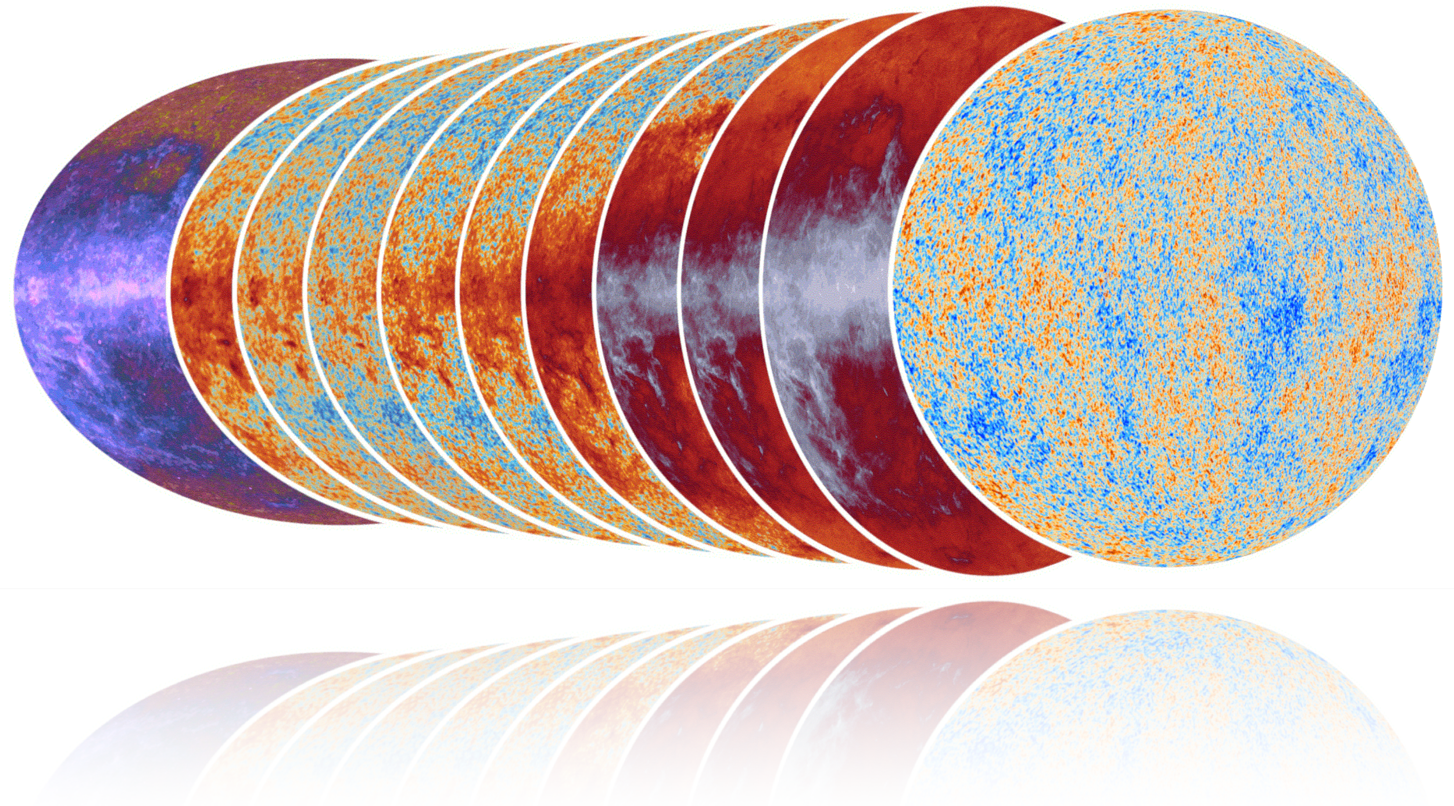

Cosmological parameters derived from the final Planck (PR4) data release

M. Tristram

ADE #7, Annecy, Nov 2023

PLANCK NPIPE Team

Cosmological parameters derived from the final (PR4) *Planck* data release

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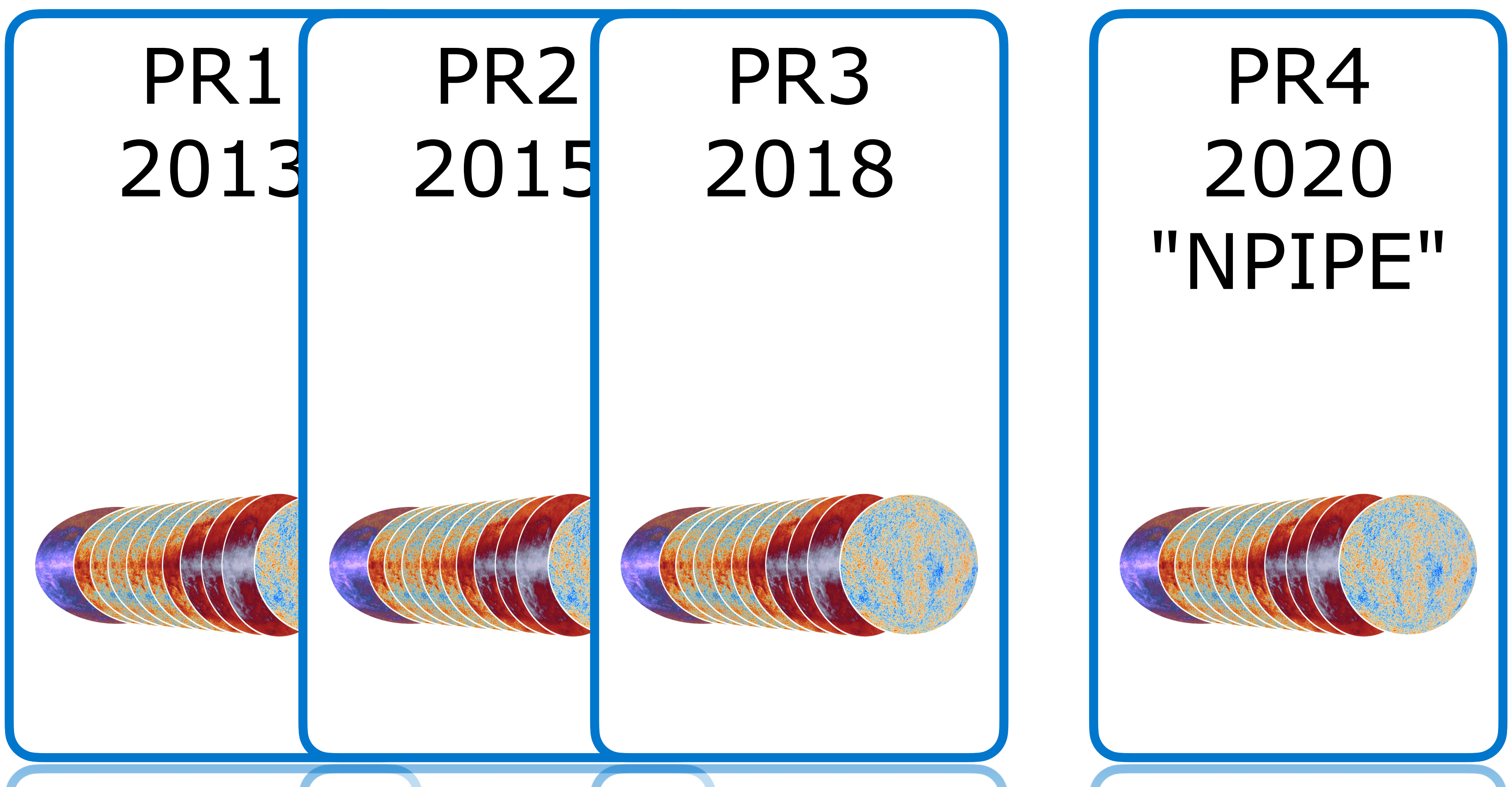
[Tristram et al. A&A (2023)]
astro-ph/2309.10034

PLANCK polarization data

- PLANCK detectors were sensitive to **one polarization direction**
- PLANCK scanning strategy did not allow for polarization reconstruction for each detector independently
  - ➡ need to **combine detectors** with different polarization orientation
- Any flux **mismatch** between detectors create spurious polarization signal through well known **I-to-P leakage**.
  In particular : ADC non-linearity, bandpass mismatch, calibration mismatch, …

this is the major Planck systematic in polarization at large scales



[Planck Collaboration Int. LVII (2020)]

PLANCK Release 4

NPIPE processing

[Planck Collaboration Int. LVII (2020)]

- **Processing applied consistently over the whole 9 PLANCK frequencies (from 30 GHz to 857 GHz)** NEW

- **NPIPE map-making includes templates for**
  - systematic effects
    (time transfer-function, ADC non-linearities, Far Side Lobes, bandpass-mismatch)
  - sky-asynchronous signals (orbital dipole, zodiacal light)

- **Provide frequency maps**
  - **cleaner**: less residuals (compared to PR3) at the price of a non-zero transfer function at large scale in polarization
  - **more accurate**: less noise (compared to PR3)
  - no residuals from template resolution mismatch (as visible in PR3)

- **Provide independent split-maps** NEW
  - PR3: time-split (half-mission or half-ring) ➡ correlated
  - PR4: detector-split (detset) ➡ independent

- **Provide low-resolution maps with pixel-pixel noise covariance estimates across all PLANCK frequencies** NEW

