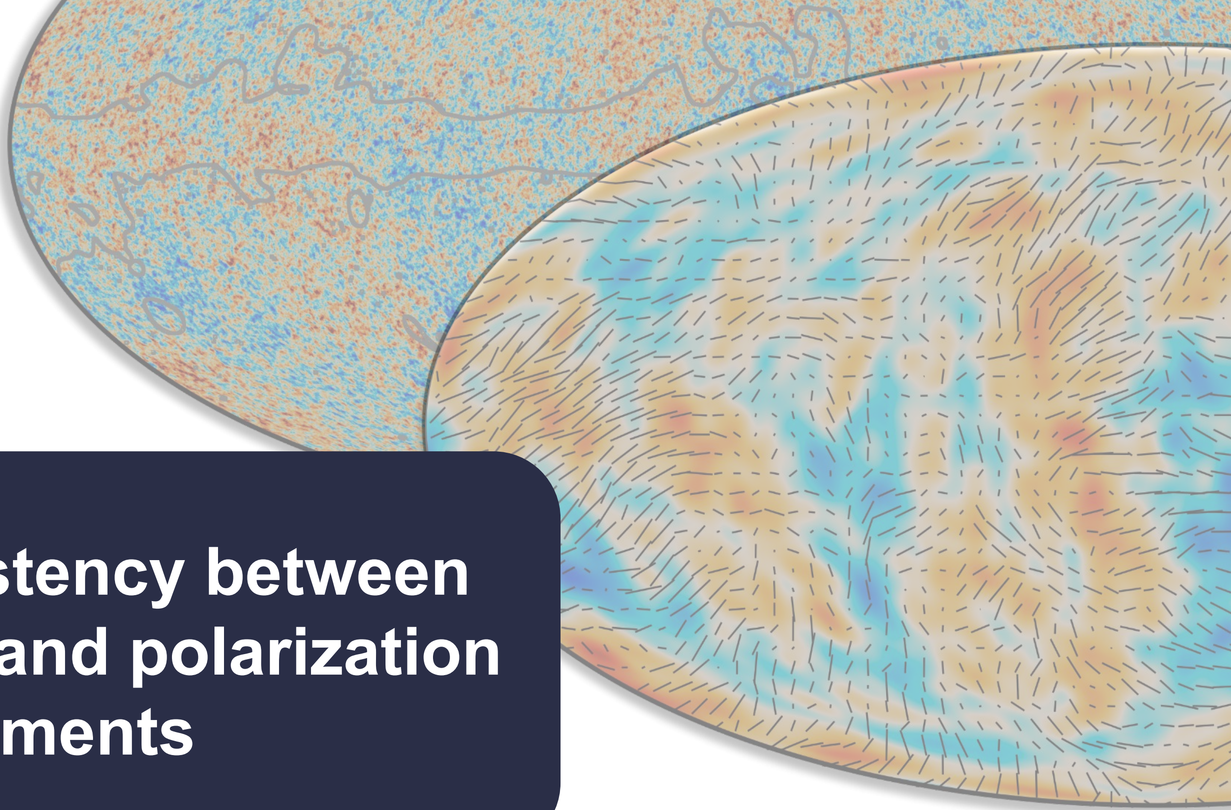
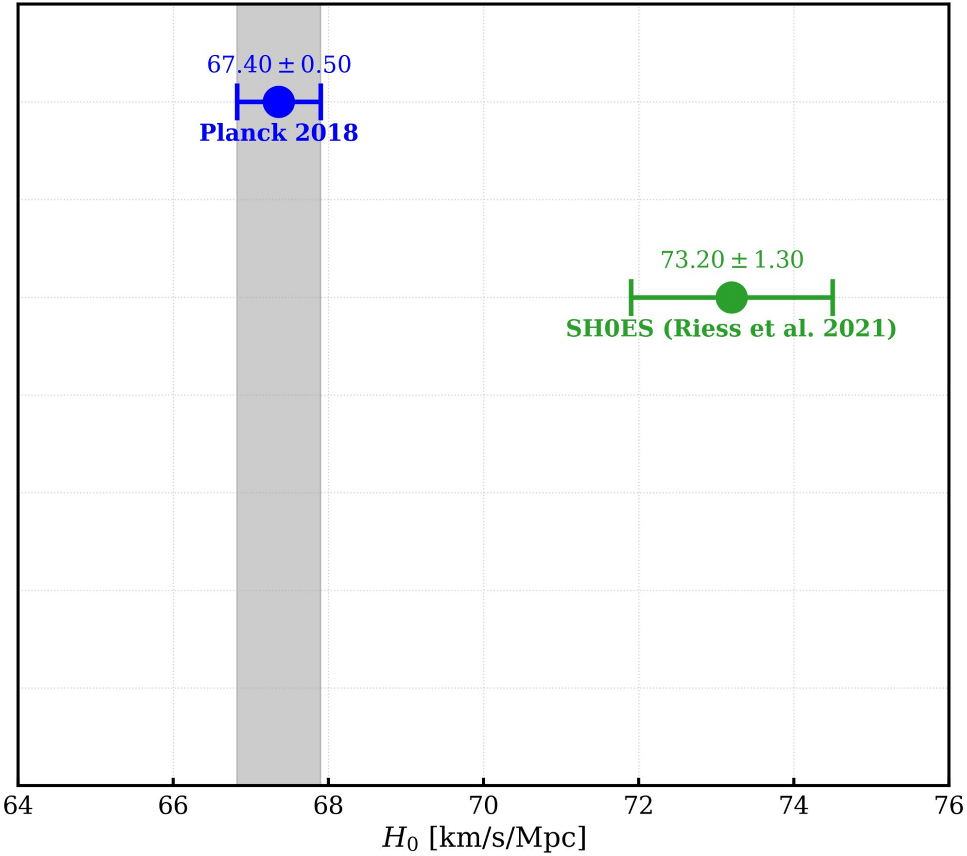


Assessing consistency between CMB temperature and polarization measurements

Adrien La Posta - IJClab

The Hubble tension



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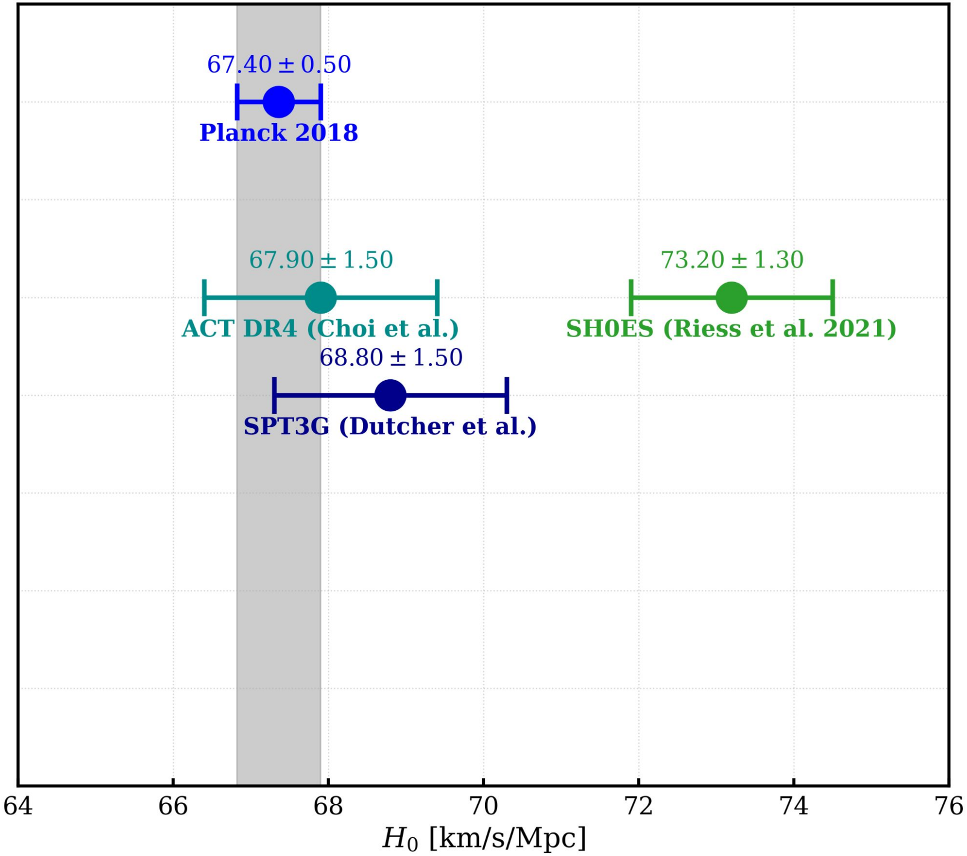

