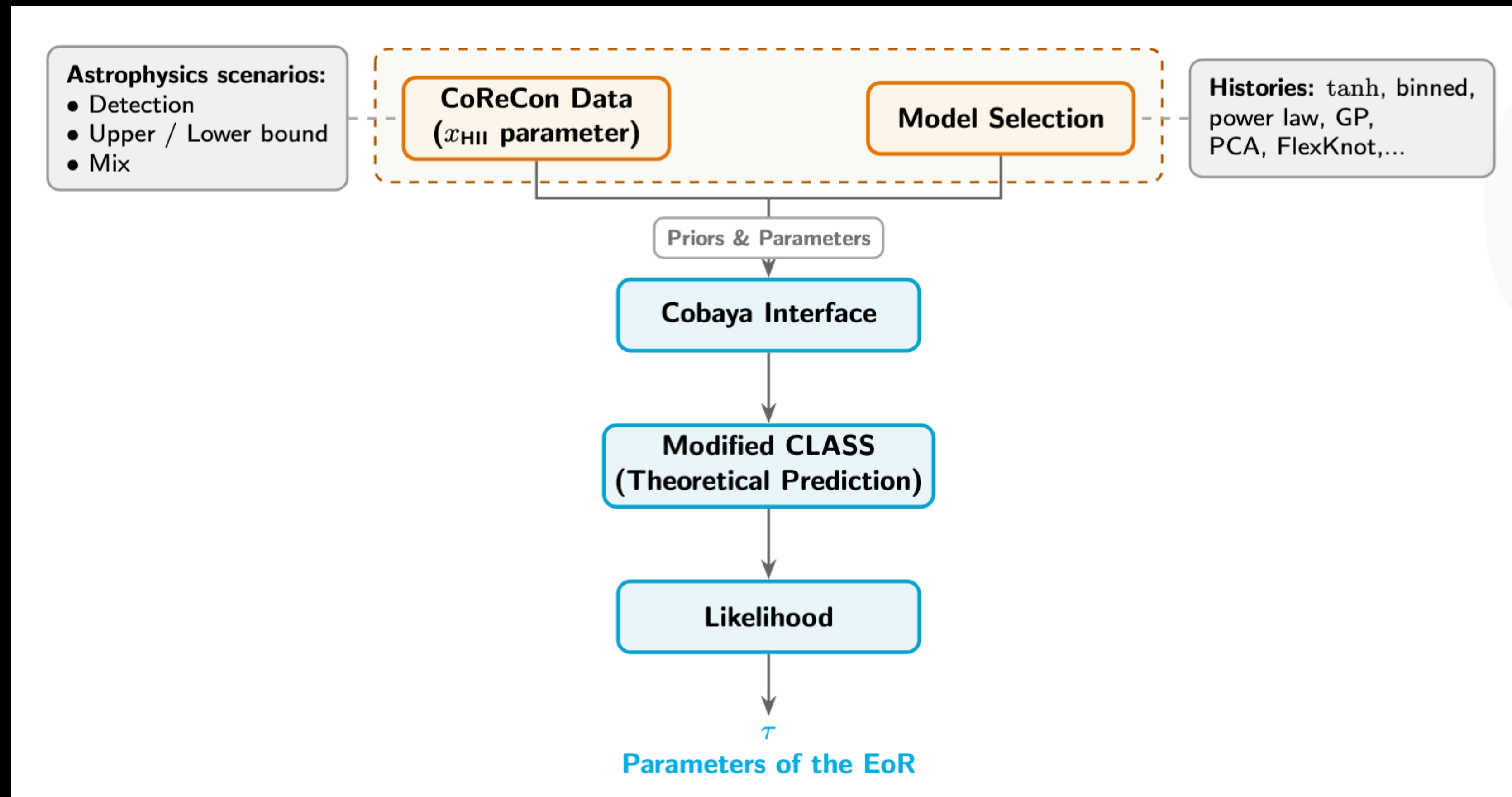
The commonly adopted tanh parametrization is not sufficient anymore



Credits: Y. Kageura-A New Constraint on the Optical Depth from the Reionization History Independent of CMB Large-Scale E-Mode Polarization

CoCoRI τ A

CoReCon for Cobaya Reionization Inference on τ Analysis



In collaboration
with Prof. Enrico
Garaldi



What is CoReCon?

corecon

CoReCon

latest

Search docs

Using CoReCon

Functions Documentation

Available constraints

Adding your constraint

/ CoReCon: open Collection of Reionization Constraints

View page source

CoReCon

CoReCon: open Collection of Reionization Constraints

CoReCon is an open collection of constraints on various physical quantities linked to the *Epoch of Reionization (EoR)*.