PLANCK Release 4

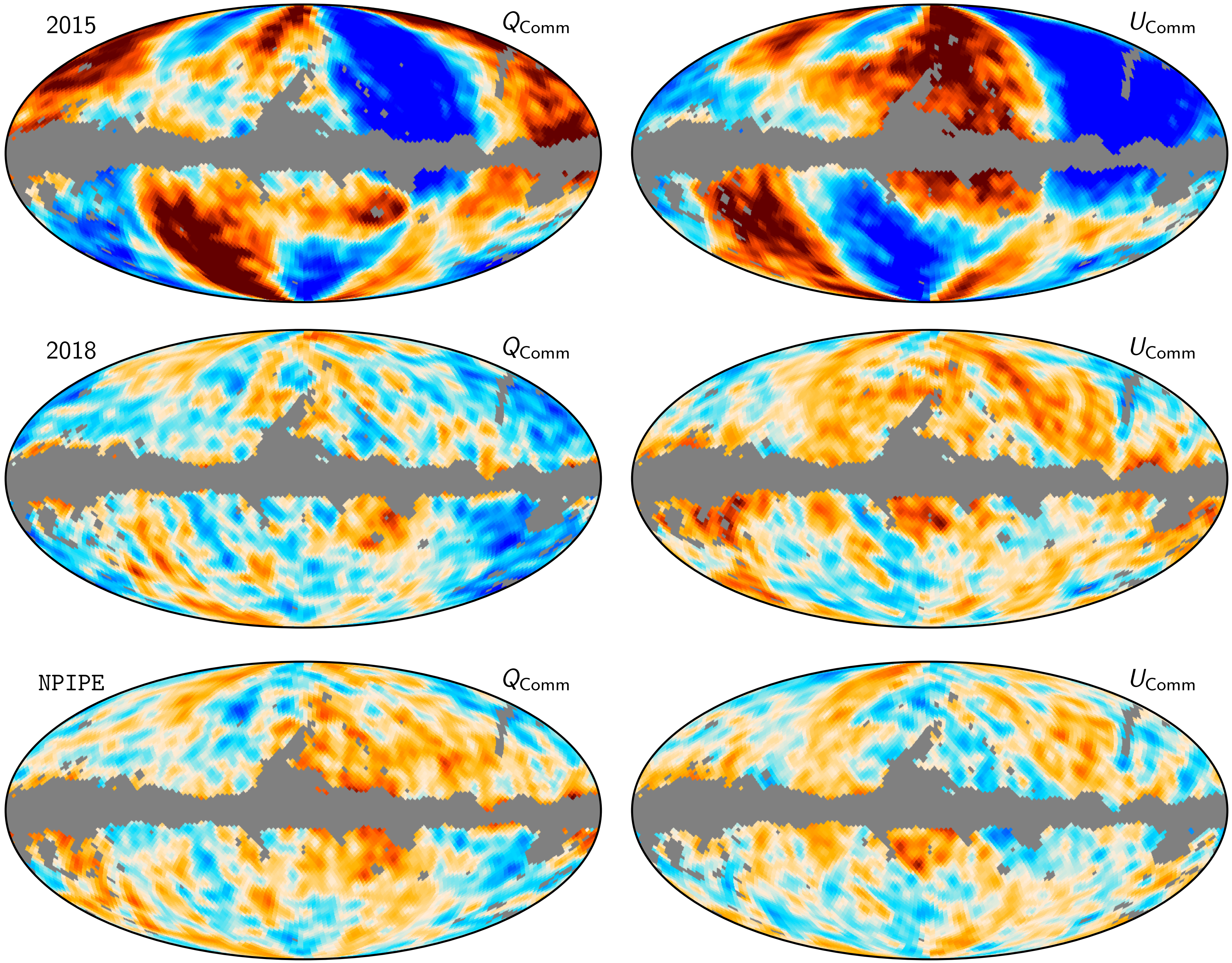
CMB polarized maps

[Planck Collaboration Int. LVII (2020)]

PR2
(2015)

PR3
(2018)

PR4
(2020)



Commander CMB Q and U maps
(large scale, 5° smoothing)

PLANCK Release 4

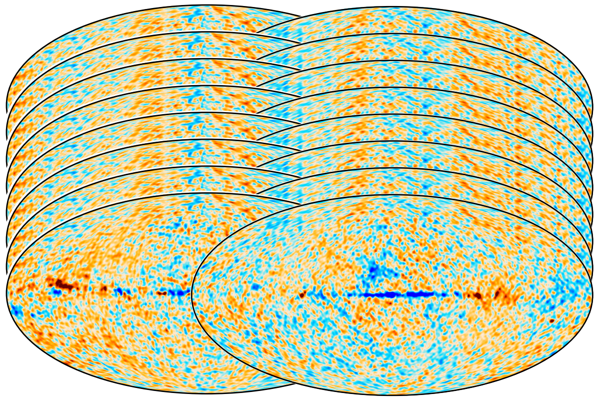
NPIPE simulations

[Planck Collaboration Int. LVII (2020)]

a realistic simulation set is essential to properly assess uncertainties especially at large angular scales

NEW

- **600 consistent simulations (frequency and split maps) - 36 TB**
- **Inputs**
  - including instrumental noise (consistent with data-split differences)
  - including models for systematics (ADC non-linearity)
  - random CMB with 4pi beam convolution
  - foreground sky model based on Commander PLANCK solution



- **Allow for**
  1. accurate effective description of the noise and **covariance** of the maps (including noise, instrumental systematics, foreground residuals)
  2. estimation of the **transfer function** of the PLANCK processing

Planck PR4 likelihoods

[Tristram+ (2023)]

Planck likelihoods are splits in **two parts** due to different **statistical assomptions**

large scales (low ℓ)

- **lowT: Commander**
  [Planck Collaboration V 2020]

Bayesian posterior Gibbs sampling that combines astrophysical component separation and likelihood estimation

- **lowE(B): Lollipop**
  [Tristram et al. 2022]

H&L likelihood based on cross-spectra between CMB clean maps on 50% of the sky

ℓ = 2-30

small scales (high ℓ)

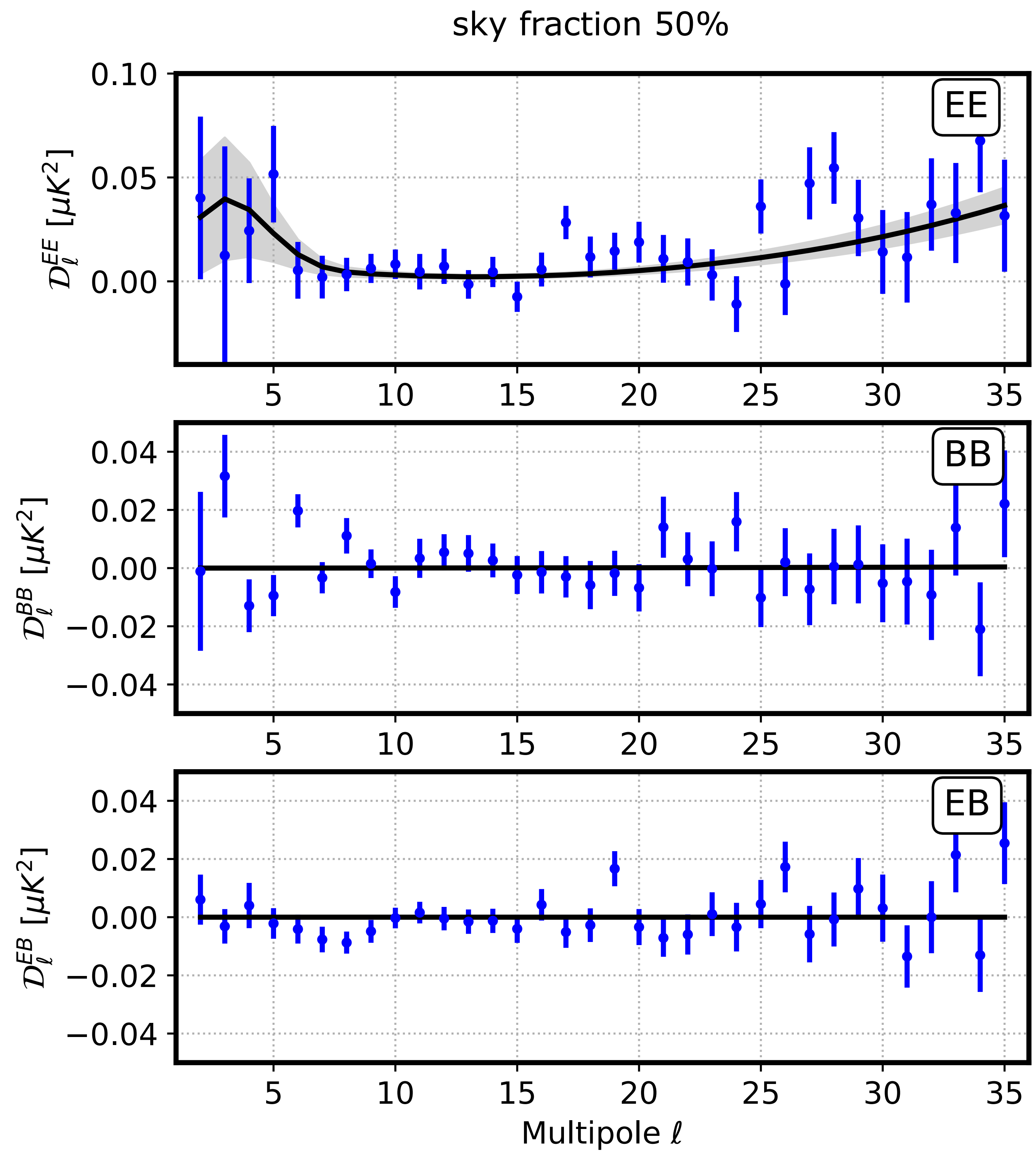
- **Hillipop: TT, TE, EE, TTTEEE**
  [Tristram et al. 2023]

Gaussian likelihood based on cross-spectra from frequency maps on 75% of the sky, including models for the foreground residuals

ℓ = 30-2500

Lollipop

PR4 power-spectra



xQML

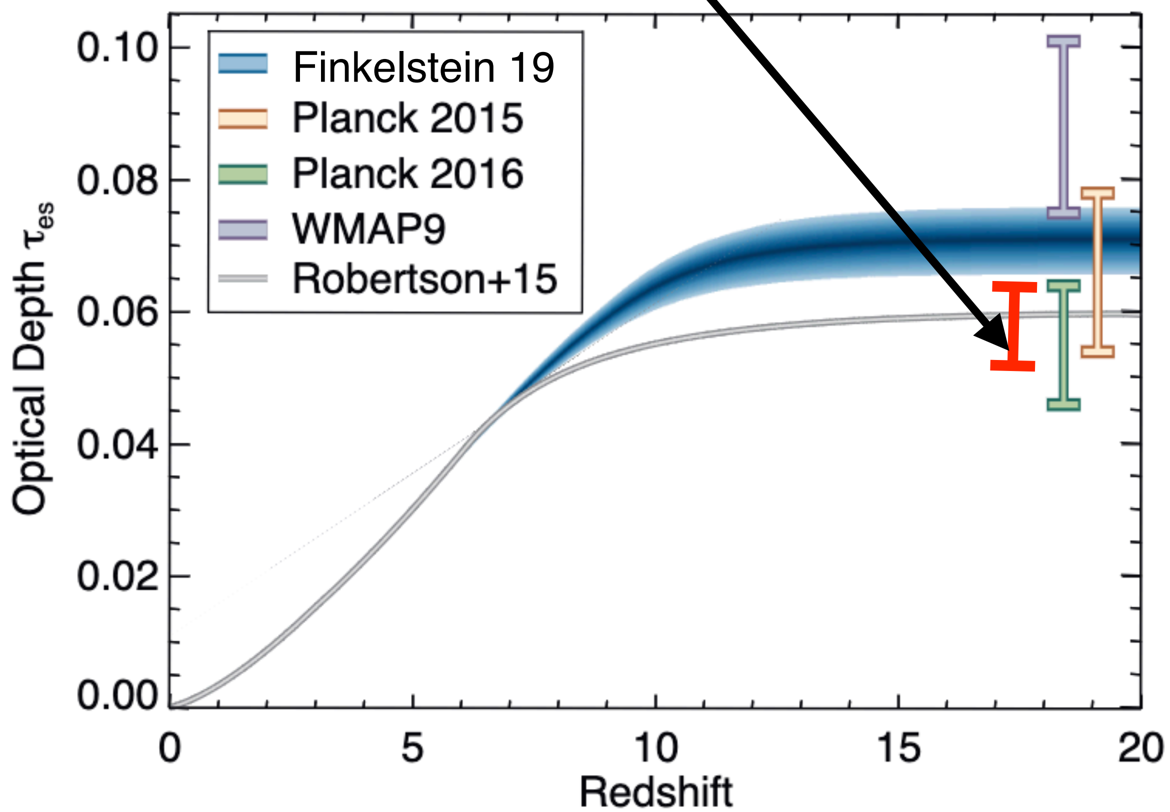
[https://gitlab.in2p3.fr/xQML]

