# LACK OF POWER ANOMALY with the latest Planck Temperature and Polarisation data

***Presented by:***

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**Cosmology from Home 2023**

Image credits:
The Planck Collaboration (ESA)

# OUTLINE

## 1. INTRODUCTION TO CMB RADIATION

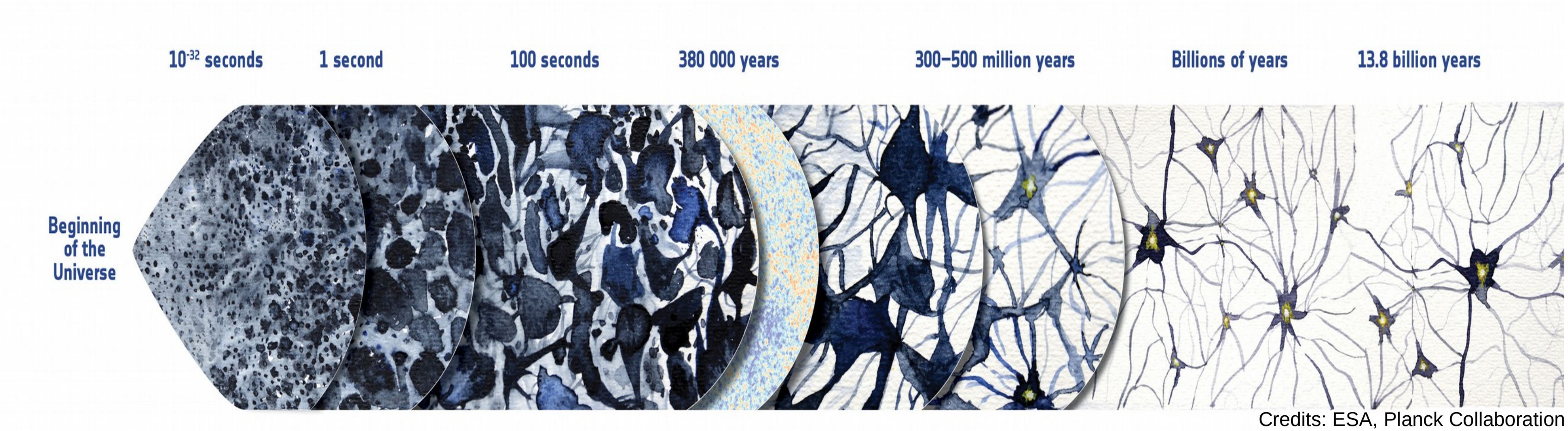
## 2. LACK OF POWER ANOMALY

- *M. Billi, A. Gruppuso, N. Mandolesi, L. Moscardini, P. Natoli.*
  *"Polarisation as a tracer of CMB anomalies: Planck results and future forecasts",*
  *Phys. Dark Univ. 26 (2019) 00327*

- *M. Billi, R.B. Barreiro, E. Martínez-González.*
  *"Lack of power anomaly: new constraints from Planck 2018 and 2020 temperature and polarisation data"*
  *To be submitted*