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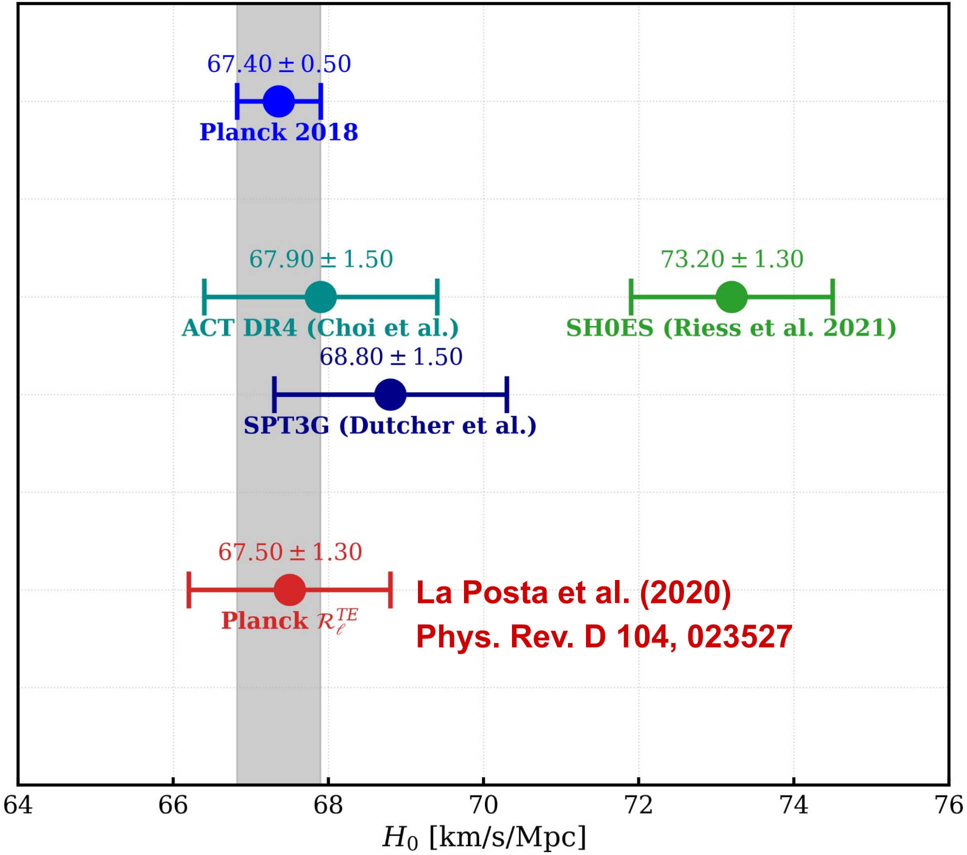
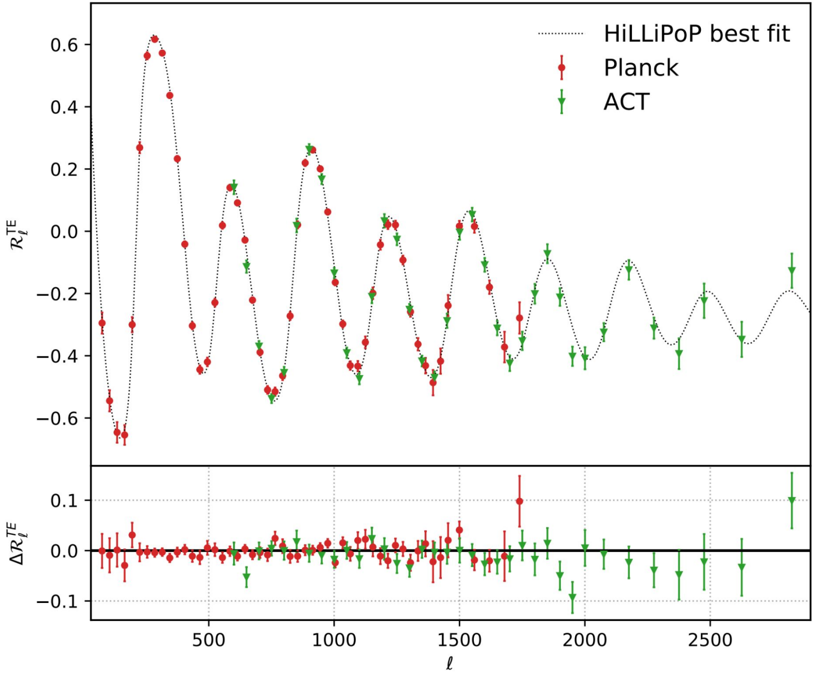
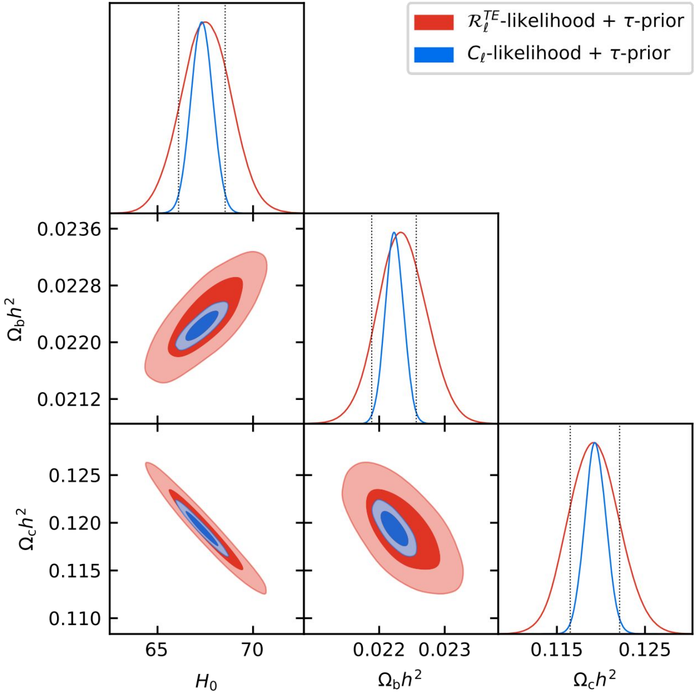