It is built to be easily complemented by contribution from the scientific community, thanks to a simple data form that supports two different ways of input data.

CoReCon takes care of loading and interpreting the data, and presenting them in an organic and ready-to-use way. It also implement simple slicing capabilities, which allow to perform simple data filtering.

A square QR code with a red and black pixelated pattern, used for quick access to the CoReCon website.

Credits: E. Garaldi-CoReCon: an open, community-powered collection of Reionization constraints

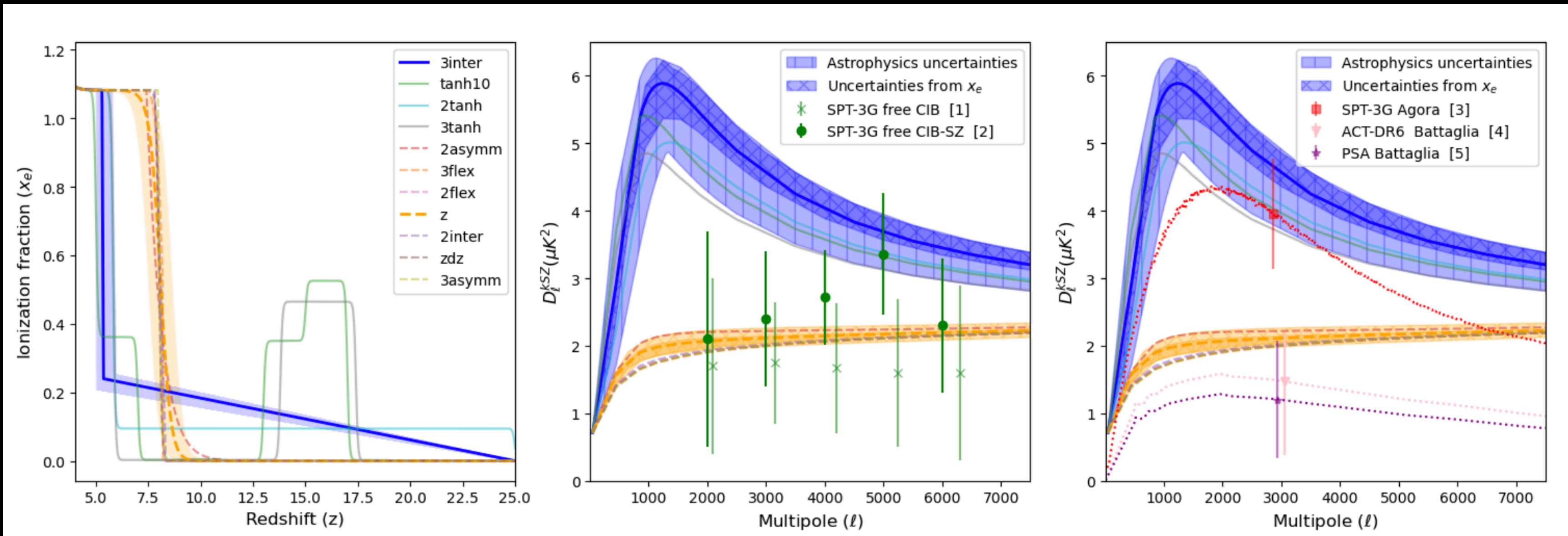
35

A single red puzzle piece is centered in a field of white puzzle pieces. The red piece is slightly offset from the grid, creating a sense of being out of place. The text "Are we missing something?" is written in bold black font on the red piece.