## 3. CONCLUSIONS

# 1.1 INTRODUCTION TO CMB



Credits: ESA, Planck Collaboration

**FIRST LIGHT EMITTED 380000 YEARS AFTER THE BIG-BANG, WHEN THE UNIVERSE BECOMES TRASPARENT**

**PERFECT BLACK-BODY SPECTRUM**

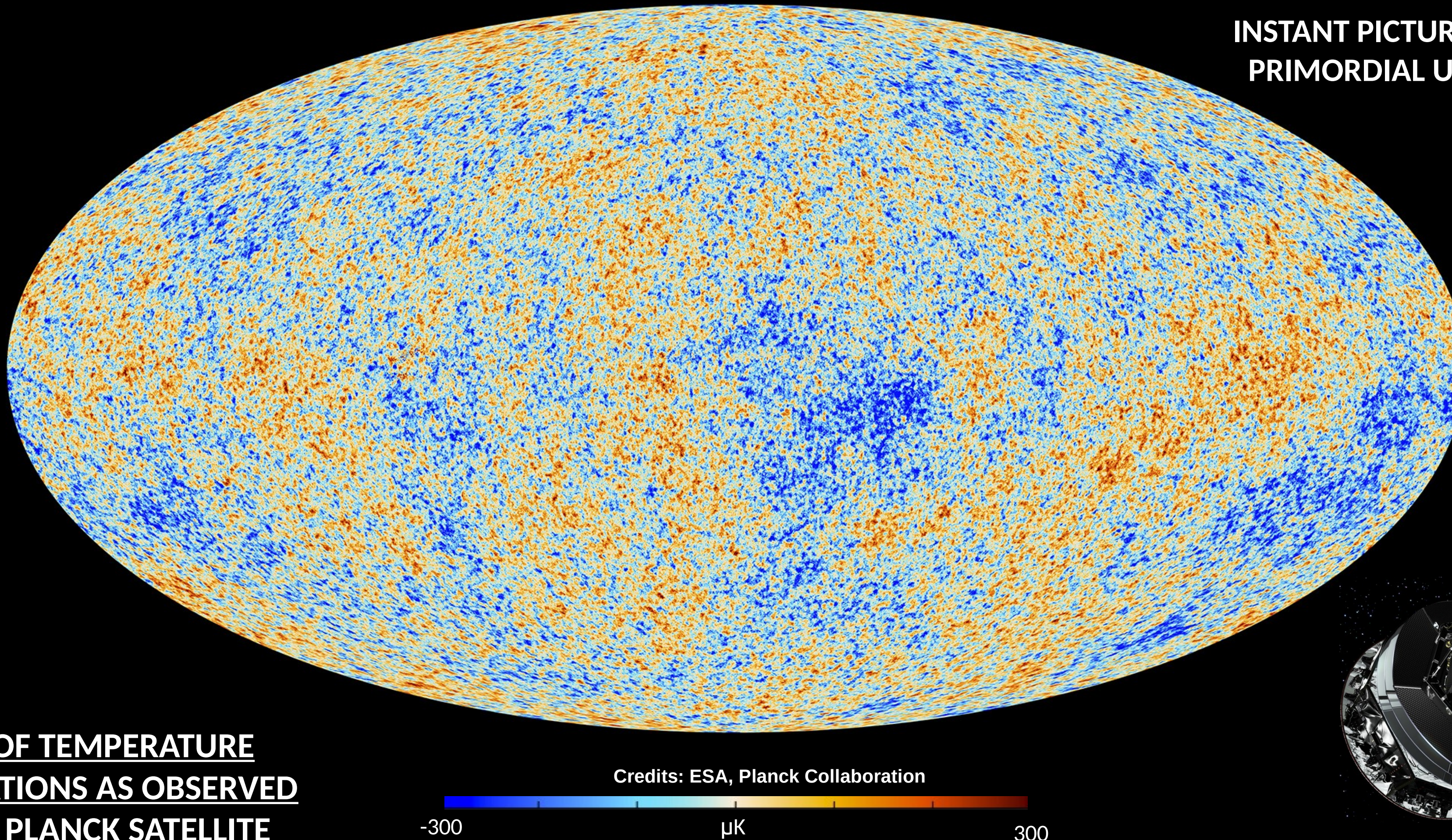
EVIDENCE FOR THE HOT BIG BANG MODEL

**CMB FLUCTUATIONS AT THE ORDER OF $10^{-5}$**

- EVIDENCE FOR THE COSMOLOGICAL PRINCIPLE
- TRACER OF INITIAL CONDITIONS FOR THE FORMATION OF LARGE SCALE STRUCTURES

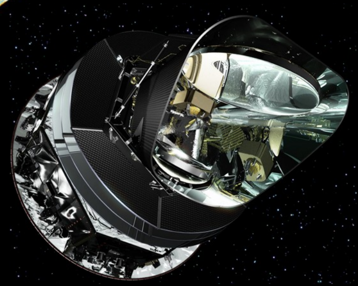
# 1.2 – CMB TEMPERATURE ANISOTROPIES

**INSTANT PICTURE OF THE PRIMORDIAL UNIVERSE**

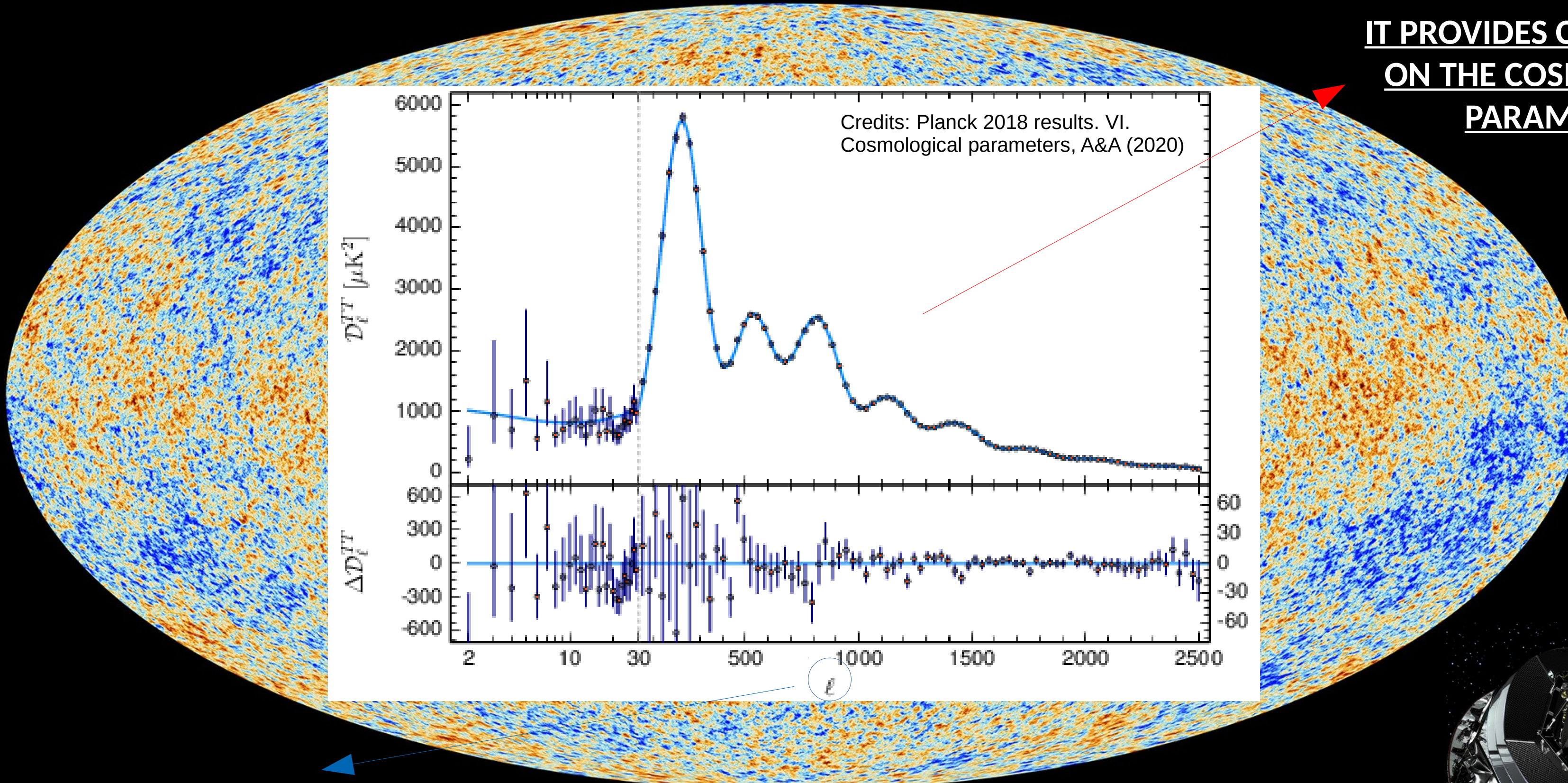



**MAP OF TEMPERATURE FLUCTUATIONS AS OBSERVED BY THE PLANCK SATELLITE**

**Planck Satellite**



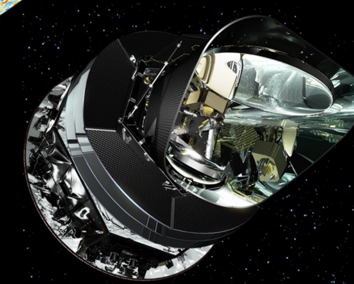
# 1.3 – CMB TEMPERATURE POWER SPECTRUM




**IT PROVIDES CONSTRAINTS ON THE COSMOLOGICAL PARAMETERS**

INVERSE OF THE ANGULAR DISTANCE