Lollipop

Tensor-to-scalar ratio & Reionization

Reionization optical depth
(scattering of photons by free electrons)

$$\tau = 0.0580 \pm 0.0062$$



Galaxies become more efficient producers of ionizing photons at higher redshifts and fainter magnitudes

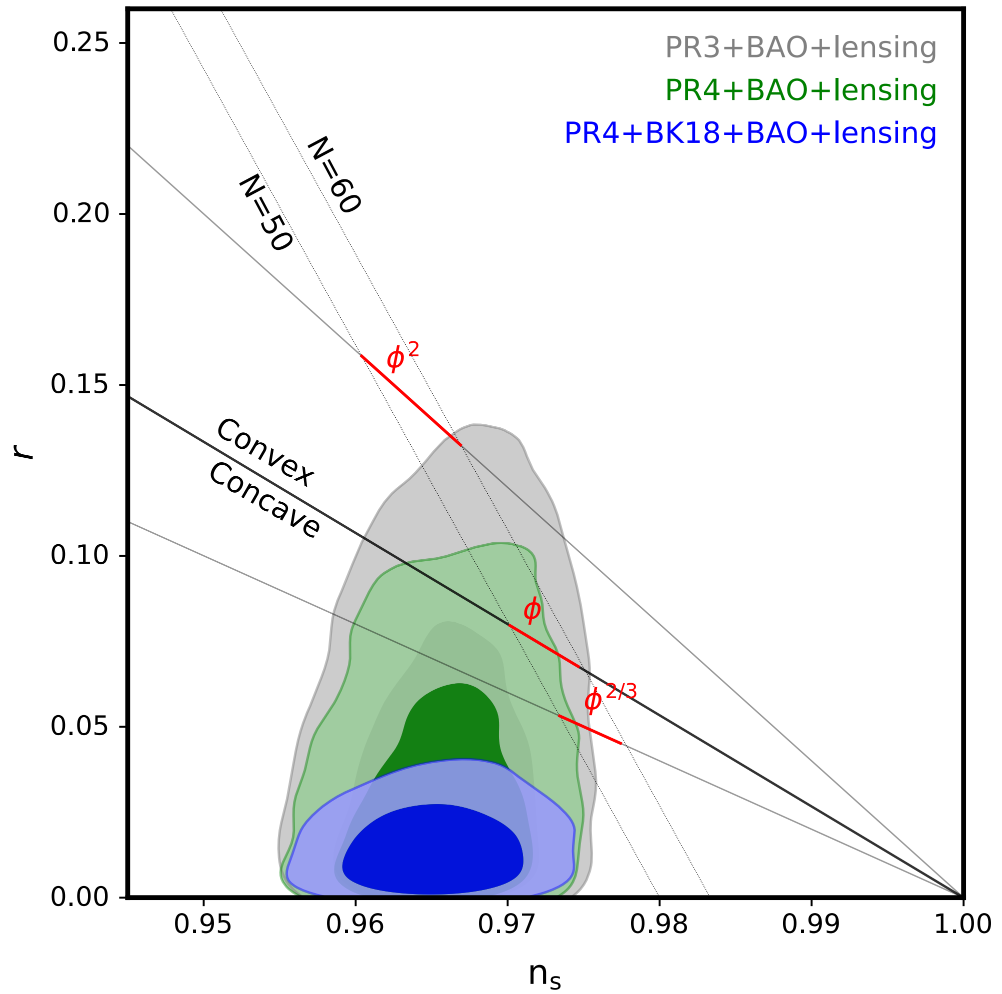
Faintest galaxies (MUV > –15) dominate the ionizing emissivity

[Tristram et al. A&A 647, A128 (2021)]
[Tristram et al. PRD 105, 083524 (2022)]

$r_{0.05} < 0.042$	BICEP2/Keck 2018	1% of the sky
$r_{0.05} < 0.069$	Planck EB (2020)	50% of the sky

[Tristram et al. PRD 105, 083524 (2022)]

$$r_{0.05} < 0.032 \quad \text{(Planck + BK18)}$$

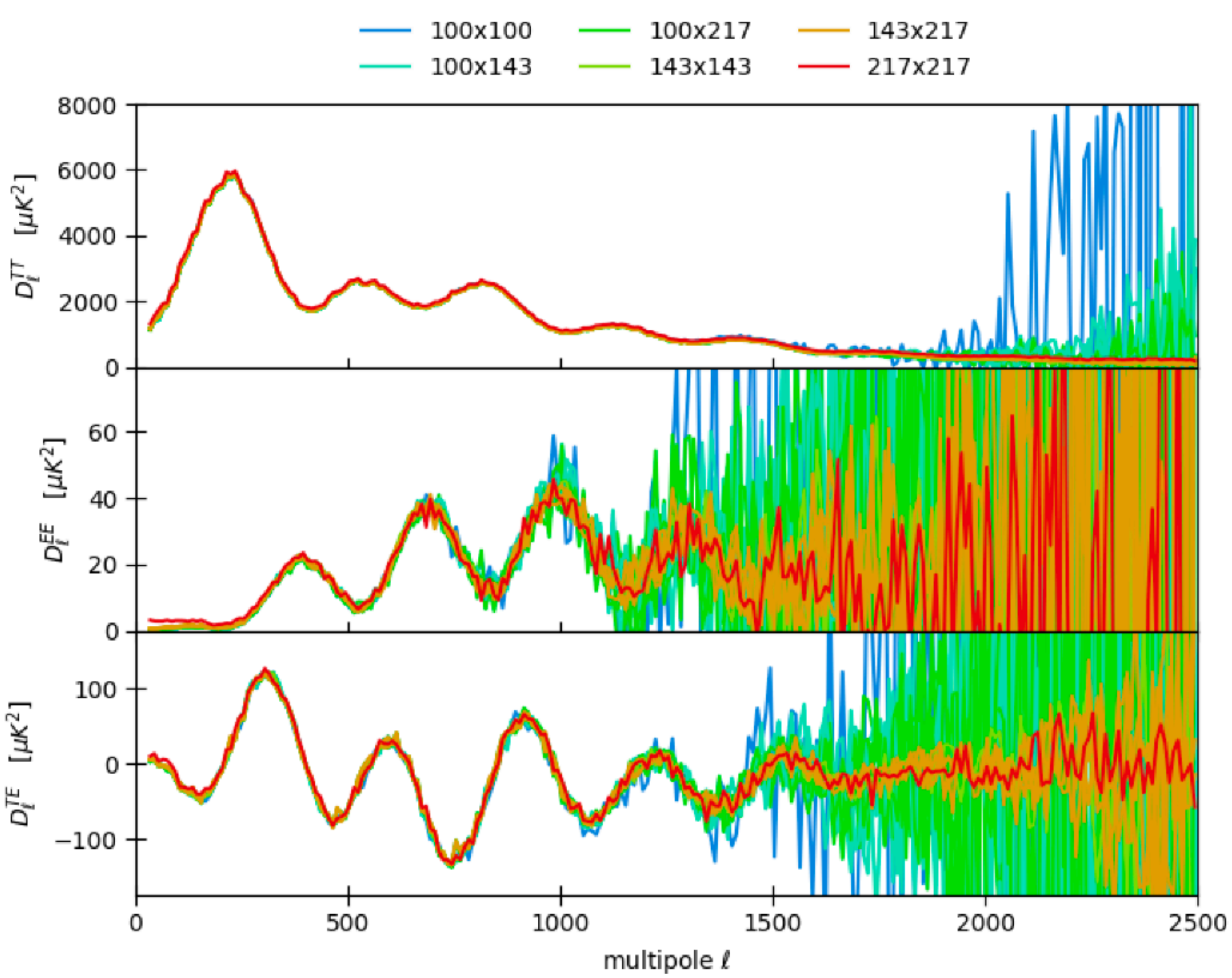


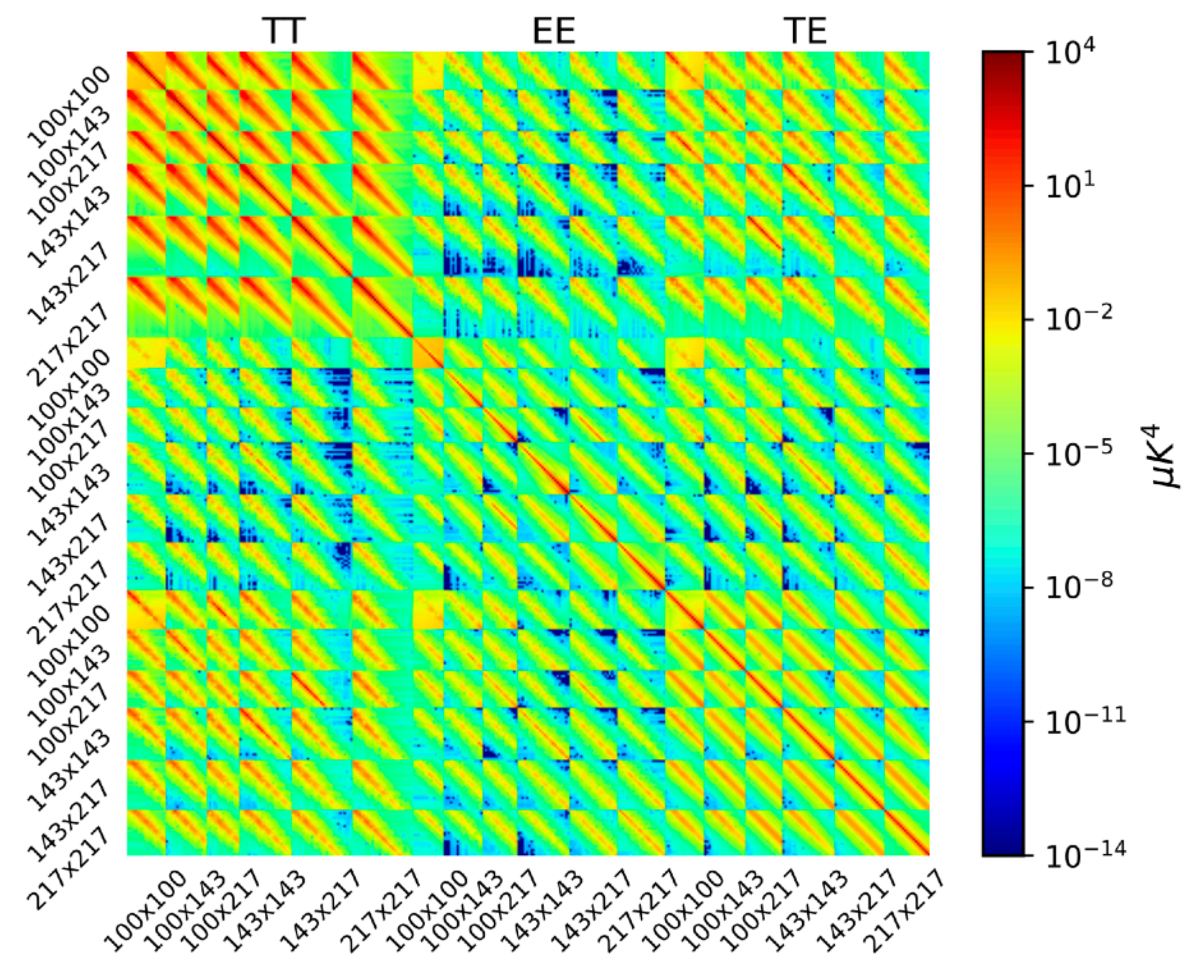
Hillipop

PR4 power-spectra

[Tristram+ (2023)]