**Are we
missing
something?**

Kinetic Sunyaev–Zel’dovich vs Reionization histories

The total (late + patchy) kSZ compared with binned estimates from SPT-3G { Late = after the end of reionisation
Patchy= during reionisation

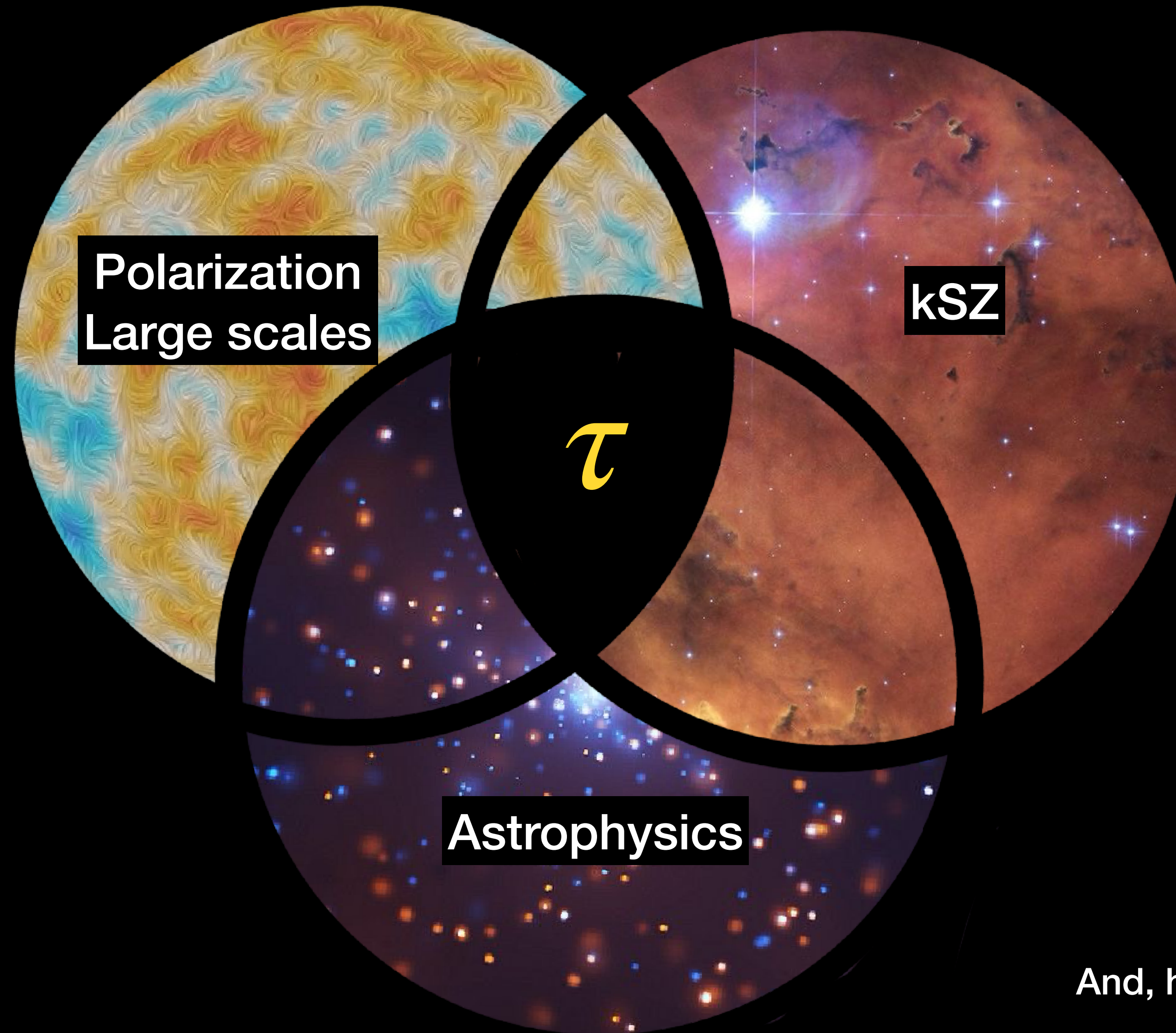


‘early’ history spectra dominated by the patchy contribution.

‘late’ history spectra dominated by the late-time contribution.