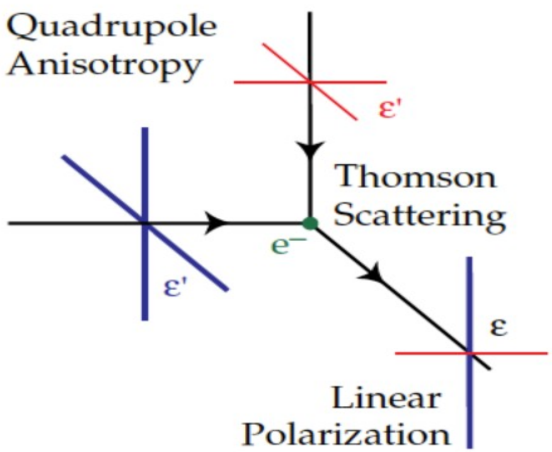
**Planck Satellite**



**CMB TEMPERATURE ANGULAR POWER SPECTRUM**

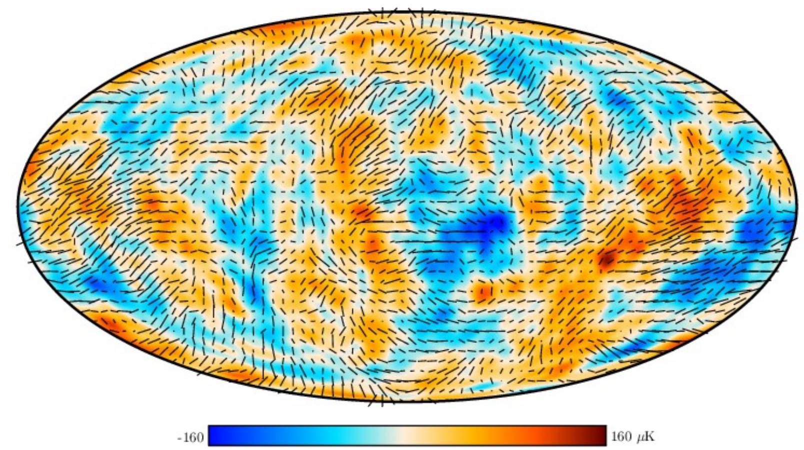
# 1.4 – CMB POLARISATION ANISOTROPIES

**THE CMB IS ALSO LINEARLY POLARISED AT THE LEVEL OF 10% DUE TO THOMSON SCATTERING OF FREE ELECTRONS AT THE LAST SCATTERING SURFACE**




**THOMSON SCATTERING AT THE SURFACE OF LAST SCATTERING**

Credits: Planck 2018 results. I. Overview and the cosmological legacy of Planck, A&A (2020)



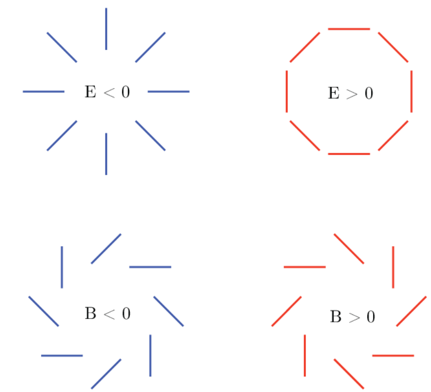

**LARGE-SCALE MAP OF THE CMB POLARISATION ANISOTROPIES**

# 1.5 – CMB POLARISATION POWER SPECTRA

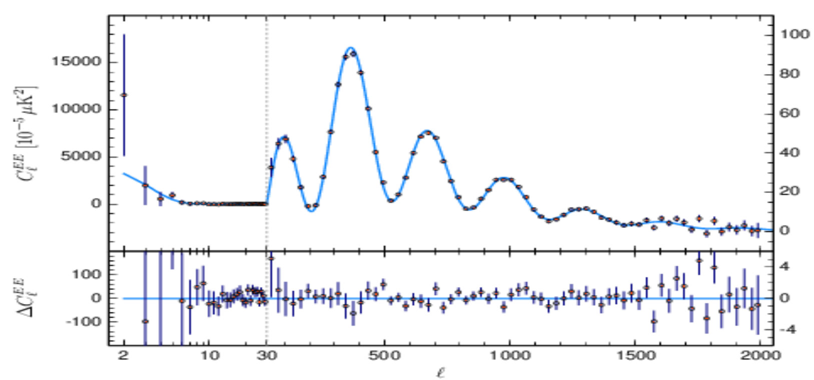
## E- AND B MODE FIELDS

**STARTING FROM THE OBSERVED Q AND U STOKES PARAMETERS, IN ORDER TO FORMULATE COSMOLOGICAL PREDICTIONS, TWO ROTATIONALLY INVARIANT QUANTITIES ARE BUILT**