2 maps per frequencies at 100, 143 and 217 GHz
15 cross-spectra at 6 cross-frequencies





xpol

[https://gitlab.in2p3.fr/tristram/xpol]

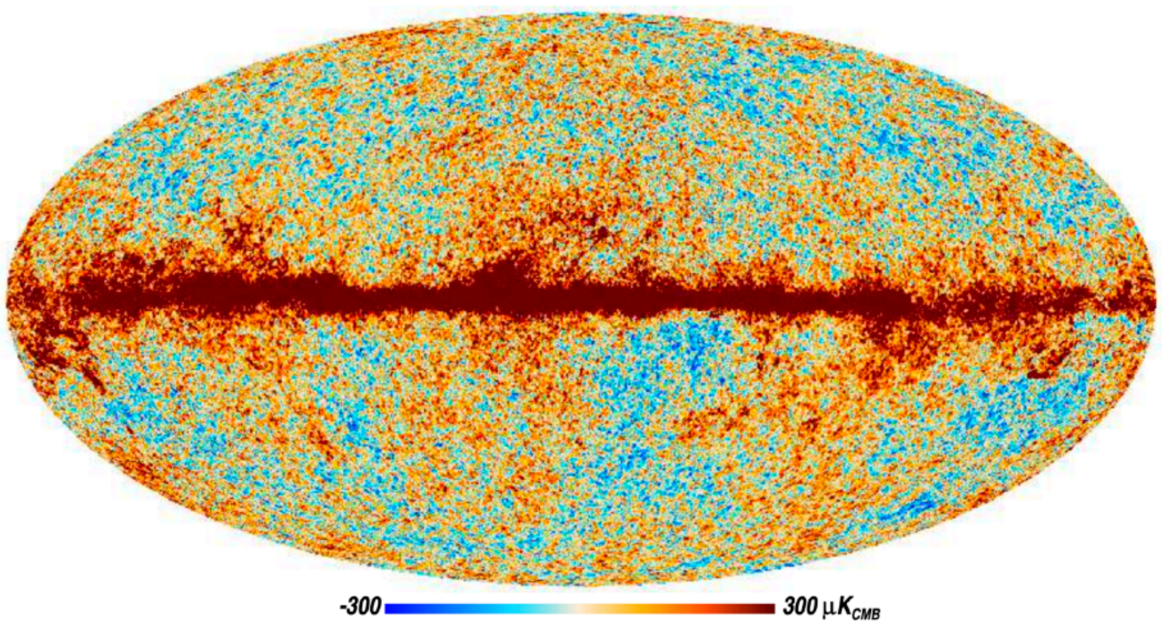
Hillipop

PR4 TT-TE-EE likelihood

[Tristram+ (2023)]

An accurate masking

- our Galaxy
- point sources
- nearby extended galaxies (e.g. M31)