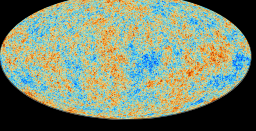
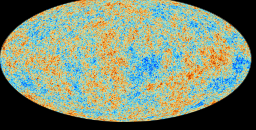
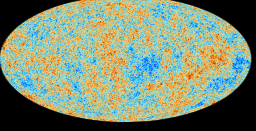
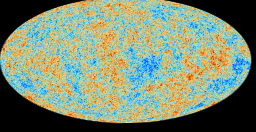
Credits: M. Douspis-Discriminating Planck Reionisation Histories with the kSZ Effect

When you want to play with reionization keep in mind the bigger picture:



And, hopefully, soon the 21 cm signal.

In conclusion:

-  ELiCA exploited all available data on large scales for E-mode polarisation achieving the tightest bound on τ to date from CMB.
-  ELiCA provide the state of the art for large scales before LiteBIRD's cosmic variance limited case.
-  ELiCA severely constrains the possibility of explaining, or even significantly reducing, the tension between DESI-BAO and CMB observations with a high value of τ . A joint CMB–astrophysics analysis will be needed to clarify this tension.
-  The likelihood package can be installed via pip and used in Cobaya.

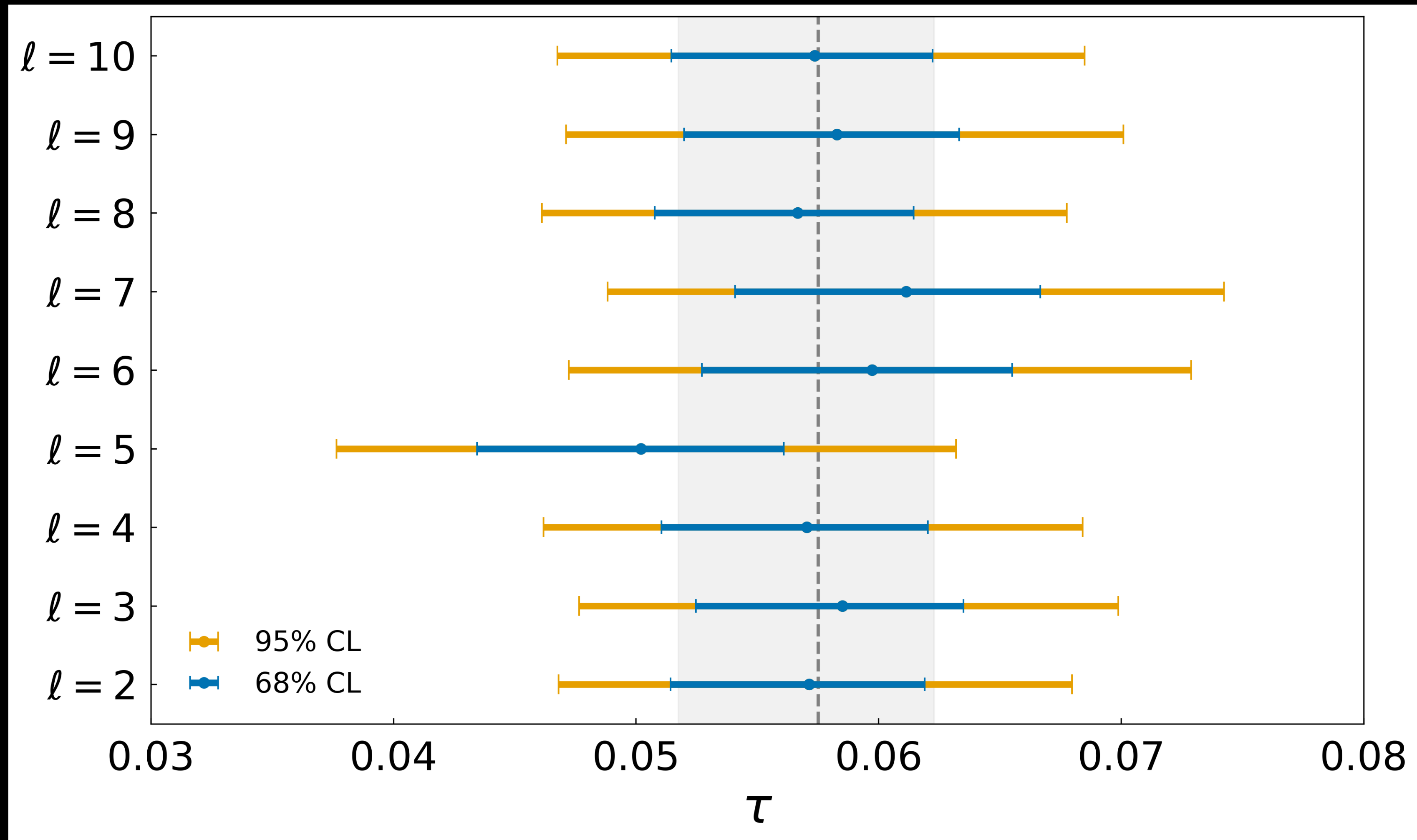


Check: Genesini et al.-Cross-spectra likelihood for robust τ constraints from all satellite polarisation data (2026) arXiv:2603.22454

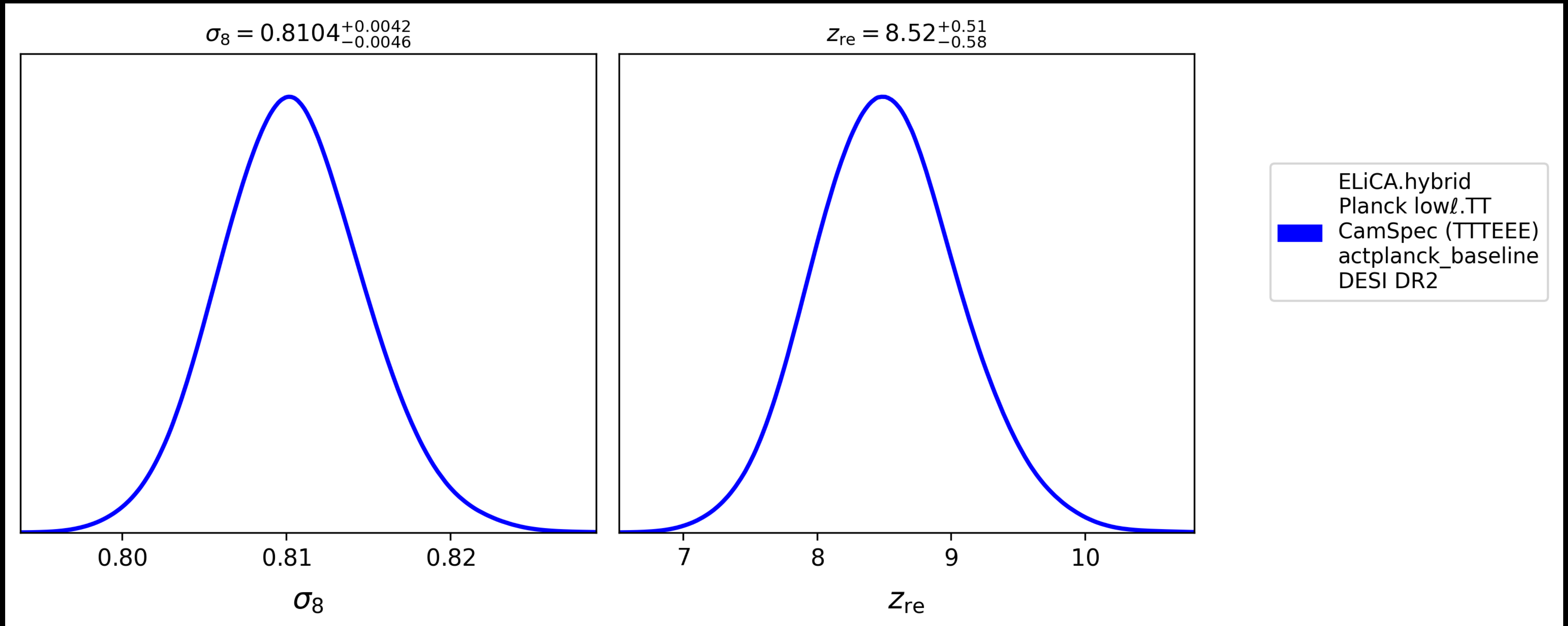
**Thanks for
the
attention**

What can ELiCA.hybrid reveal about low- ℓ modes?