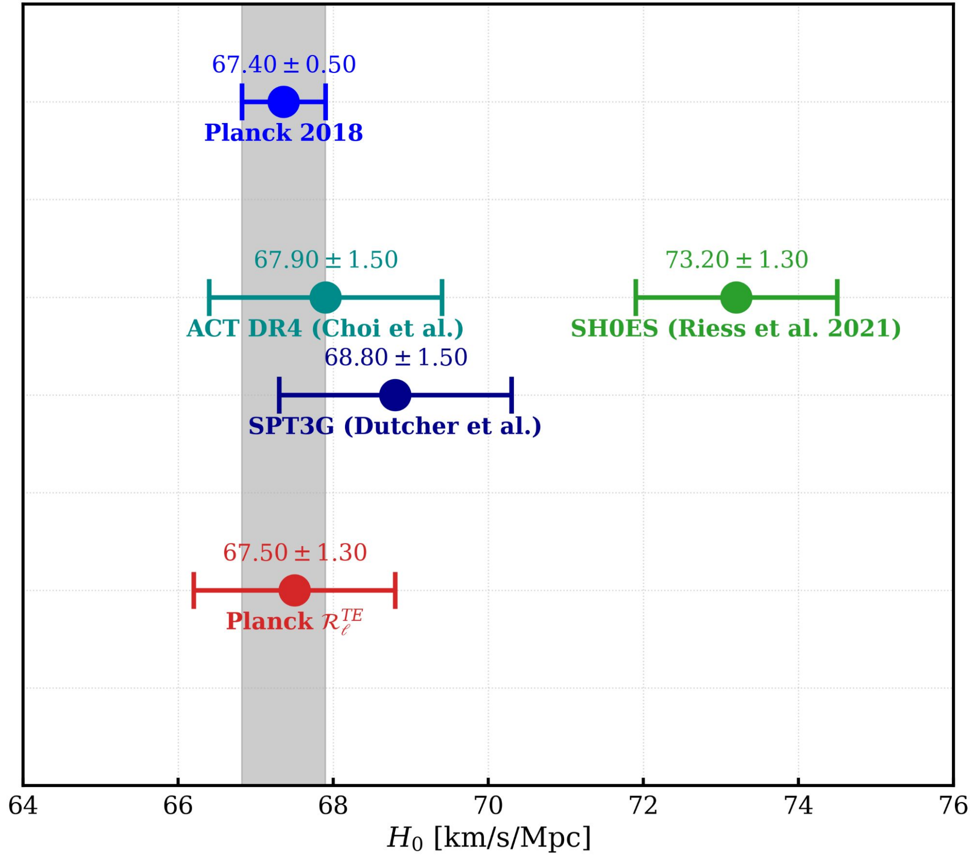
T-E Correlation coefficient

$$\mathcal{R}_\ell^{TE} = \frac{C_\ell^{TE}}{\sqrt{C_\ell^{TT} C_\ell^{EE}}}$$





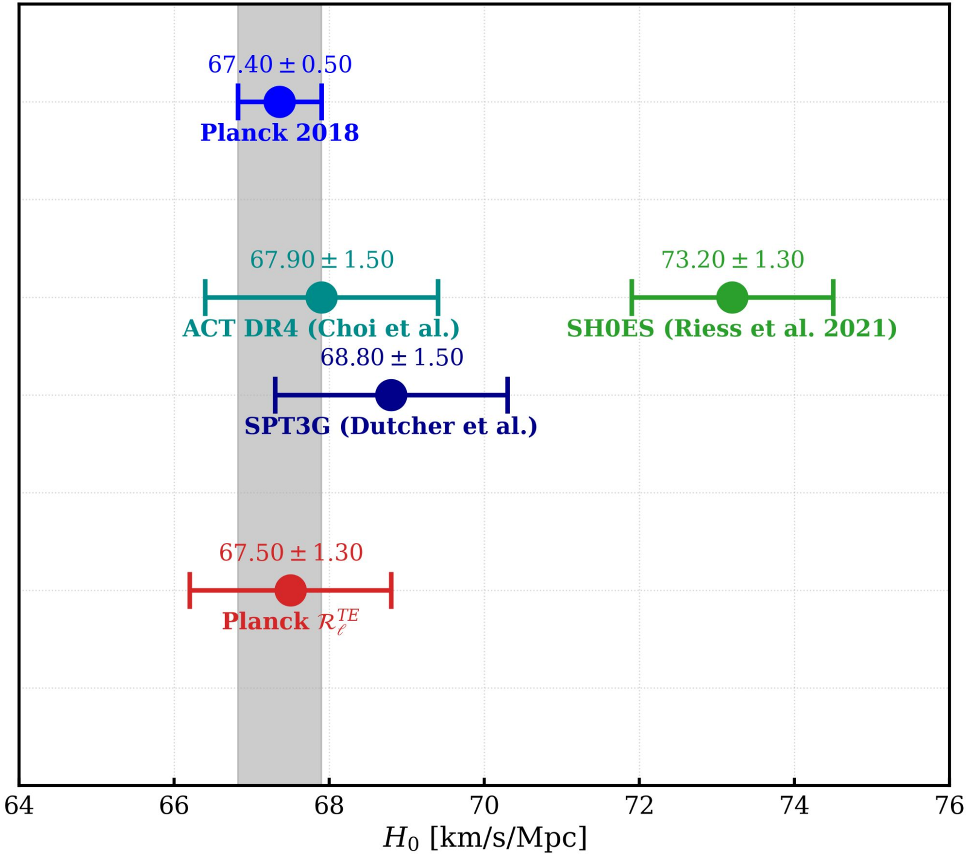
Solutions to the Hubble tension ?



Option 1 :

Systematics affecting the local measurements of H_0 ?

Solutions to the Hubble tension ?



Option 1 :

Systematics affecting the local measurements of H_0 ?

Option 2 :

Physics beyond ΛCDM that shift the constraints on H_0 derived from the CMB

Beyond ΛCDM

The H_0 Olympics: A fair ranking of proposed models

Nils Schöneberg[a,*], Guillermo Franco Abellán[b], Andrea Pérez Sánchez[a], Samuel J. Witte[c], Vivian Poulin[b], Julien Lesgourgues[a]

[a] *Institute for Theoretical Particle Physics and Cosmology (TTK), RWTH Aachen University, D-52056 Aachen, Germany.*

[b] *Laboratoire Univers & Particules de Montpellier (LUPM), CNRS & Université de Montpellier (UMR-5299), Place Eugène Bataillon, F-34095 Montpellier Cedex 05, France.*

[c] *GRAPPA Institute, Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*

arXiV:2107.10291

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	−6.10	−4.10	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	−9.57	−7.57	✓	✓
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	−8.83	−4.83	✗	✗
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	−8.92	−4.92	✗	✗
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	−4.98	1.02	✗	✗
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	−15.49	−9.49	✓	✓
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	−11.42	−9.42	✓	✓
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	−12.27	−10.27	✓	✓
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	−17.26	−13.26	✓	✓
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	−21.98	−15.98	✓	✓
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	−18.93	−12.93	✓	✓
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	−18.56	−12.56	✓	✓
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DM → DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	−0.19	3.81	✗	✗
DM → DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	−0.53	3.47	✗	✗

Table 1: Test of the models based on dataset $\mathcal{D}_{\rm baseline}$ (Planck 2018 + BAO + Pantheon), using the direct measurement of M_b by SH0ES for the quantification of the tension (3rd column) or the computation of the AIC (5th column). Eight models pass at least one of these three tests at the 3σ level.

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Early Dark Energy

Goal : obtain a higher expansion rate H_0

$$\theta_* = \frac{r_s^*}{D_A^*}$$

θ_* → **Fixed by observations**

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$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

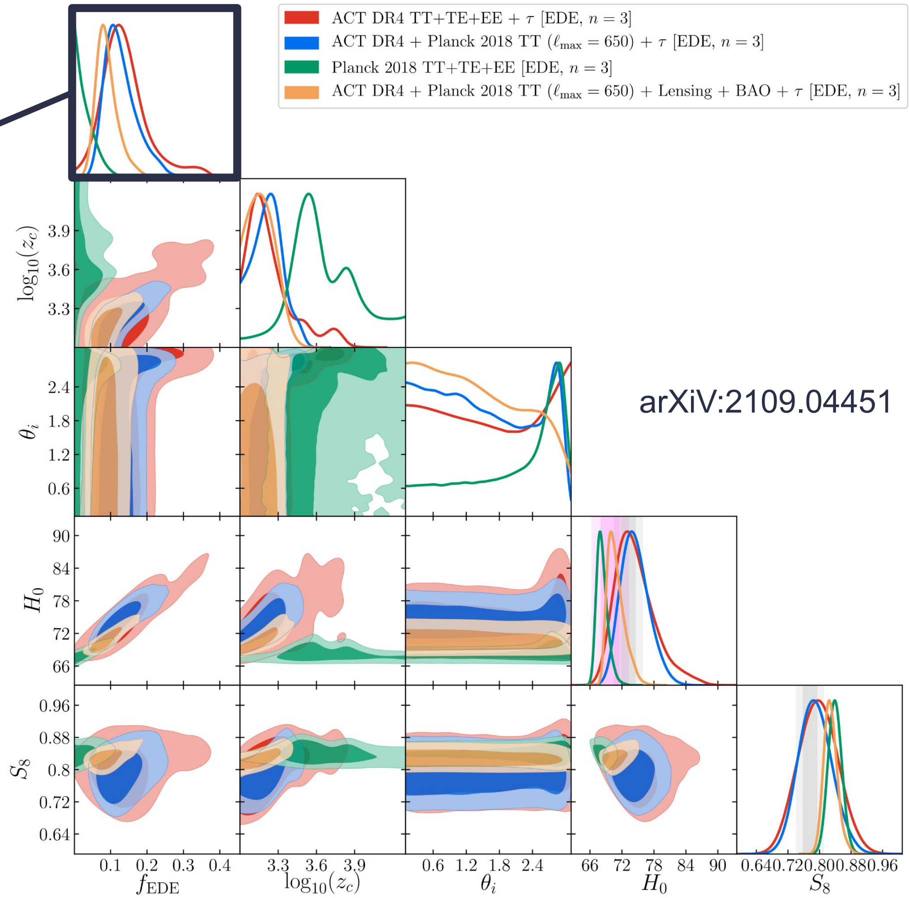
$$V_n(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$

- **Field initially frozen :** act as dark energy at early times
- Starts to oscillate when H~m

Early Dark Energy - ACT DR4 results

- **ACT DR4 data shows a preference for EDE (improvement of the χ^2) with a ~2.5 σ evidence**