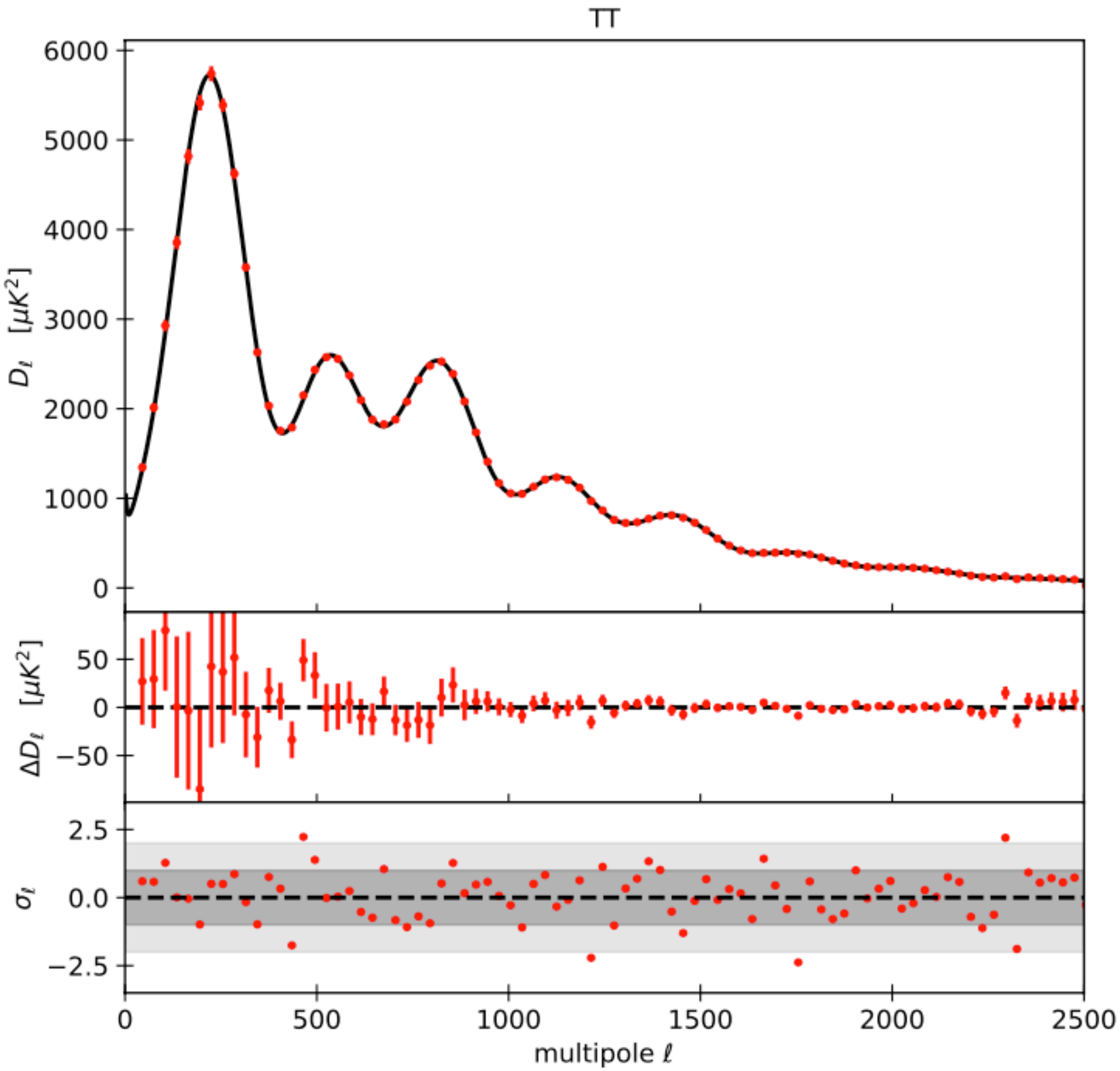


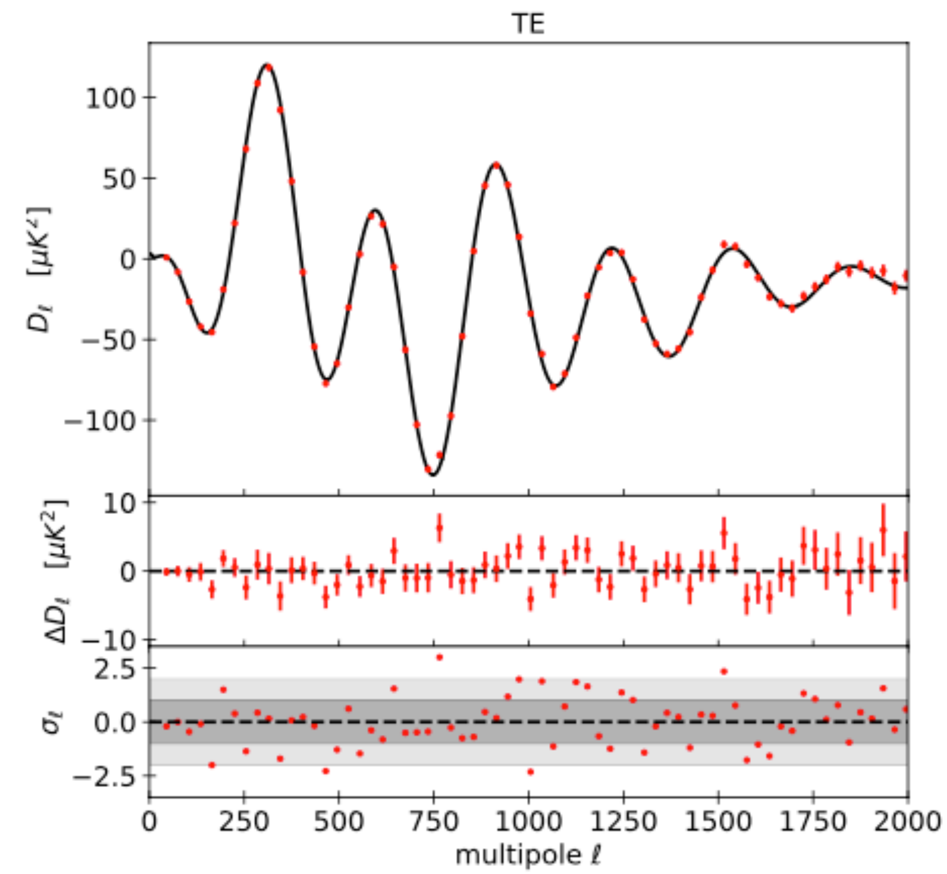
An accurate foreground model

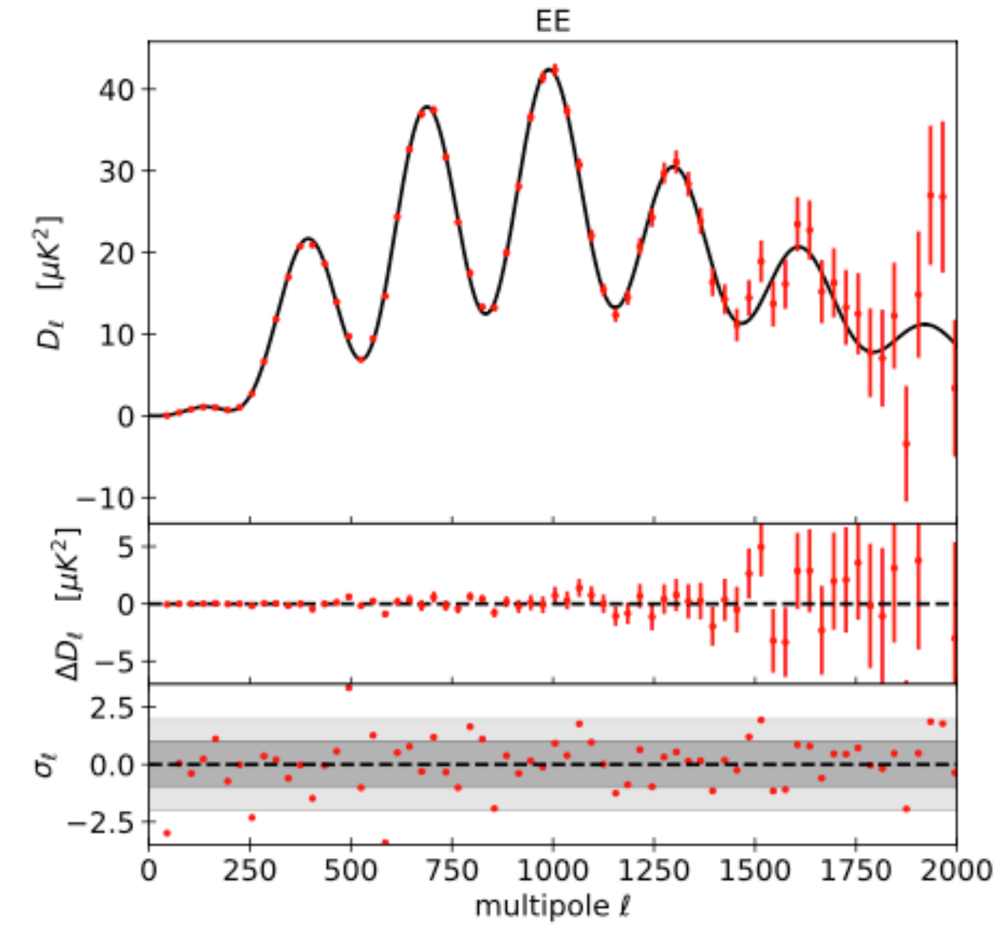
- Galactic dust
- cosmic infrared background (CIB)
- thermal (tSZ) and kinetic (kSZ) Sunyaev-Zeldovich components
- Poisson-distributed point sources from radio and infrared star-forming galaxies
- the correlation between CIB and the tSZ effect (tSZ×CIB)

Hillipop

PR4 CMB power-spectra







ΛCDM cosmology
model

- **6 parameters**
  - 3 for the primordial matter spectra

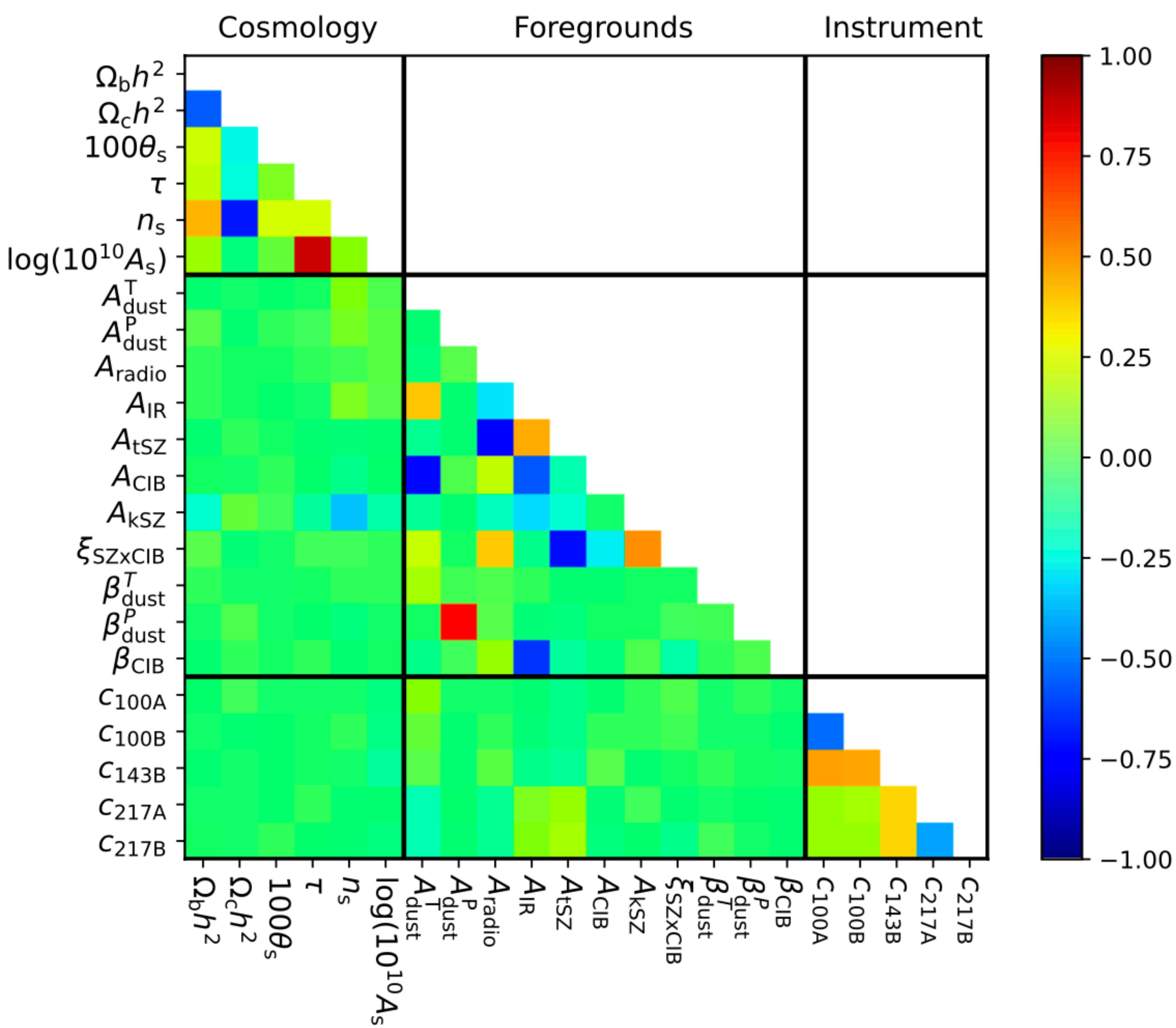
$$\mathscr{P}_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

  - 1 expansion rate H_0 (in practice sound horizon θ_s)
  - 2 parameters for densities $\Omega_b h^2$ $\Omega_c h^2$
  - reionization τ

- **hypothesis**
  - flat Universe $\Omega_k = 0$
  - No running $dn_s/d\ln k = 0$
  - no tensor $r = 0$
  - 3 neutrinos $N_{\rm eff} = 3.044$
  - standard neutrinos with low mass $\sum m_\nu = 0.06$ eV

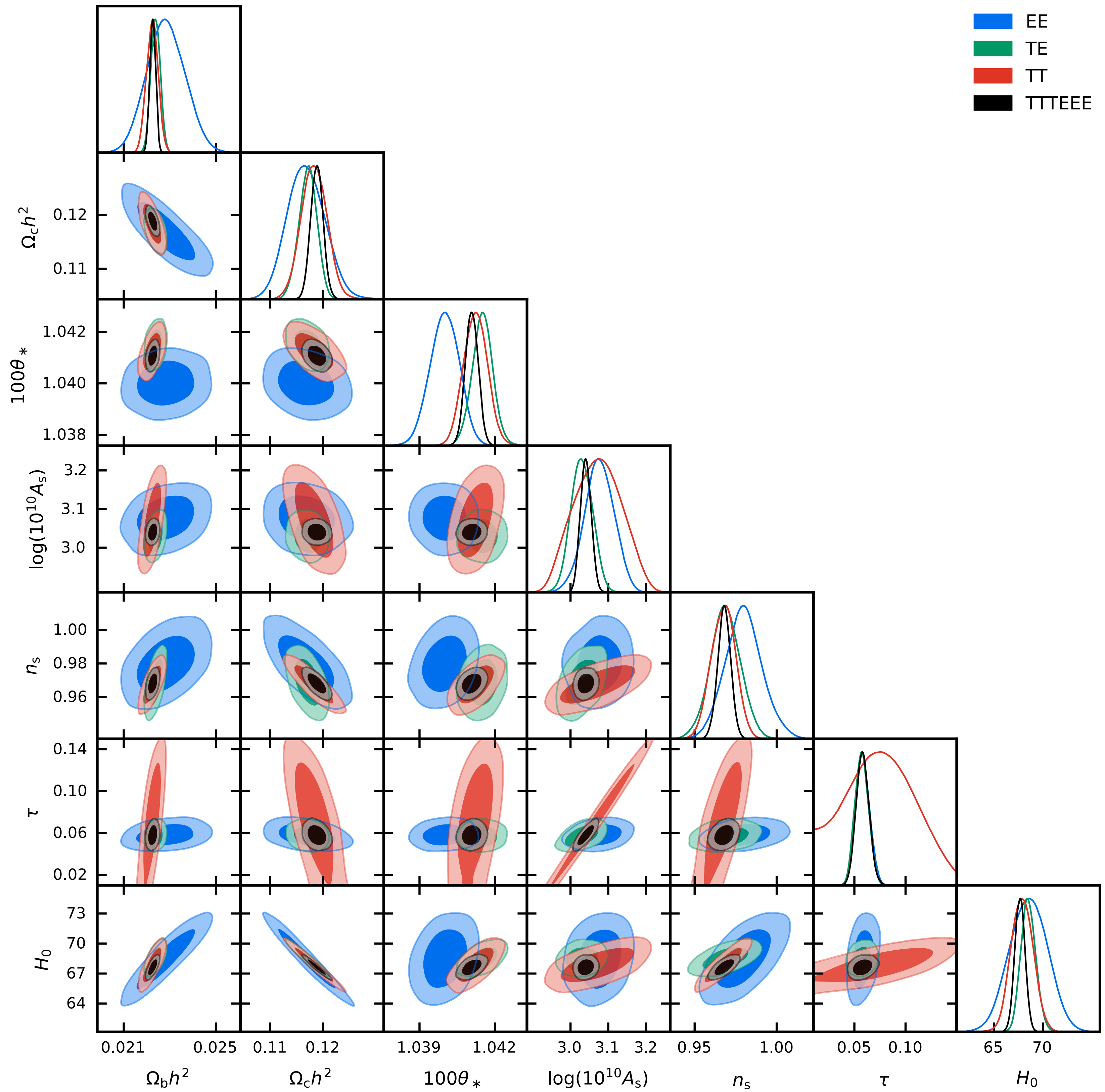
ΛCDM cosmology
parameters

[Tristram+ (2023)]