Robustness check:



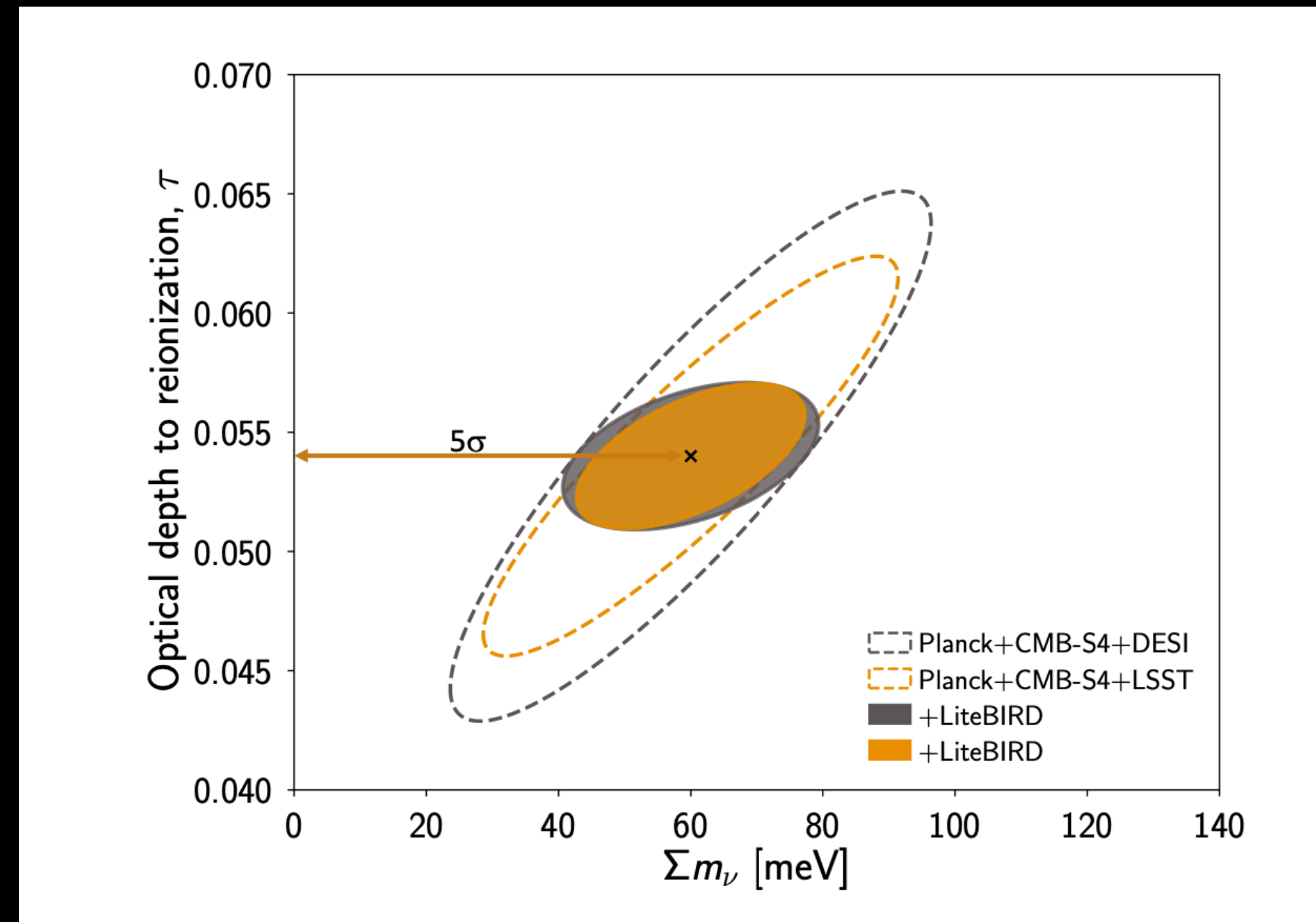
Derived parameters:



Check: Genesini et al. -Cross-spectra likelihood for robust τ constraints from all satellite polarisation data (2026)