- **However, there is no evidence for EDE in Planck data alone**



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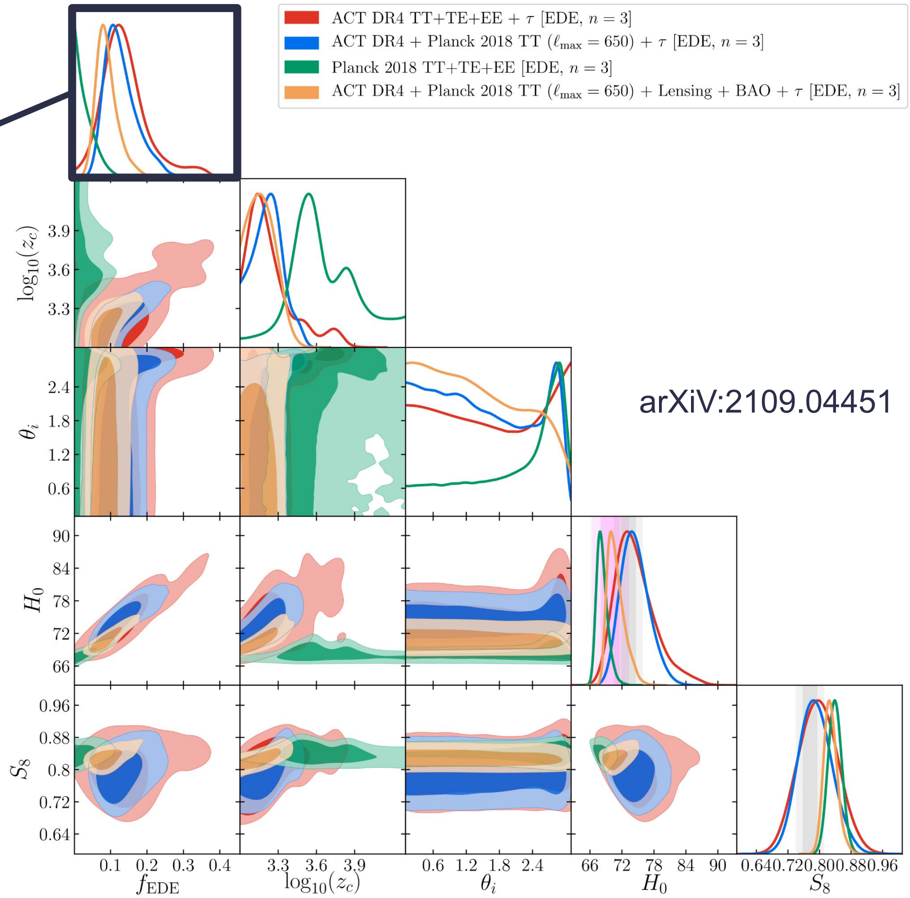
We need additional constraints on EDE



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Model independent constraints

Many models have already been proposed to solve the Hubble tension

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- **Option 1 :** Put constraints on all available model with different experiments to have a strong evidence for some of them …

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Idea : Sample the joint posterior distribution of cosmological parameters and extra-parameters modelling the inconsistency between temperature and polarization measurements.

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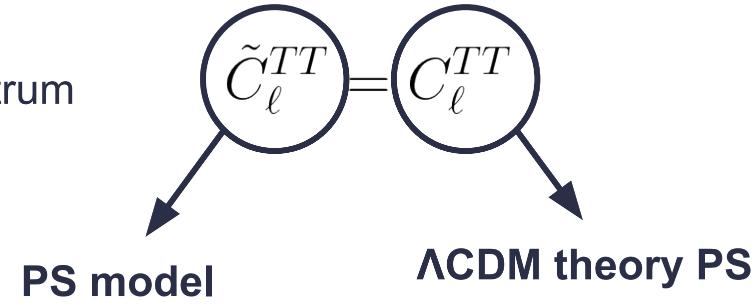
We fix the cosmology with the TT power spectrum



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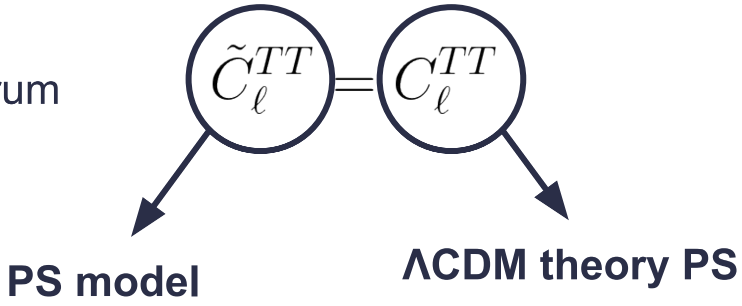


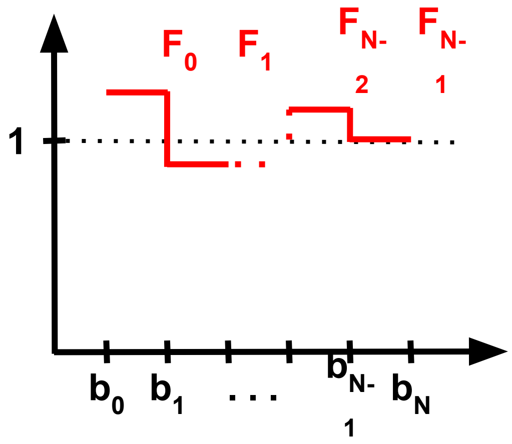
We have to define a model for $\tilde{C}_\ell^{TE}$ and $\tilde{C}_\ell^{EE}$

Modelling deviations with transfer functions

Transfer function × Theory Power Spectrum = Power Spectra Model

Modelling deviations with transfer functions

N extra-parameters



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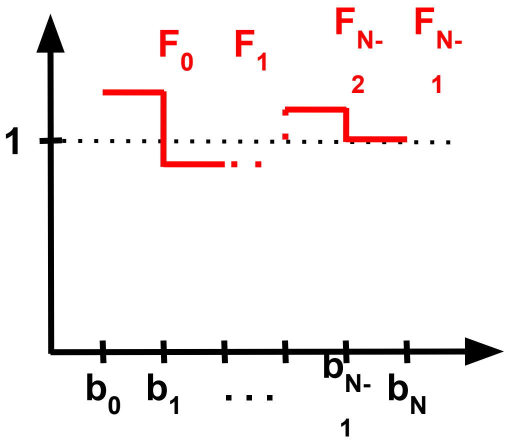

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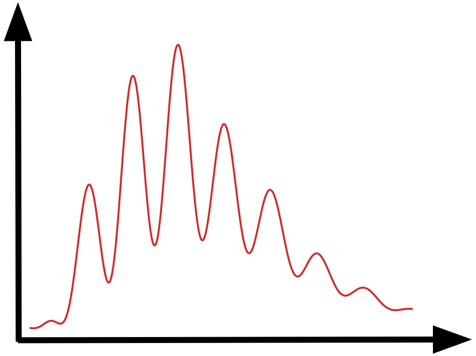
ΛCDM parameters



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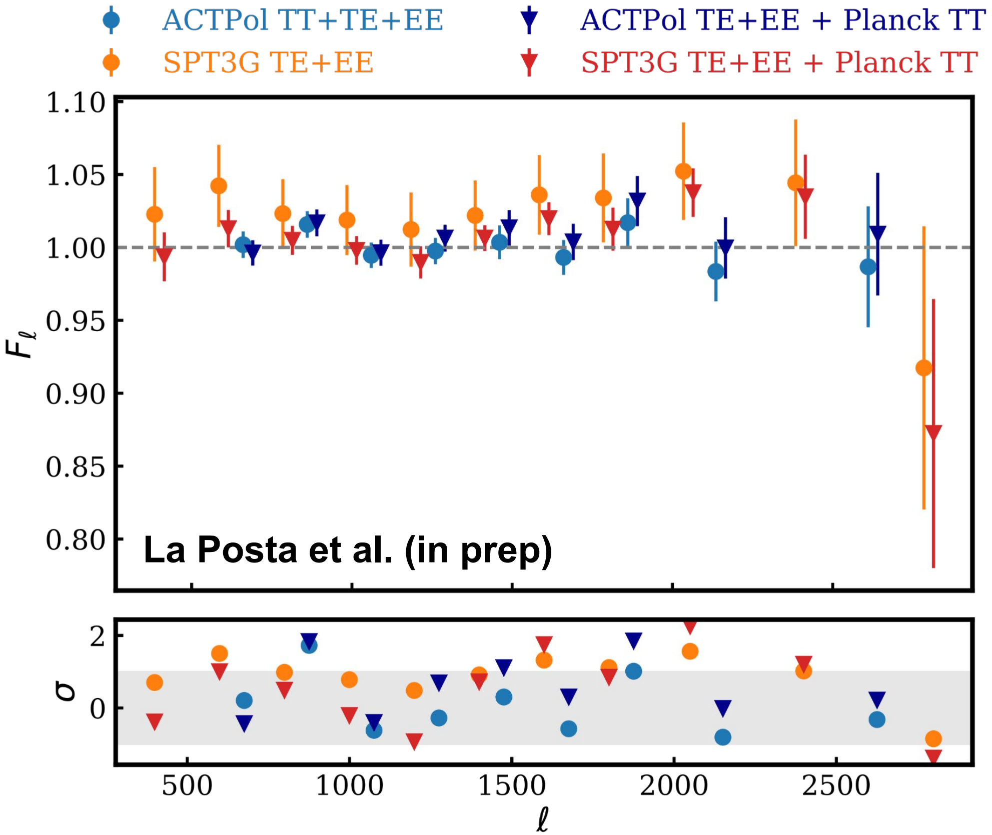
Power Spectra Model