ΛCDM cosmology
TT, TE, EE

[Tristram+ (2023)]



ΛCDM cosmology
+lensing+BAO

[Tristram+ (2023)]

Parameter	TTTEEE	TTTEEE +lensing	TTTEEE +lensing+BAO	
$\Omega_b h^2$	0.02226 ± 0.00013	0.02226 ± 0.00013	0.02229 ± 0.00012	0.5 %
$\Omega_c h^2$	0.1188 ± 0.0012	0.1190 ± 0.0011	0.1186 ± 0.0009	0.75 %
$100\theta_*$	1.04108 ± 0.00026	1.04107 ± 0.00025	1.04111 ± 0.00024	0.02 %
$\log(10^{10}A_s)$	3.040 ± 0.014	3.045 ± 0.012	3.048 ± 0.012	0.39 %
n_s	0.9681 ± 0.0039	0.9679 ± 0.0038	0.9690 ± 0.0035	0.36 %
τ	0.0580 ± 0.0062	0.0590 ± 0.0061	0.0605 ± 0.0059	9.75 %
H_0	67.64 ± 0.52	67.66 ± 0.49	67.81 ± 0.38	0.56 %
σ_8	0.8070 ± 0.0065	0.8113 ± 0.0050	0.8118 ± 0.0050	0.61 %
S_8	0.819 ± 0.014	0.824 ± 0.011	0.821 ± 0.009	1.09 %
Ω_m	0.3092 ± 0.0070	0.3092 ± 0.0066	0.3071 ± 0.0051	1.66 %

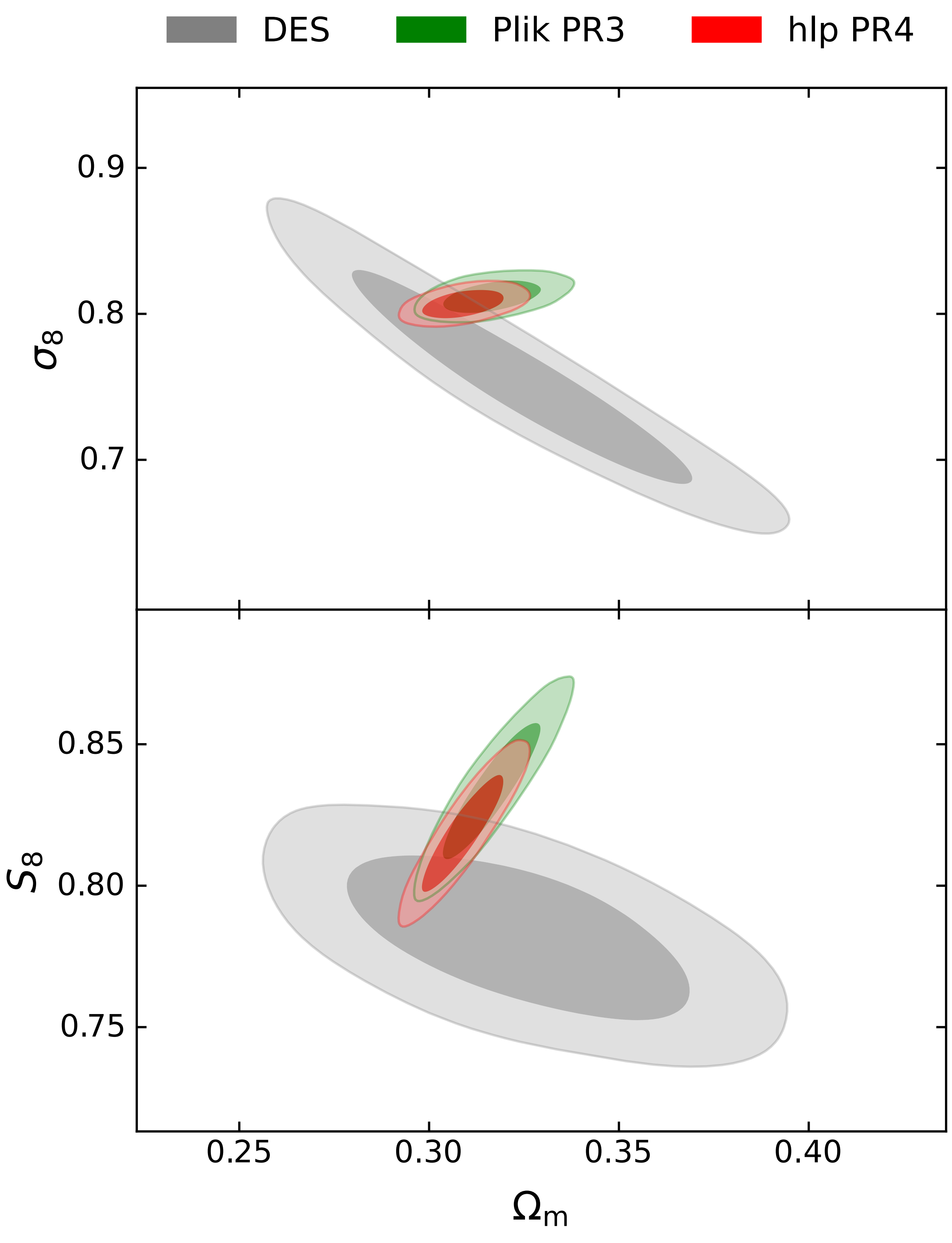
But still:

- **low H0** compared to SNIa

$H_0 = 67.64 \pm 0.52$ km s^{-1} Mpc^{-1} (TTTEEE)

$H_0 = 67.81 \pm 0.38$ km s^{-1} Mpc^{-1} (TTTEEE+lensing+BAO)

ΛCDM cosmology
growth of structures



- **DES**

$$S_8 = 0.782 \pm 0.019 \quad \text{(DES-Y3)}$$

- **Planck**

$$S_8 = 0.834 \pm 0.016 \quad \text{(PR3 TTTEEE)}$$

$$S_8 = 0.819 \pm 0.014 \quad \text{(PR4 TTTEEE)}$$

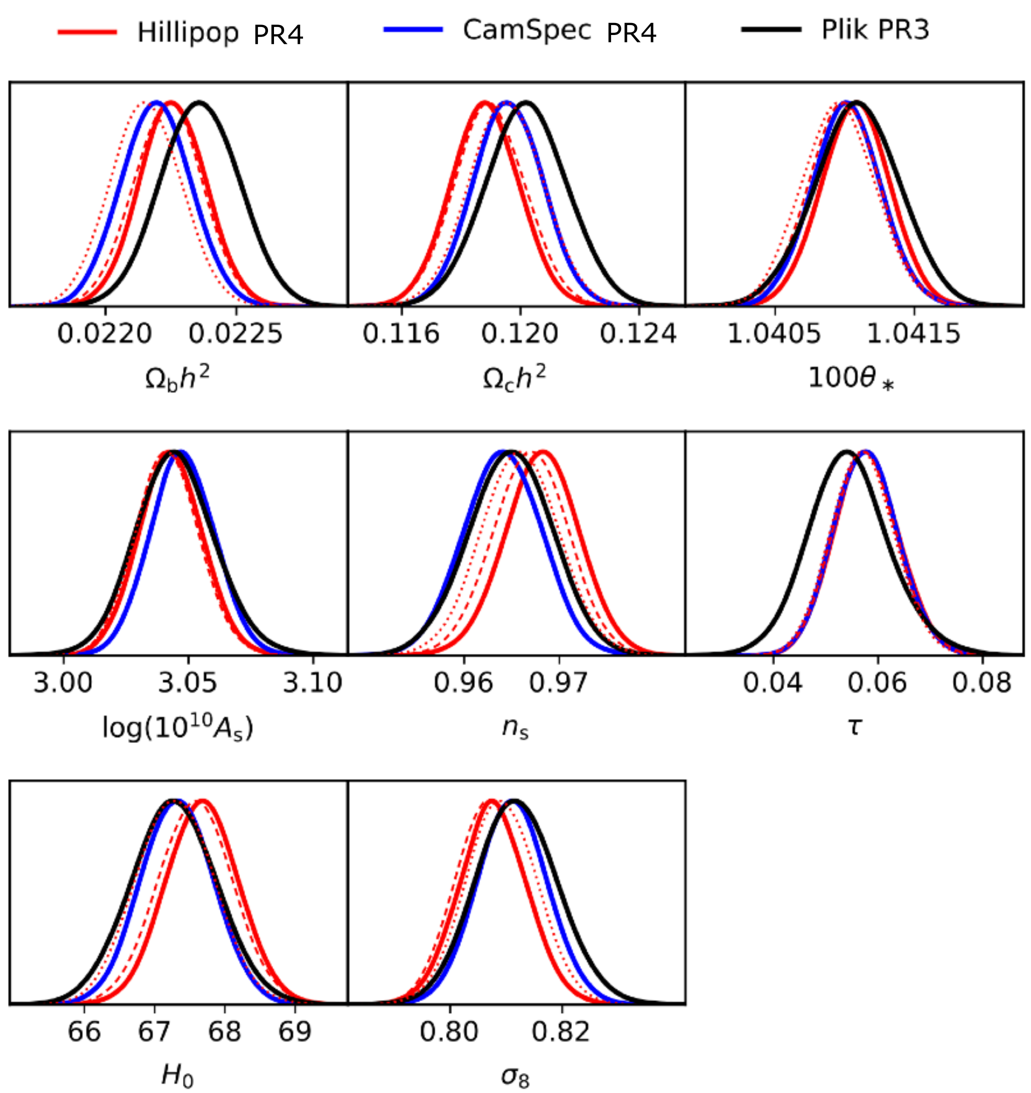
reduced from 2.1σ to 1.5σ

ΛCDM cosmology

Comparison with PR3 and CamSpec

[Planck 2018 Results. VI. (2020)]
[Rosenberg, Gratton, Efstathiou, MNRAS, 517, 4620 (2022)]
[Tristram+ (2023)]

- **Good consistency between the PR4 and PR3 power spectra**, which translates to very good agreement on cosmological parameters as well.
- Lower noise of the NPIPE maps + improvement in polarization signal provides **tighter parameter constraints**, with more than **10% improvement** for ΛCDM parameters in TTTEEE