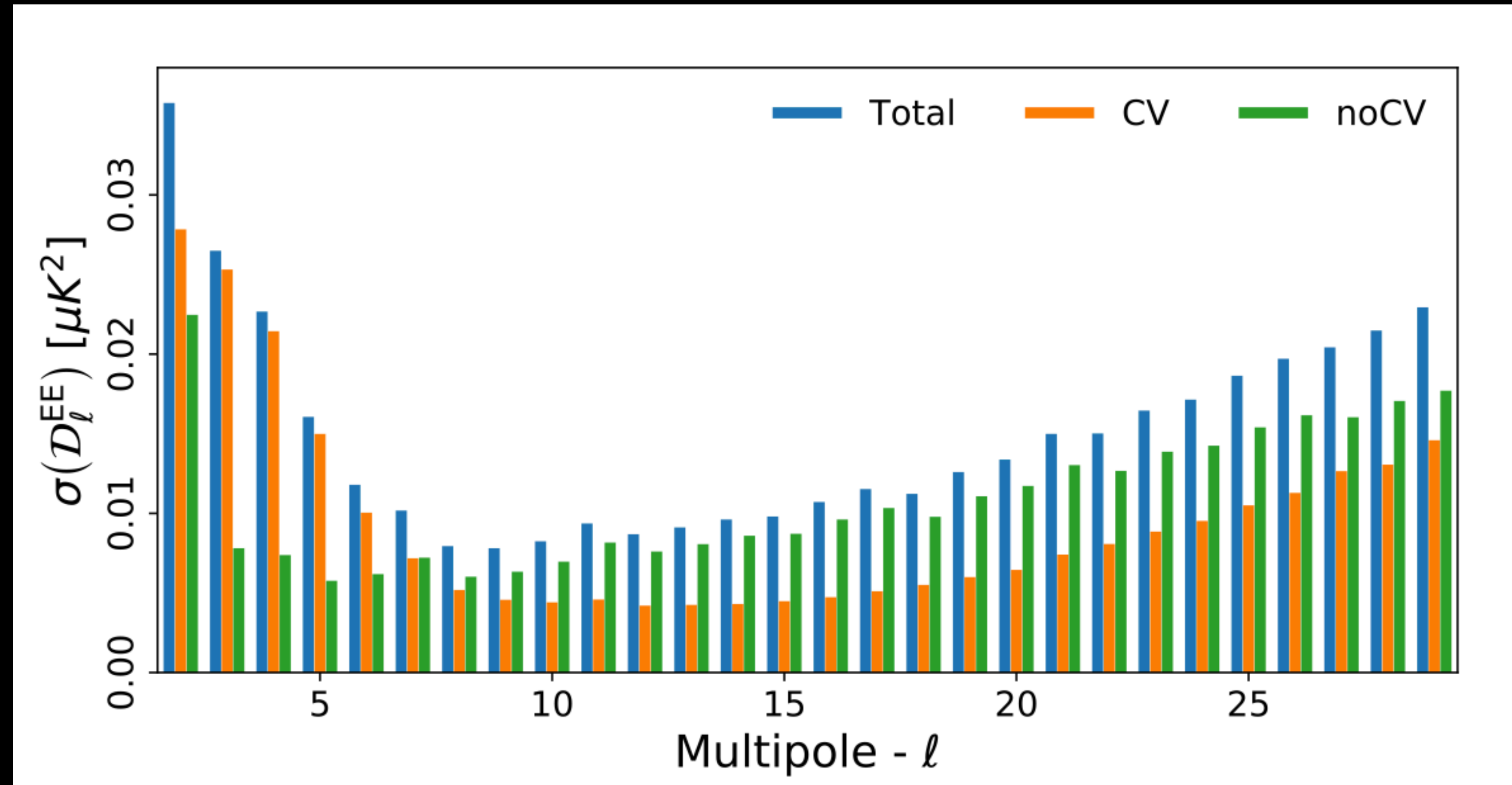
What is the impact of LiteBIRD's future τ constraint on extensions of the Λ CDM model?