Polarization transfer function

$$\tilde{C}_\ell^{TE} = F_\ell C_\ell^{TE}$$
$$\tilde{C}_\ell^{EE} = F_\ell^2 C_\ell^{EE}$$



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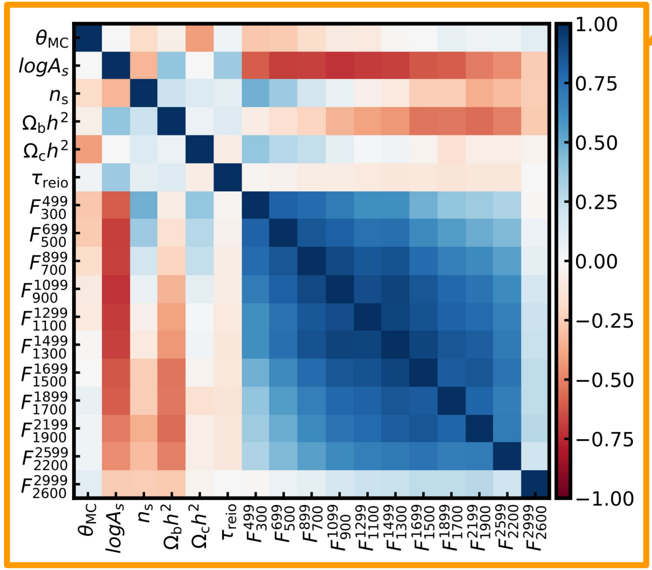

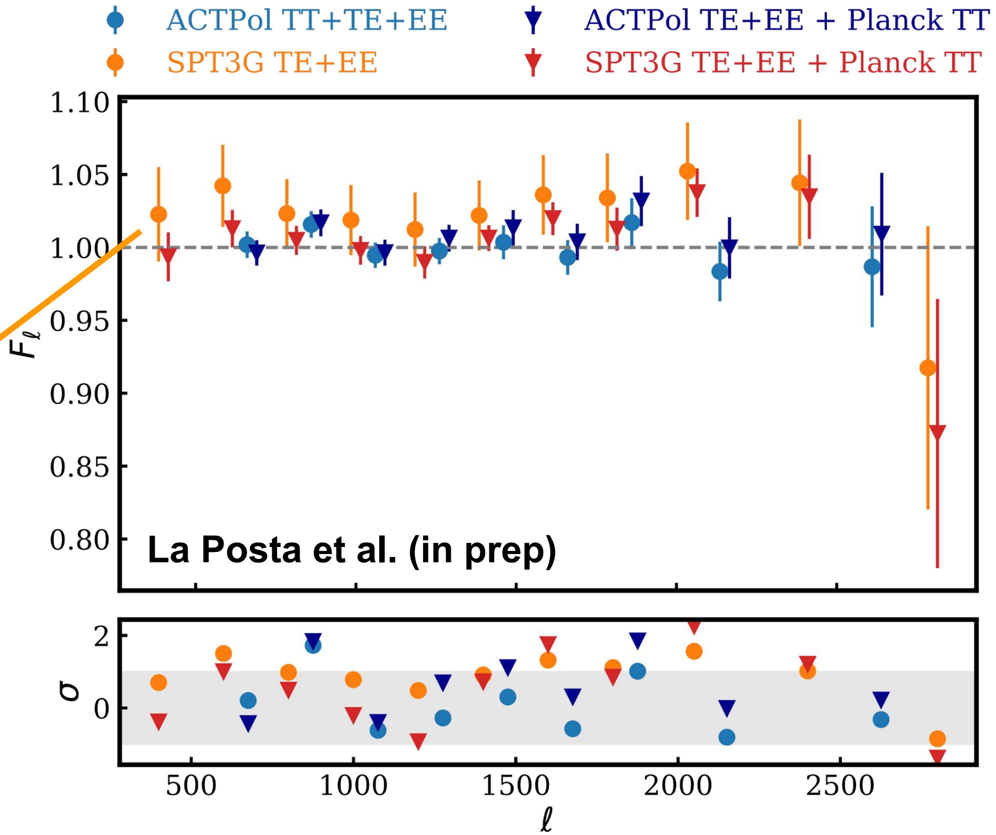

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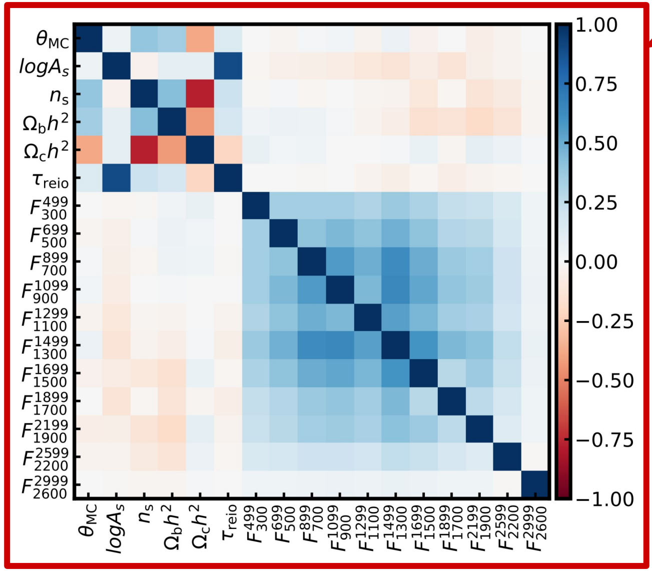

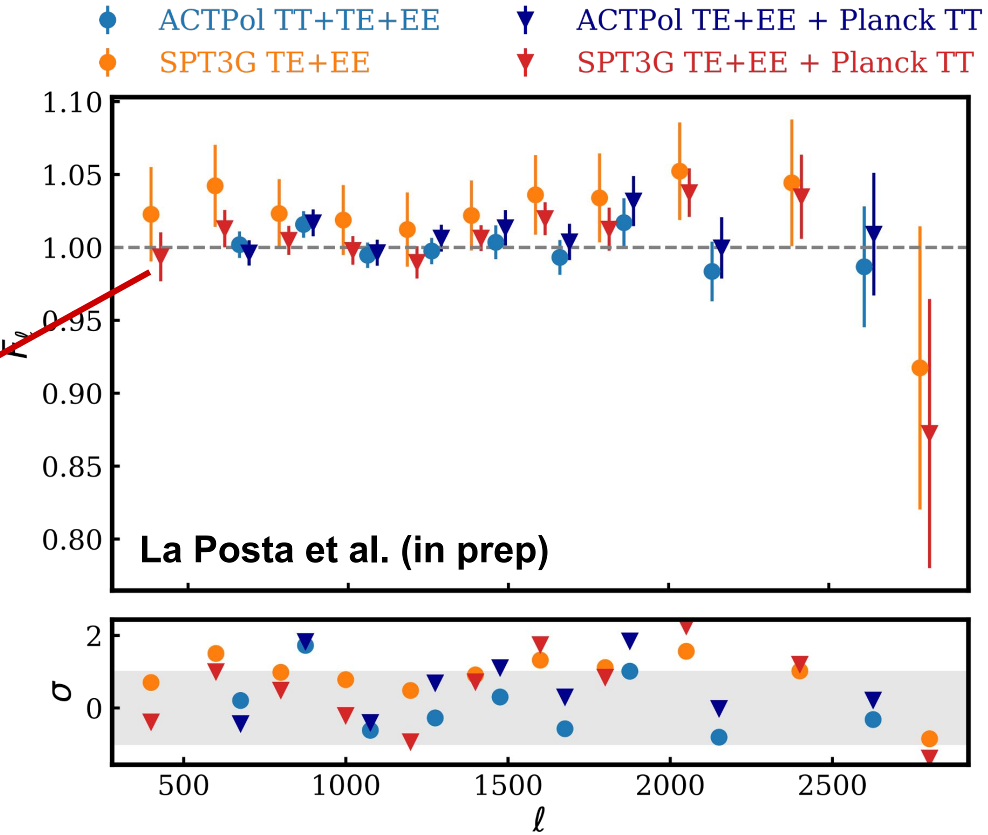

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Polarization transfer function