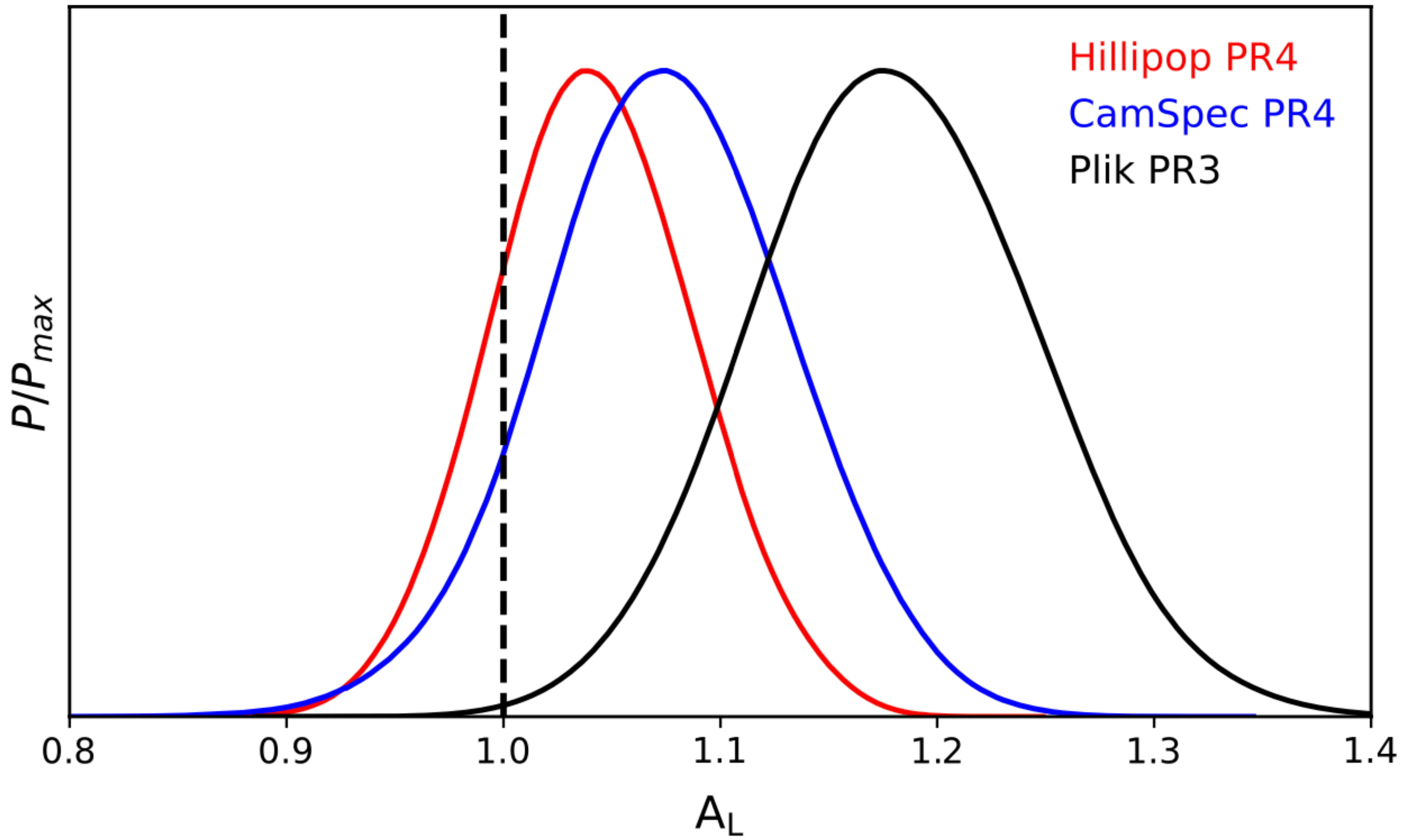


improvement wrt Planck 2018

Parameter	$\Delta\sigma$
$\Omega_b h^2$	-13.7 %
$\Omega_c h^2$	-15.2 %
$100\theta_*$	-16.1 %
$\log(10^{10}A_s)$	-12.0 %
n_s	-11.0 %
τ	-21.4 %
H_0	-13.7 %
σ_8	-11.5 %
S_8	-14.2 %
Ω_m	-16.1 %

ΛCDM extensions
A_{lens}

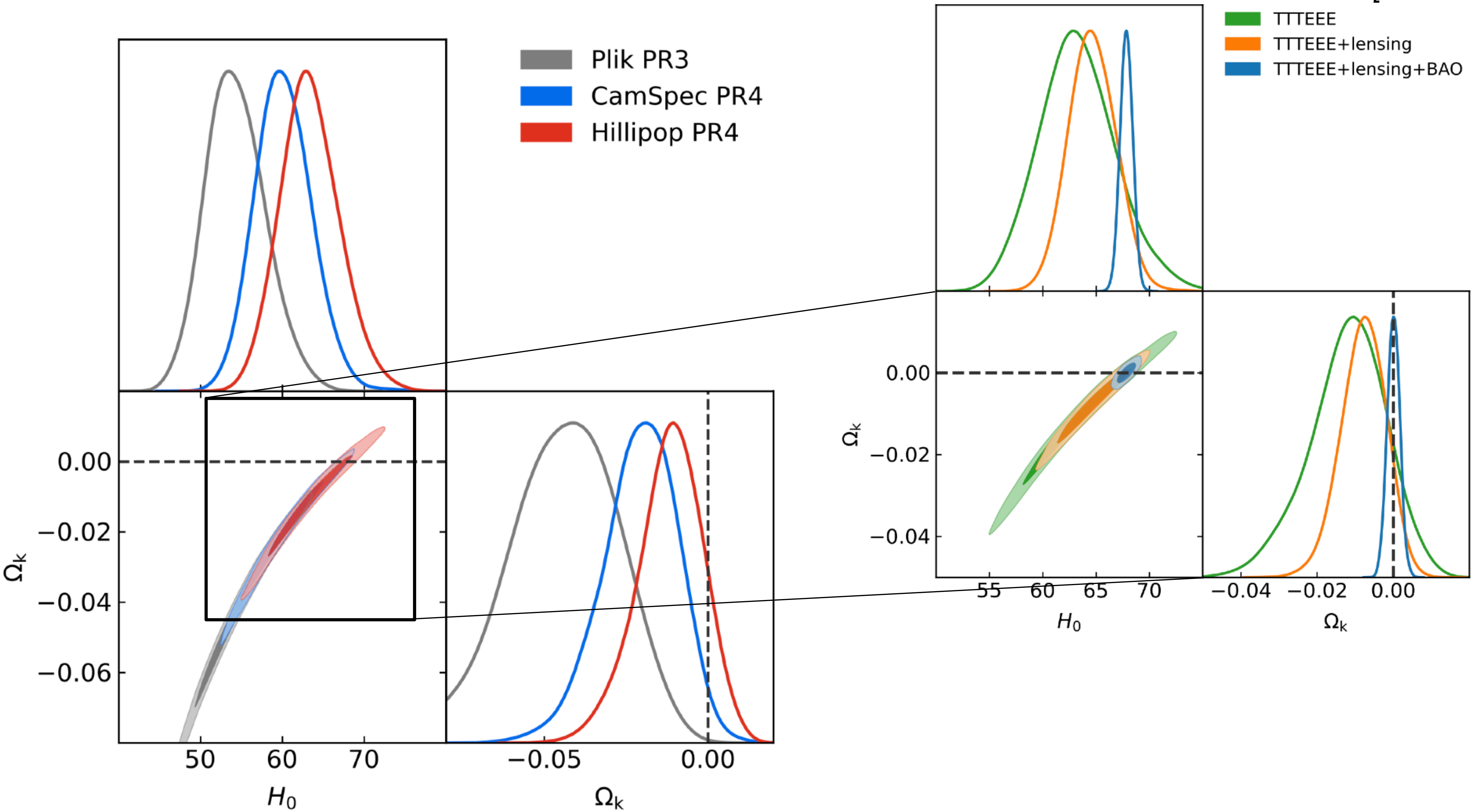
[Tristram+ (2023)]



$$A_{\text{lens}} = 1.039 \pm 0.052 \quad \text{(TTTEEE)}$$
$$A_{\text{lens}} = 1.037 \pm 0.037 \quad \text{(TTTEEE+lensing)}$$

ΛCDM extensions
curvature Ω_K

[Tristram+ (2023)]

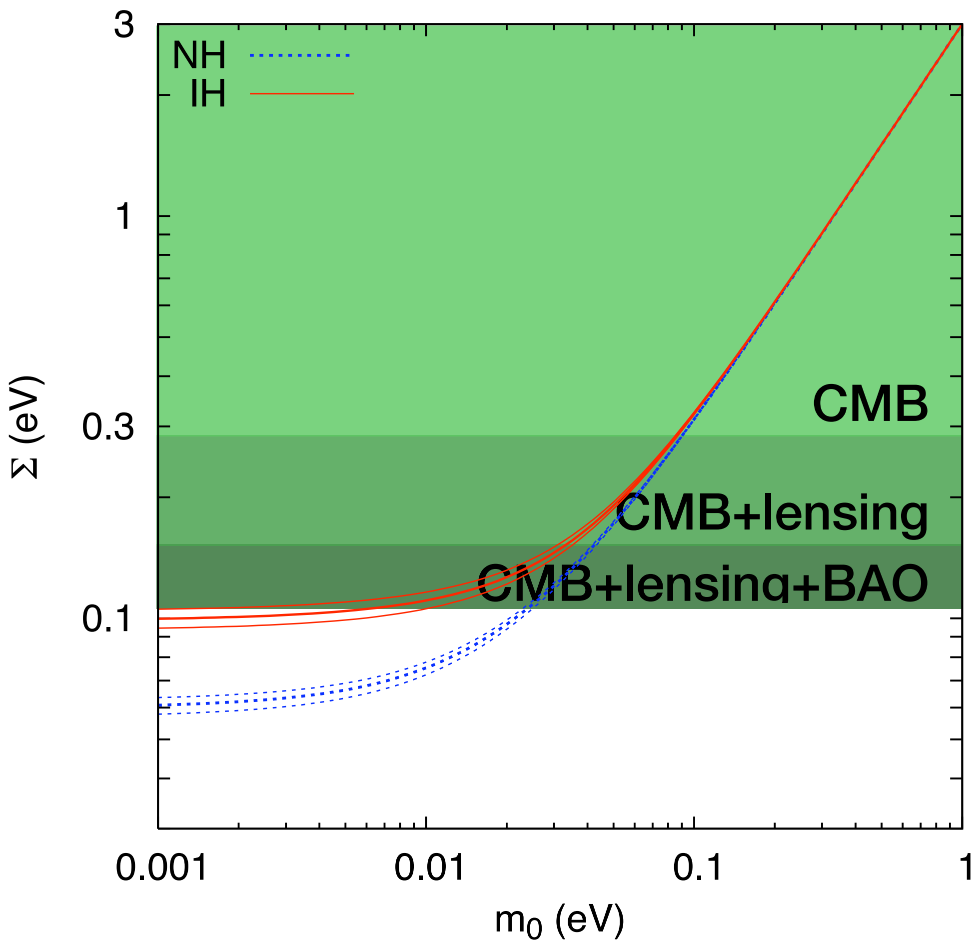


$$\Omega_K = -0.012 \pm 0.010 \quad \text{(TTTEEE)}$$
$$\Omega_K = 0.0000 \pm 0.0016 \quad \text{(TTTEEE+lensing+BAO)}$$