E- and B-mode polarisation pattern

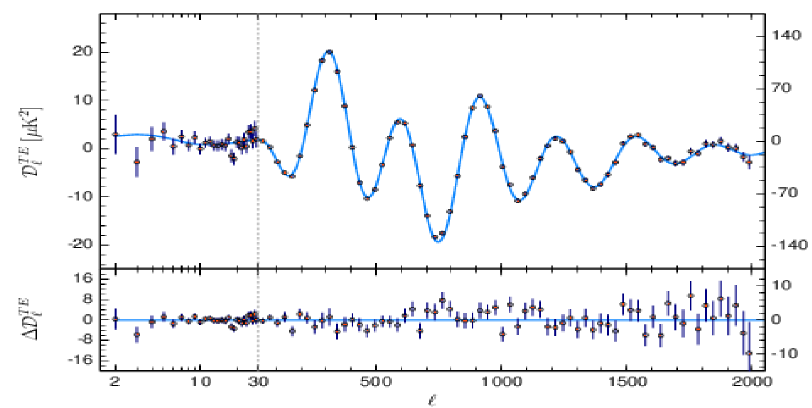



## EE ANGULAR POWER SPECTRUM

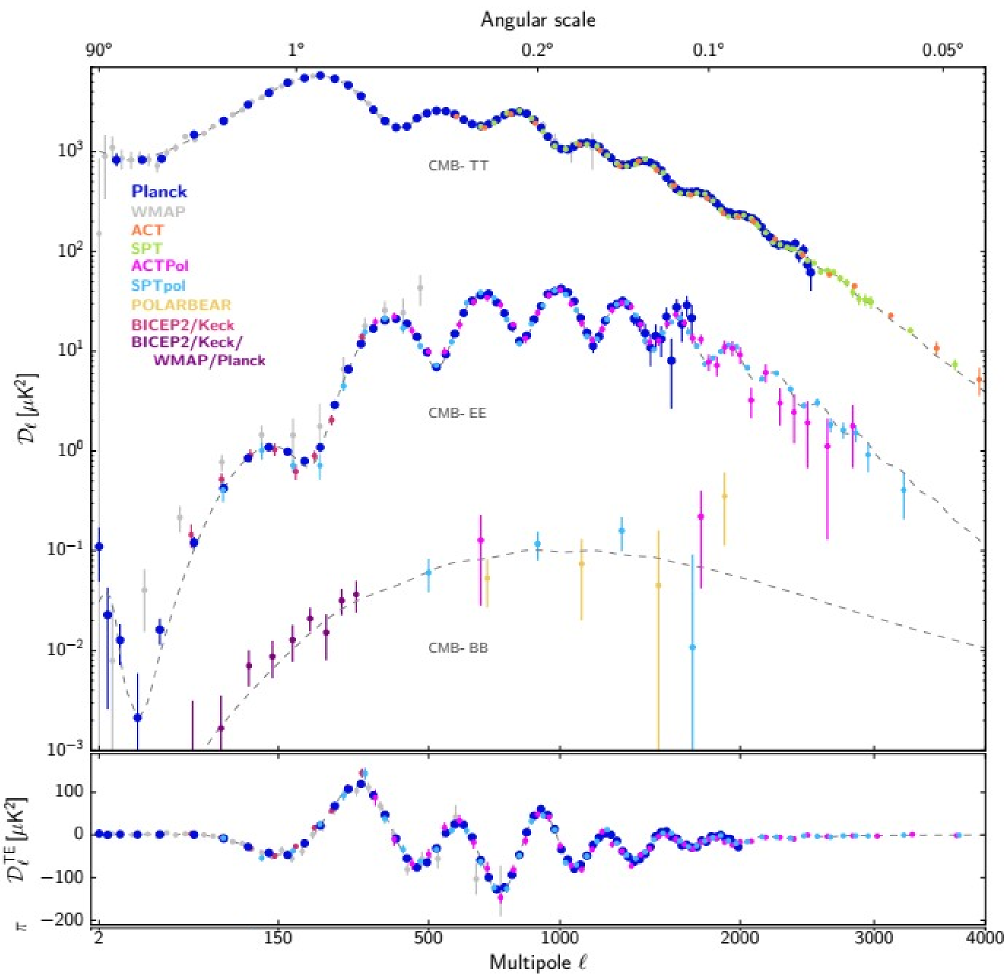



Credits: Planck 2018 results. VI. Cosmological parameters, A&A (2020)

## TE ANGULAR POWER SPECTRUM



# 1.6 – STATE OF ART AND FUTURE CHALLENGES




Credits: Planck 2018 results. I. Overview and the cosmological legacy of Planck, A&A (2020)

**POLARISATION REMAINS TO BE FULLY INVESTIGATED**

NEXT GENERATION CMB EXPERIMENTS:

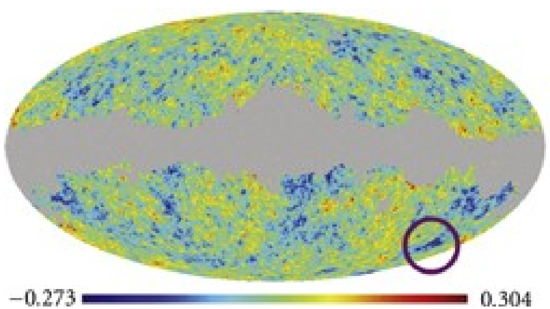
**PRIMORDIAL B-MODES**

**STANDARD SEARCH WITH B-MODES**

- PRIMORDIAL GRAVITATIONAL WAVES
- ENERGY SCALE OF THE INFLATION ERA
- CONSTRAINTS ON INFLATIONARY MODELS

# 2.1 – CMB ANOMALIES

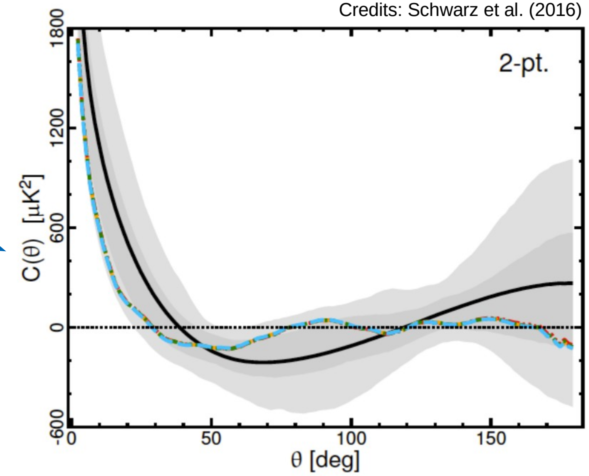
**UNEXPECTED FEATURES OBSERVED AT LARGE ANGULAR SCALE IN THE CMB MAPS THAT DEVIATE FROM ΛCDM MODEL WITH A STATISTICAL SIGNIFICANCE AROUND 2-3 σ C.L.**



Credits: Schwarz et al. (2016)

- **DIRECTIONAL ANOMALIES:**
  - a hemispherical power asymmetry;
  - alignments of low multipole moments.
- **ROTATIONALLY INVARIANT ANOMALIES:**
  - lack of power and lack of correlation at angular scales larger than 60 degrees;
  - a preference for odd parity modes.
- **LOCAL FEATURES:**
  - a large cold spot in the Southern hemisphere.