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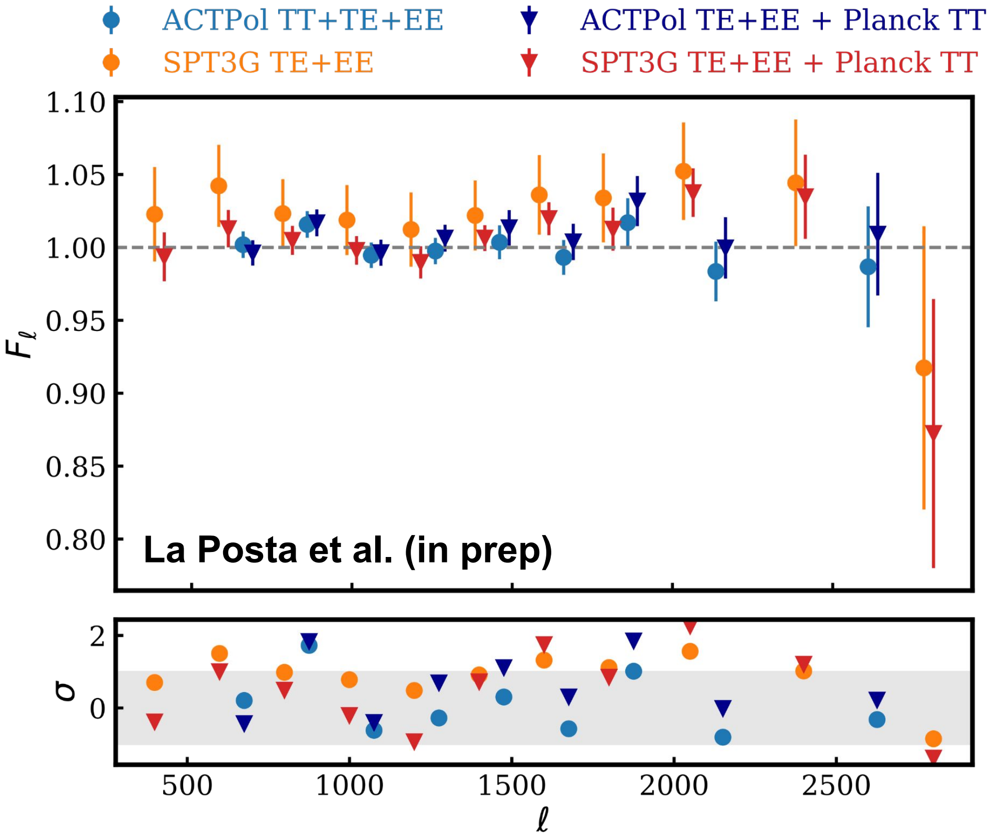
	χ^2 / dof (PTE)
ACT TT/TE/EE	**6.00/9 (0.74)**
ACT TE/EE + Planck TT	**8.64/9 (0.47)**
SPT3G TE/EE	**12.82/11 (0.31)**
SPT3G TE/EE + Planck TT	**18.39/11 (0.07)**



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T to E leakage

$$\tilde{C}_\ell^{TE} = C_\ell^{TE} + \beta_\ell C_\ell^{TT}$$
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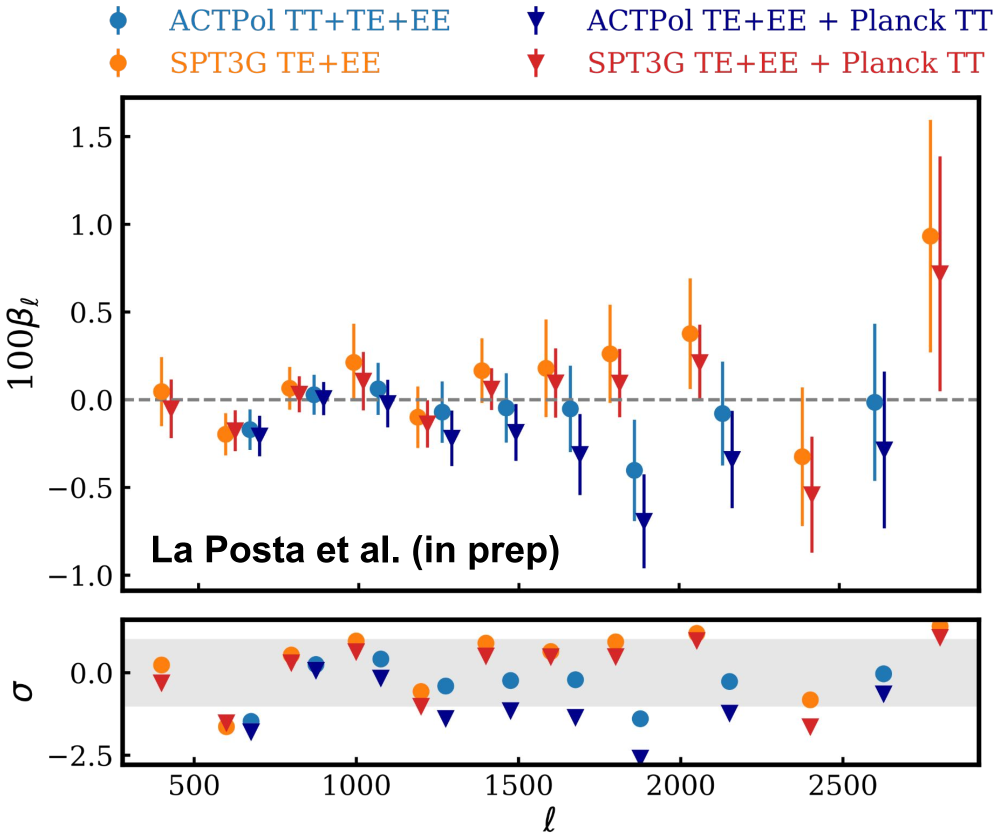

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	χ^2 / dof (PTE)
ACT TT/TE/EE	4.63/9 (0.87)
ACT TE/EE + Planck TT	15.11/9 (0.09)
SPT3G TE/EE	11.06/11 (0.44)
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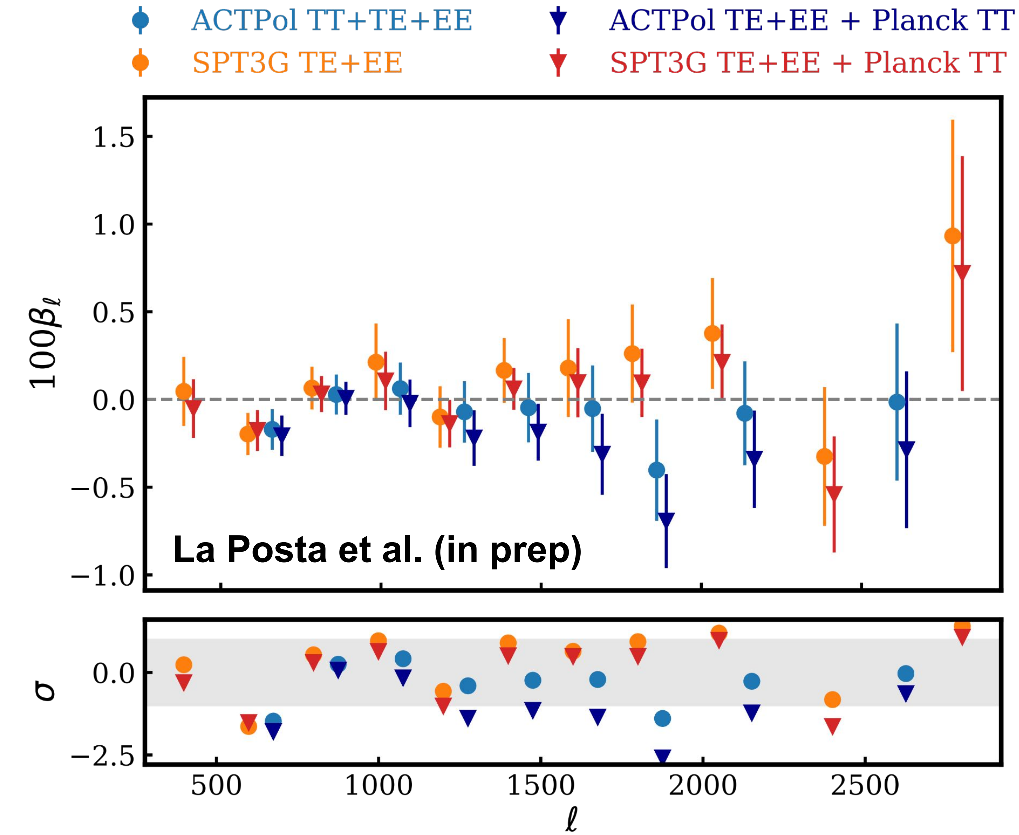