ΛCDM extensions

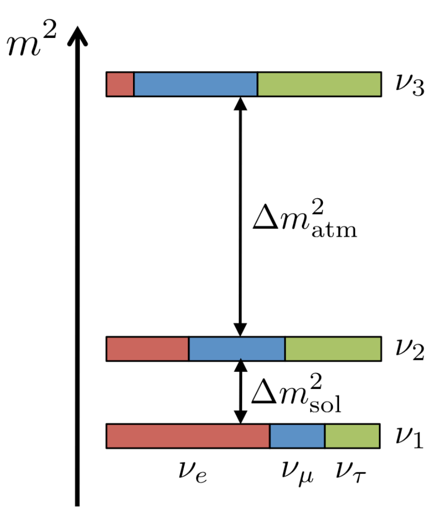
Sum of neutrino masses, Σm_ν

[Tristram+ (2023)]

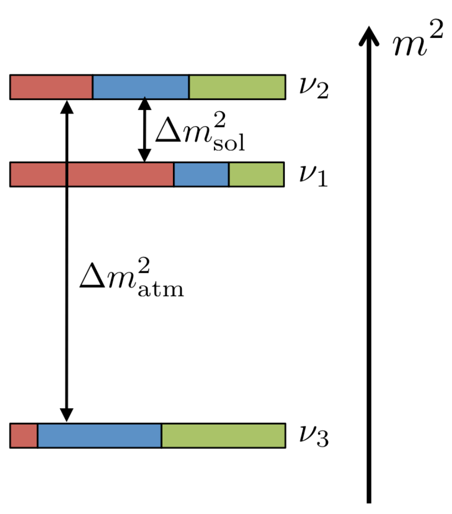


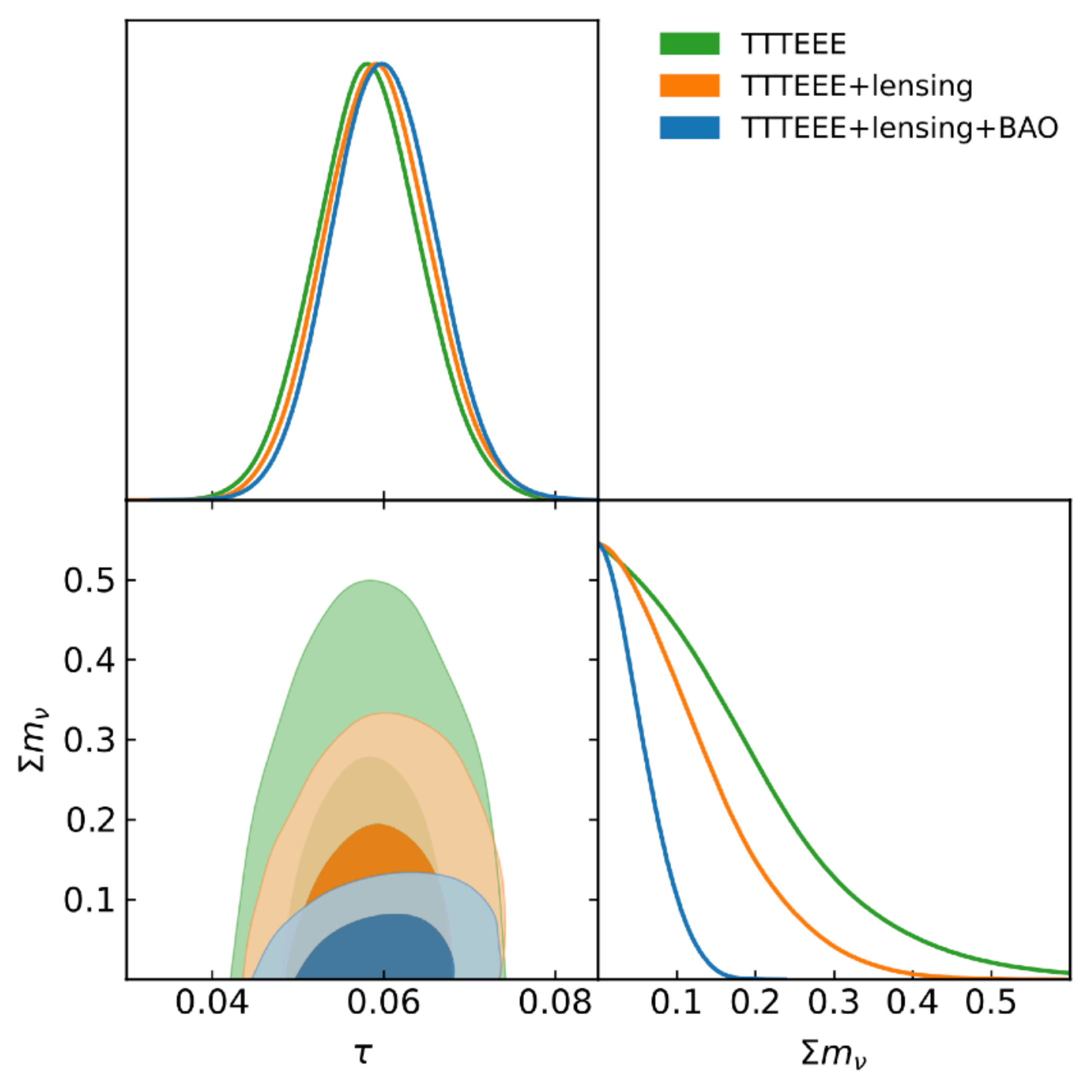
$$\sum m_\nu < 0.39 \quad \text{(95\% CL, TTTEEE)}$$
$$\sum m_\nu < 0.26 \quad \text{(95\% CL, TTTEEE+lensing)}$$
$$\sum m_\nu < 0.11 \quad \text{(95\% CL, TTTEEE+lensing+BAO)}$$

normal hierarchy (NH)

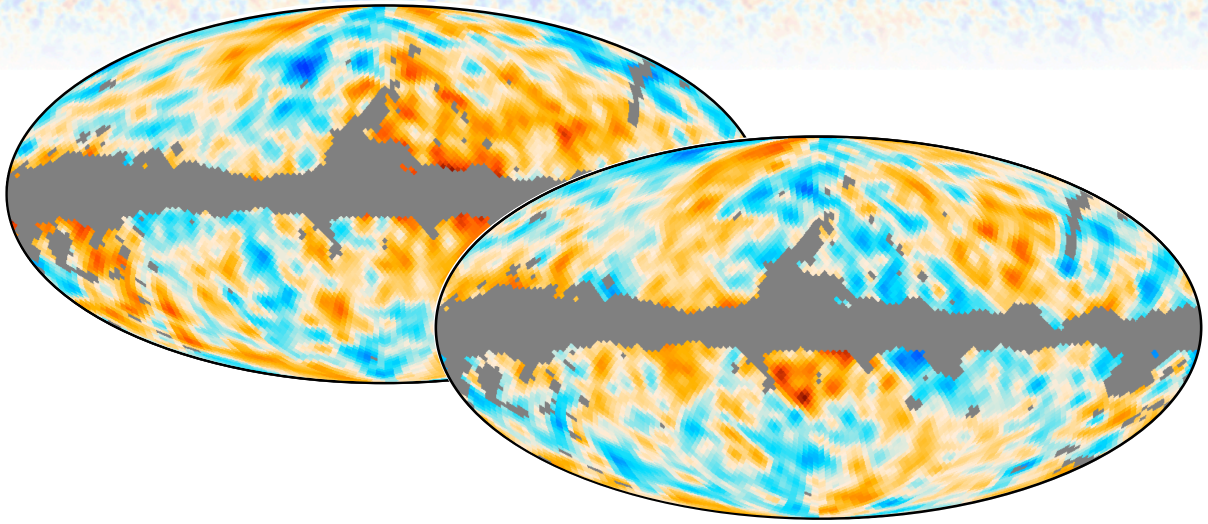


inverted hierarchy (IH)

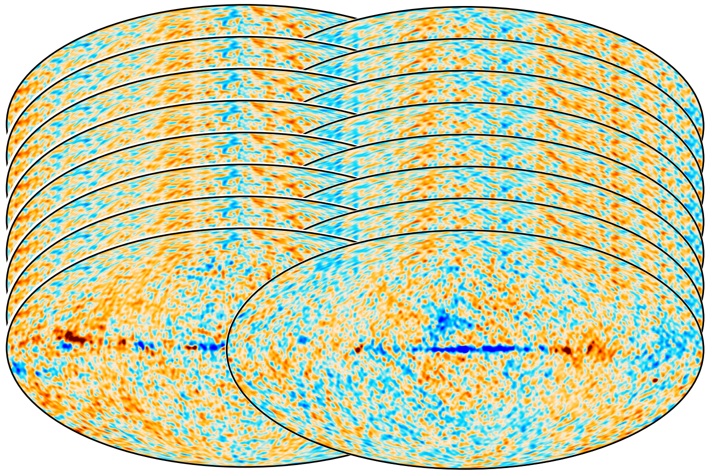




Conclusions



- **PR4 final PLANCK maps**
  - **cleaner** (less systematics)
  - **more sensitive** (less noisy)
  - split-maps not correlated



- **NPIPE sims**
  - consistent with the data
  - **allow for TF and variance estimation**
  - include uncertainties from systematics (both instrumental and astrophysical)

- **CMB likelihoods (Lollipop & Hillipop)** https://github.com/planck-npipe
  - Cosmology consistent with the PR3 and with CamSpec
  - about **10% improvement** in most of ΛCDM parameters
  - give the tightest constraints from Planck CMB today
  - **no deviation from standard ΛCDM**

$$A_{\rm lens} = 1.039 \pm 0.052$$

$$\Omega_K = -0.012 \pm 0.010$$

Science with PR4...

- **ΛCDM with CMB**
  - Lollipop+Hillipop [Tristram et al., A&A (2023)]
  - CamSpec [Rosenberg et al., MNRAS 517 4620 (2022)]
- **CMB at large scales (tensor modes, reionization)**
  - [Tristram et al., PRD 105 083524 (2022)] *Improved limits on the tensor-to-scalar ratio using BICEP and Planck*
- **Lensing**
  - [Carron, Mirmelstein, Lewis, JCAP 2022 039 (2022)] *CMB lensing from Planck PR4 maps*
- **Cosmic Birefringence**
  - [Diego-Palazuelos et al., PRL 128 091302 (2022)] *Cosmic Birefringence from Planck Public Release 4*
- **Inflation**
  - [Campeti et al., JCAP 2022 039 (2022)] *New constraints on axion-gauge field dynamics during inflation from Planck and BICEP/Keck data sets*
  - [Galloni et al., JCAP 2023 062 (2022)] *Updated constraints on amplitude and tilt of the tensor primordial spectrum*
- **Sunyaev-Zeldovich**
  - [Tanimura et al., MNRAS 509 300 (2022)] *Constraining cosmology with a new all-sky y-map from the Planck PR4 data*
  - [Chandran, Remazeilles, Barreiro, MNRAS 526 4 (2023)] *An updated and improved tSZ y-map from Planck PR4 data*
- **Cross-correlation**
  - [Carron, Lewis, Fabbian, PRD 106 103507 (2022)] *Planck ISW-lensing likelihood and the CMB temperature*

and many others...