Credits: Schwarz et al. (2016)

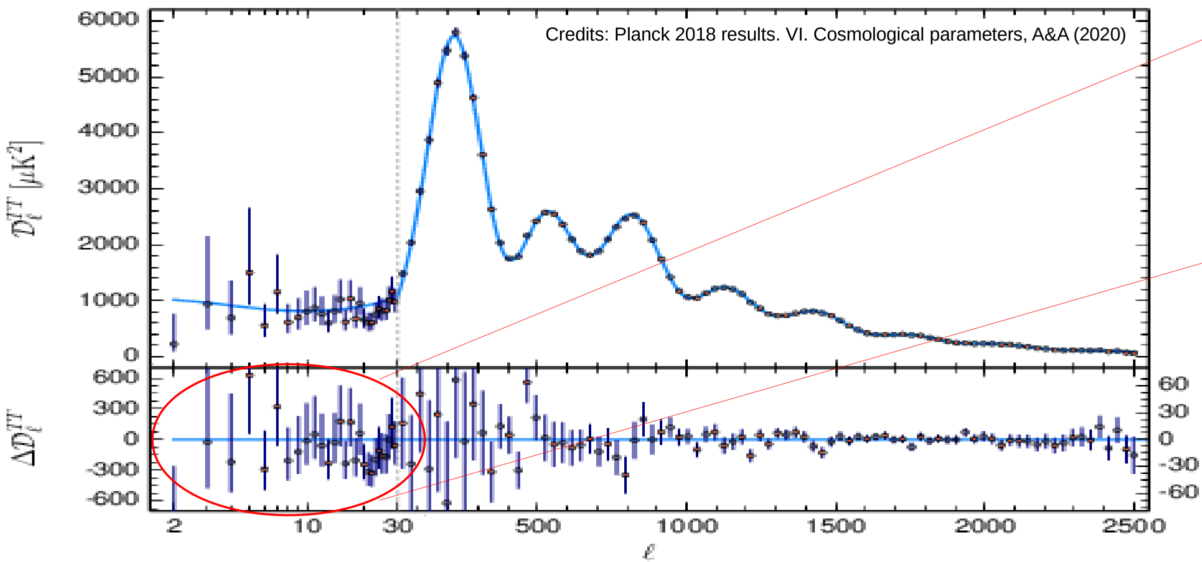


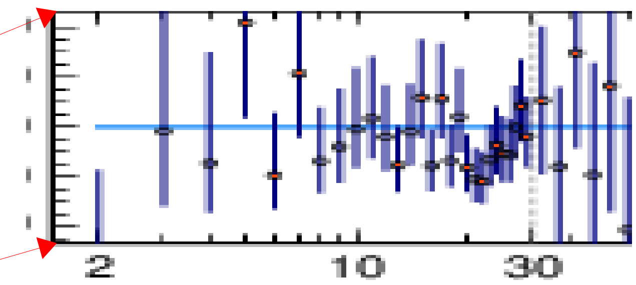

**INDEPENDENT EXPERIMENTS, WMAP AND PLANCK, ALL WELL AGREE ON THEM: LOW POSSIBILITY OF INSTRUMENTAL SYSTEMATICS**

**FUTURE CMB POLARISATION OBSERVATIONS ON LARGE SCALES WILL BE CRITICAL FOR THE UNDERSTANDING OF THESE FEATURES!**

# 2.2 – LACK OF POWER ANOMALY (LoP)

**MISSING POWER WITH RESPECT TO THAT PREDICTED BY THE ΛCDM MODEL:**
**studied with WMAP and Planck Temperature data**




***NEW COSMOLOGICAL PHASE BEFORE THE STANDARD INFLATIONARY ERA***

**LOW STATISTICAL SIGNIFICANCE WITH ONLY OBSERVATIONS IN TEMPERATURE**

**WE DEVELOP A NEW 1-D ESTIMATOR ABLE TO CONSTRAIN THE LoP ANOMALY TAKING JOINTLY INTO ACCOUNT BOTH TEMPERATURE AND POLARISATION DATA**

# 2.3 – NORMALISED ANGULAR POWER SPECTRA

AT LARGE ANGULAR SCALES TT, EE AND TE POWER SPECTRA HAVE AMPLITUDES WITH DIFFERENT ORDER OF MAGNITUDE

**NORMALISED ANGULAR POWER SPECTRA (NAPS)**

$$x_\ell^{(1)} = \frac{C_\ell^{TT}}{C_\ell^{TT,th}}$$

$$a_\ell \equiv \sqrt{C_\ell^{TE,th} C_\ell^{TT,th} - (C_\ell^{TE,th})^2}$$

$$x_\ell^{(2)} = \frac{C_\ell^{TT,th}}{a_\ell^2} C_\ell^{EE} - \frac{C_\ell^{TT,th}}{a_\ell^2} \left( \frac{C_\ell^{TE,th}}{C_\ell^{TT,th}} \right)^2 C_\ell^{TT} - 2 \frac{C_\ell^{TE,th}}{a_\ell^2} \left[ C_\ell^{TE} - \frac{C_\ell^{TE,th}}{C_\ell^{TT,th}} C_\ell^{TT} \right]$$

**DIMENSIONLESS AND SIMILAR AMPLITUDE NUMBERS**

$$\langle x_\ell^{(1)} \rangle = \langle x_\ell^{(2)} \rangle = 1$$

**THEY CAN BE COMBINED TO DEFINE A 1-D ESTIMATOR IN HARMONIC SPACE**

# 2.4 – NEW ESTIMATORS FOR THE LoP

## OPTMISED JOINT ESTIMATOR

$$E_V^{joint} = \sum_{\ell=2}^{\ell_{max}} \left[ \frac{(2\ell+1)}{4\pi} \alpha_\ell x_\ell^{(1)} + \beta_\ell x_\ell^{(2)} \right] - 2 \quad \Rightarrow \quad \langle E_V^{joint} \rangle = 0$$

METHOD OF LAGRANGIAN MULTIPLIERS

$$\alpha_\ell = \frac{2}{\Gamma_{\ell_{max}}} \frac{var(x_\ell^{(2)}) - cov(x_\ell^{(1)}, x_\ell^{(2)})}{var(x_\ell^{(1)}) var(x_\ell^{(2)}) - cov^2(x_\ell^{(1)}, x_\ell^{(2)})}$$

TEMPERATURE COEFFICIENTS

$$\beta_\ell = \frac{2}{\Gamma_{\ell_{max}}} \frac{var(x_\ell^{(1)}) - cov(x_\ell^{(1)}, x_\ell^{(2)})}{var(x_\ell^{(1)}) var(x_\ell^{(2)}) - cov^2(x_\ell^{(1)}, x_\ell^{(2)})}$$

POLARISATION COEFFICIENTS

MINIMUM VARIANCE 1D-ESTIMATOR WHICH DEPENDS ON TT, EE AND TE CMB POWER SPECTRA

+

## OPTIMISED ESTIMATOR BASED ON $x^{(1)}$

$$E_V^{(1)} = \sum_{\ell=2}^{\ell_{max}} \left[ \frac{(2\ell+1)}{4\pi} \frac{[var(x_\ell^{(1)})]^{-1}}{[var^{TOT}]^{-1}} x_\ell^{(1)} \right] - 1$$