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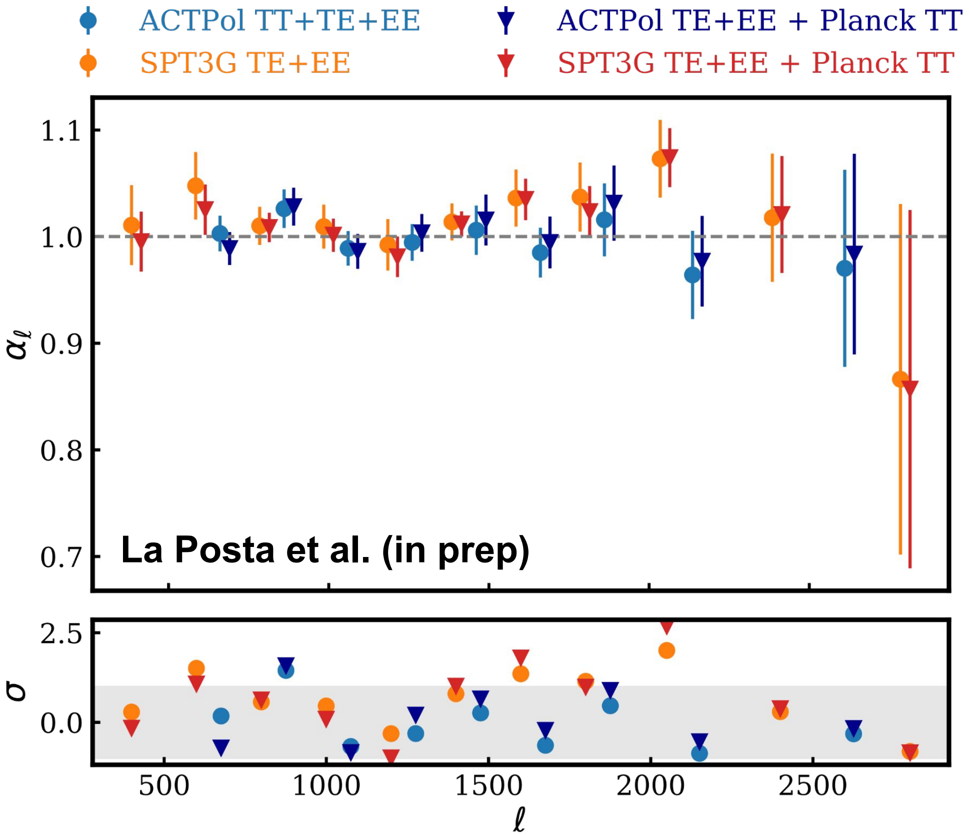

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ACT TE/EE + Planck TT	**5.81/9 (0.76)**
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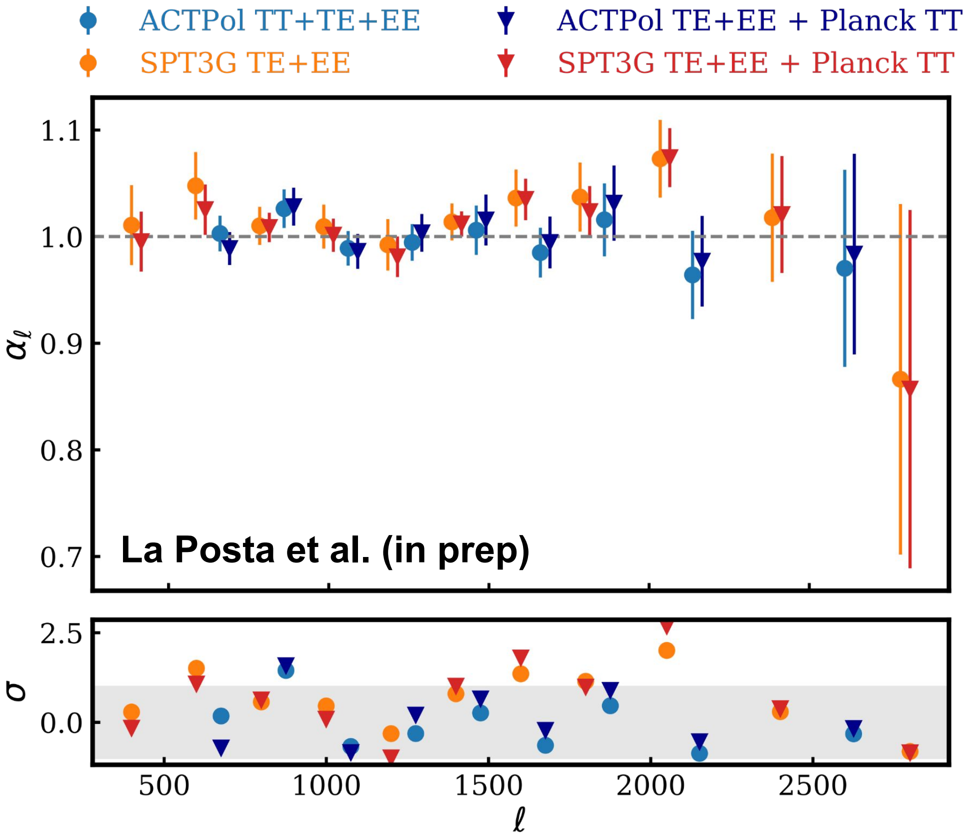

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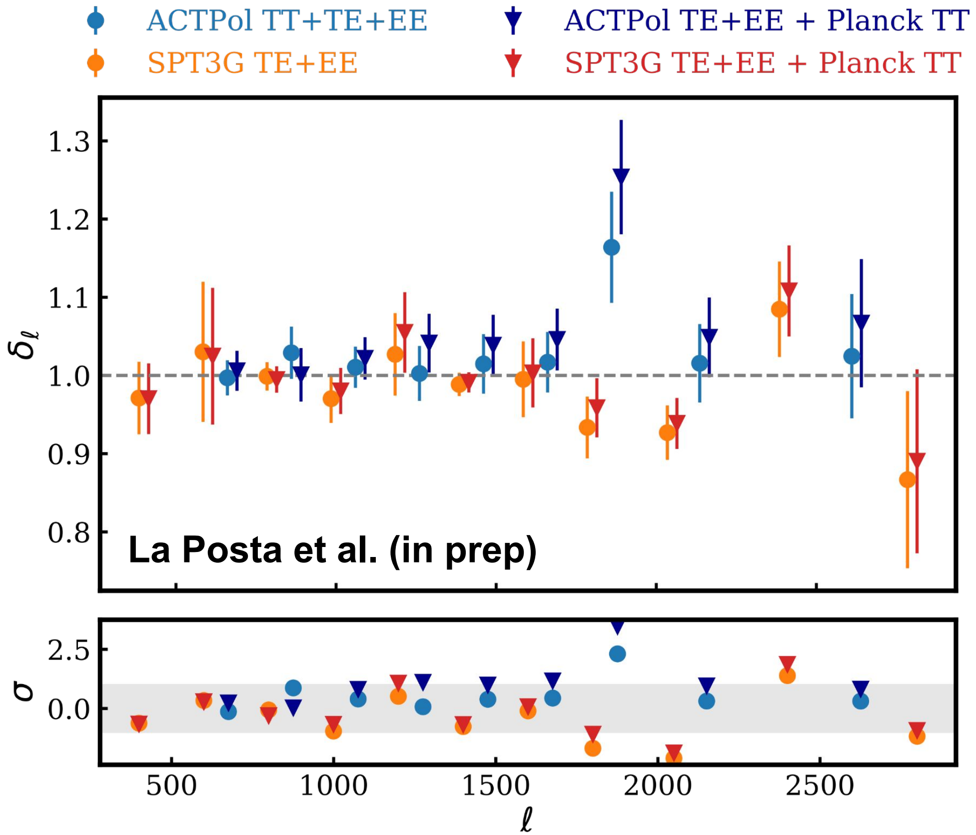
$$\tilde{C}_\ell^{TE} = \delta_\ell C_\ell^{TE}$$
$$\tilde{C}_\ell^{EE} = C_\ell^{EE}$$