Example:



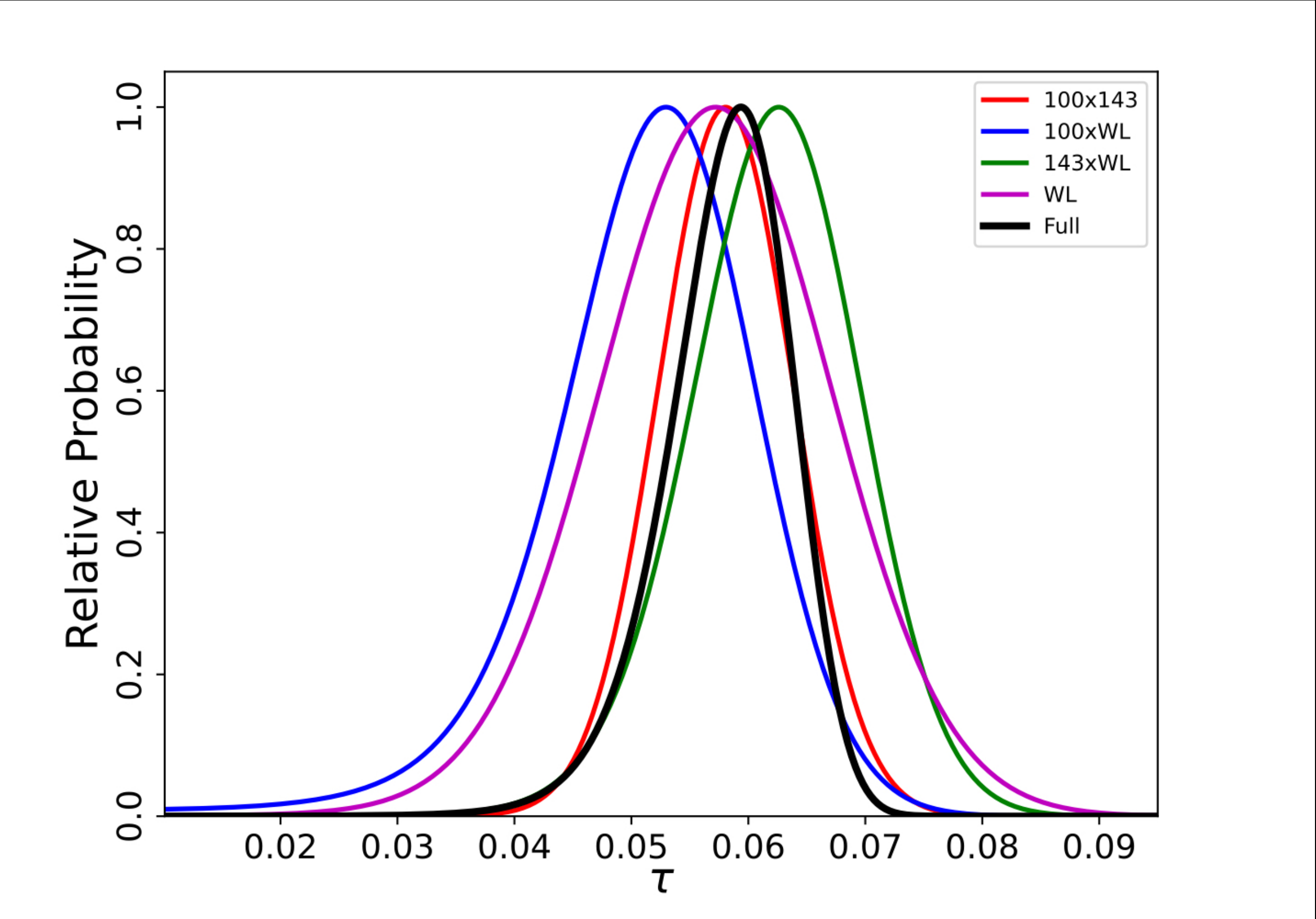
LiteBIRD collaboration. Probing cosmic inflation with the LiteBird cosmic microwave background polarization survey. (2022)

What about systematics?



Error comparison for 100x143 spectrum on 60% of the sky. In the plot you may see the total error (blue bar), the amount solely due to cosmic variance (orange), and that only due to noise and systematic effects (green). The cosmic variance shown corresponds to $\tau = 0.055$.

Constraint on the optical depth using oHL



Here I present the posterior for the datasets chosen.

Case	τ Constraint
100×143	0.0581 ± 0.0060
$100 \times WL$	0.0530 ± 0.0083
$143 \times WL$	0.0626 ± 0.0074
$WL \times WL$	0.057 ± 0.011
Full	0.0609 ± 0.0045