## OPTIMISED ESTIMATOR BASED ON $x^{(2)}$

$$E_V^{(2)} = \sum_{\ell=2}^{\ell_{max}} \left[ \frac{(2\ell+1)}{4\pi} \frac{[var(x_\ell^{(2)})]^{-1}}{[var^{TOT}]^{-1}} x_\ell^{(2)} \right] - 1$$

$$\langle E_V^1 \rangle = \langle E_V^2 \rangle = 0$$

# 2.5 – DATA AND SIMULATIONS

## Planck DATA + REALISTIC SIMS

$2 \leq \ell \leq 31$

### Planck 2018 (PR3)

Planck component-separation methods:

- COMMANDER
- NILC
- SEVEM
- SMICA

### Planck 2020 (PR4)

Planck component-separation methods:

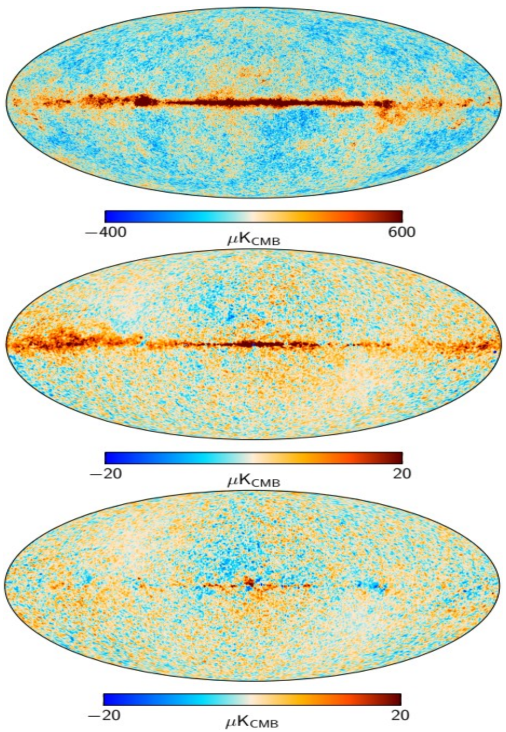
- COMMANDER
- SEVEM

TO TEST THE ROBUSTNESS OF THE ANALYSIS WE APPLY OUR APPROACHES TO ALL THE PIPELINES OBTAINING WELL COMPATIBLE RESULTS FOR EACH DATASET

**Previous work (Billi et al. 2019): Lack of Power anomaly with Planck 2015 Data (PR2)**
when polarisation is taken into account the statistical significance of this feature increases

# 2.6 – PREPARATION OF THE DATASETS

## OBSERVABLES



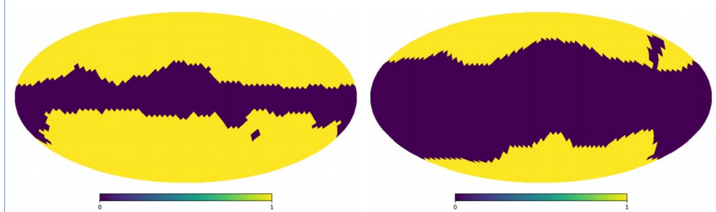

*Planck Collaboration 2020, A&A, 641, A2*

**HIGH RESOLUTION T,Q,U MAPS**

LOW RESOLUTION MAPS

↓

SKY MASKS




T MASK:

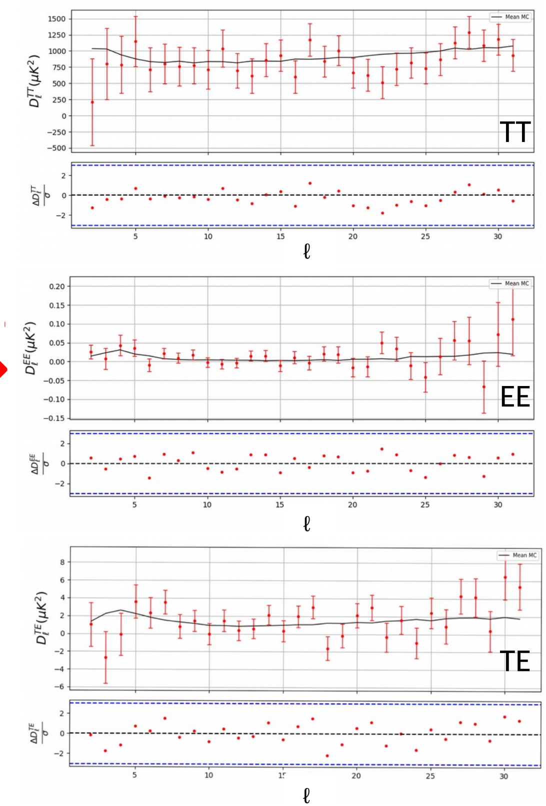
$f_{sky}$ = 71.4%

Q,U MASK:

$f_{sky}$ = 34.3%

***QML-METHOD "ECLIPSE"***

## INPUT ESTIMATORS

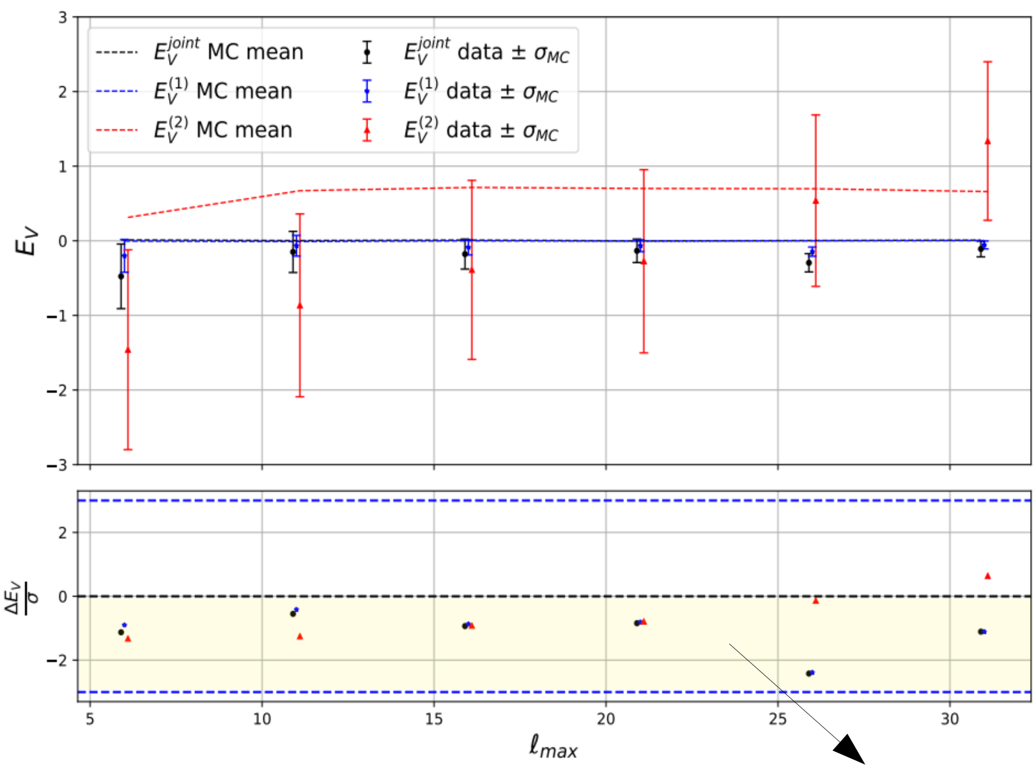



**ANGULAR POWER SPECTRA**
(PR4 SEVEM Data)

# 2.7 – APPLICATION TO PLANCK DATASETS: SEVEM PIPELINE

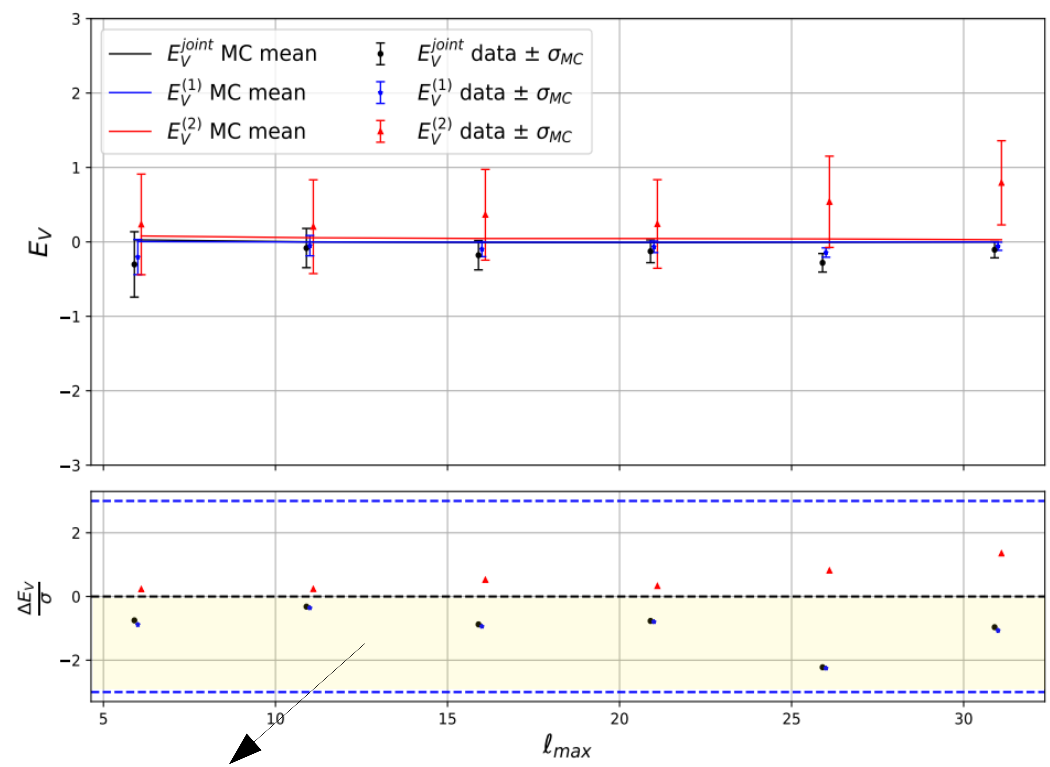
## Planck 2018 Data

DATA + 300 MC SIMULATIONS




## Planck 2020 Data

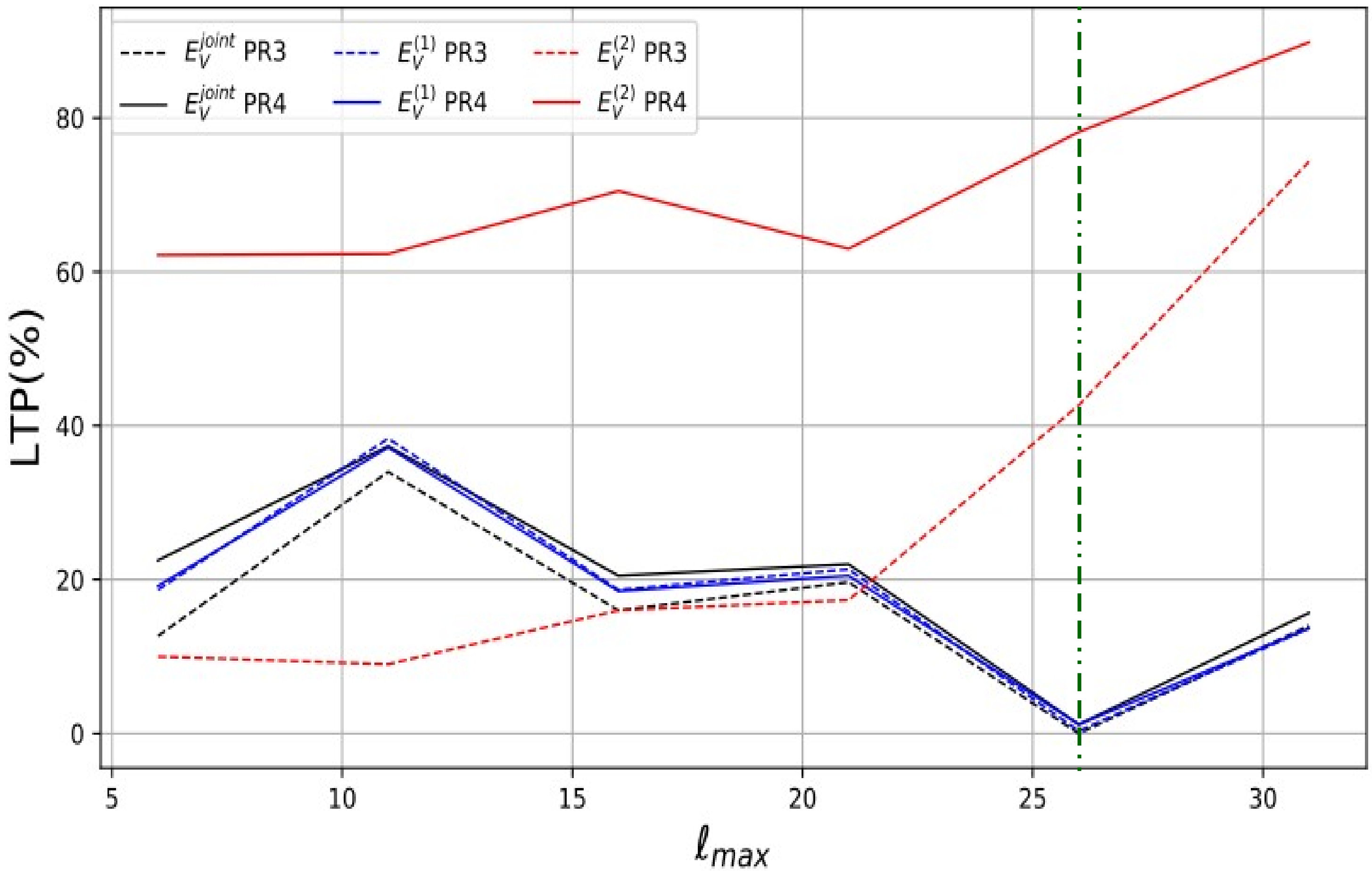
DATA + 600 MC SIMULATIONS




**POSSIBLE LACK OF POWER**

# 2.8 – LOWER-TAIL-PROBABILITY

## IN ORDER TO QUANTIFY THE STATISTICAL SIGNIFICANCE OF THIS ANOMALY WE CONSIDER THE LOWER-TAIL-PROBABILITY (LTP)




**LTP (%) AT $\ell_{max}$=26**

| PR3 | PR4 | |
|---|---|---|
| 0.33 % | 1.16 % | $E_{V(1)}$ |
| 42.66 % | 78.16 % | $E_{V(2)}$ |
| **< 0.33%** | 1.16 % | $E_{Vjoint}$ |

No sims as small as the data!

# 2.9 – TEMPERATURE AND POLARISATION CONTRIBUTION

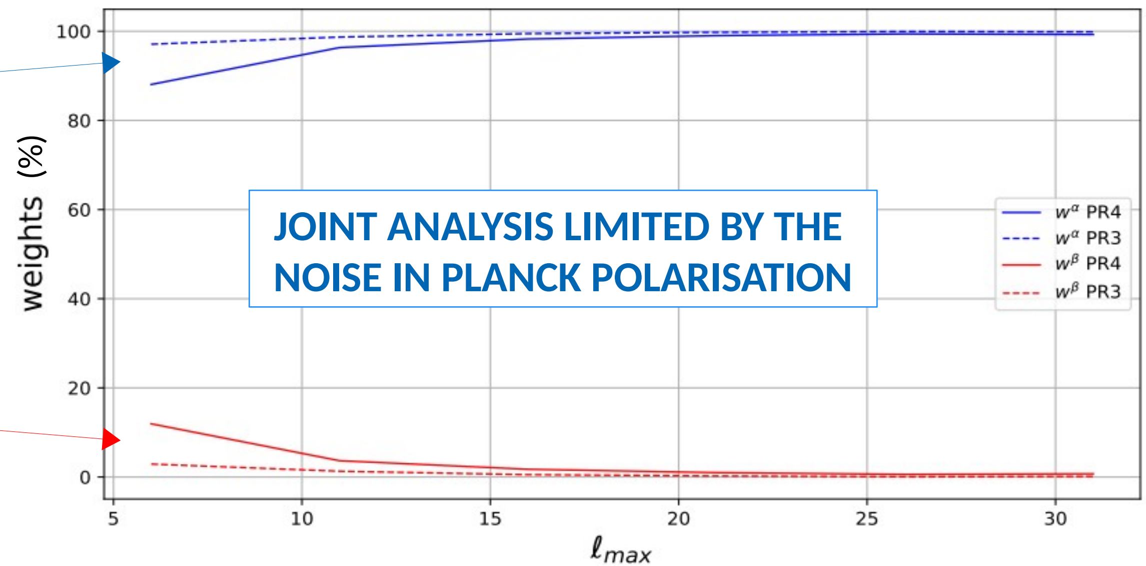
**WE DEFINE SPECIFIC WEIGHTS TO EVALUATE THE IMPACT OF POLARISATION AND TEMPERATURE DATA ON THE JOINT ESTIMATOR**

$$w_\alpha = \sum_{\ell=2}^{\ell_{max}} \left( \frac{(2\ell+1)}{8\pi} \alpha_\ell \right)$$

TEMPERATURE WEIGHTS

$$w_\beta = \sum_{\ell=2}^{\ell_{max}} \left( \frac{(2\ell+1)}{8\pi} \beta_\ell \right)$$

POLARISATION WEIGHTS




| | $W_\alpha$ | $W_\beta$ |
|---|---|---|
| **PR3** | 99.9 % | 0.1% |
| **PR4** | 99.4 % | 0.6% |

# 2.10 – CONCLUSIONS

In this talk we focused on **LACK OF POWER ANOMALY**, which might hint at the existence of new phenomena beyond the ΛCDM cosmological model.

We proposed **new optimised estimators** able to test the lack of power in **TT, TE and EE** at largest angular scales.

We apply these estimators on **PLANCK 2018** and **2020 DATA,** finding:

- the estimator based **only on temperature data confirms the presence of a lack of power** with a **LTP** equal to **0.33% (PR3)** and to **1.16% (PR4)**;
- we find significant **differences** between **PR3 and PR4** datasets when **polarisation** is taken into account, most likely **due to the different level of systematics**;
- the **joint estimator** is **limited by noise in Planck polarisation** data.

THANK YOU FOR YOUR ATTENTION!