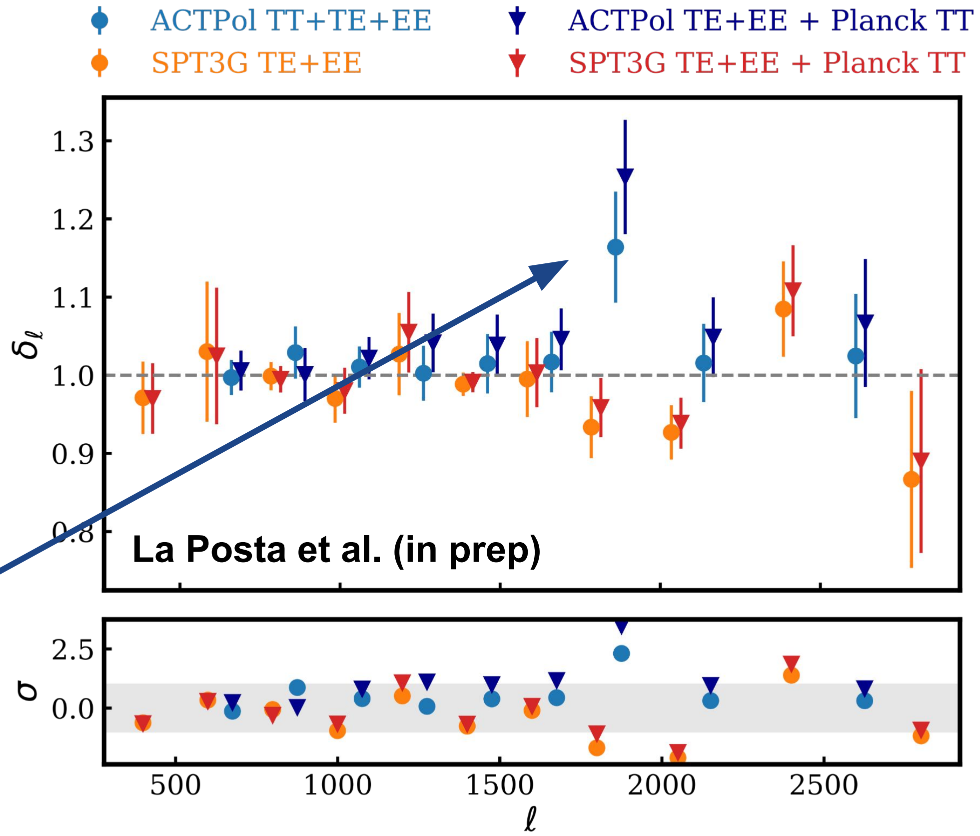


SPT3G [https://github.com/xgarrido/spt_likelihoods]
ACT DR4 [https://github.com/ACTCollaboration/pyactlike]
Planck Plik_lite [https://github.com/CobayaSampler/cobaya]

TE bias

$$\tilde{C}_\ell^{TE} = \delta_\ell C_\ell^{TE}$$
$$\tilde{C}_\ell^{EE} = C_\ell^{EE}$$

TE amplitude difference with respect to Planck have already been noticed in Aiola et al. (2020)



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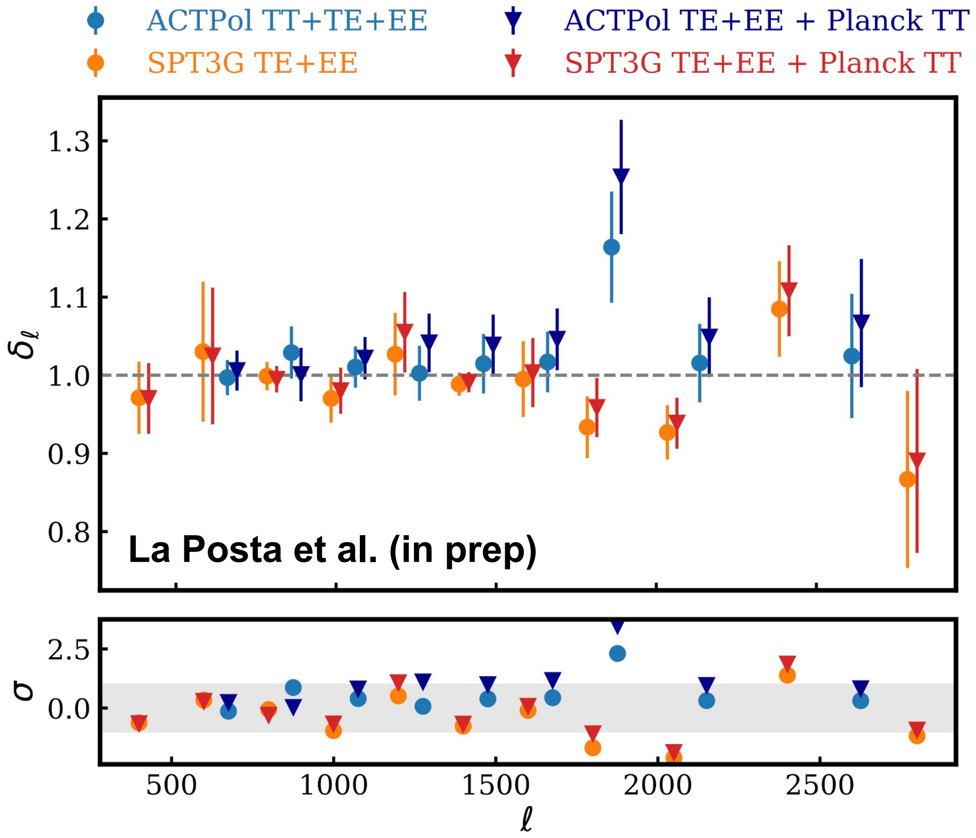
TE bias

$$\tilde{C}_\ell^{TE} = \delta_\ell C_\ell^{TE}$$
$$\tilde{C}_\ell^{EE} = C_\ell^{EE}$$

	χ^2 / dof (PTE)
ACT TT/TE/EE	6.54/9 (0.68)
ACT TE/EE + Planck TT	17.43/9 (0.04)
SPT3G TE/EE	11.93/11 (0.37)
SPT3G TE/EE + Planck TT	10.68/11 (0.47)



SPT3G [**https://github.com/xgarrido/spt_likelihoods**]
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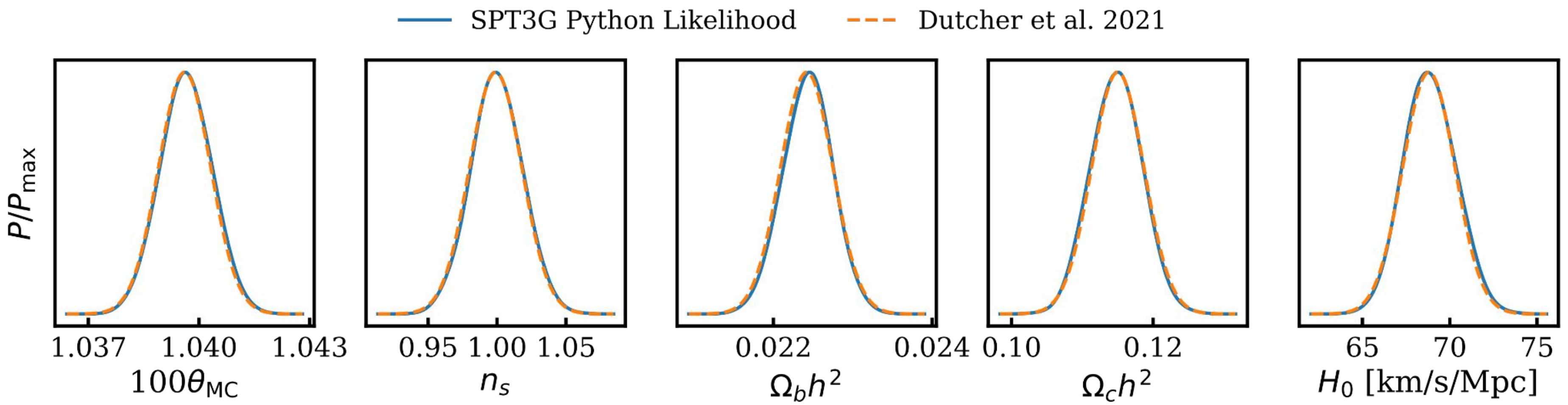
Conclusion

- We found no significant deviations from ΛCDM in this analysis of Planck, SPT3G, ACTPol data
- With these methods, we are able to spot scale dependent T-E inconsistencies in a model independent way [with respect to ΛCDM]
- These methods also catch deviations due to instrumental systematic effects

Q&A

SPT3G Likelihood



Computing the conditional power spectra

This method have already been applied to Planck data
(Planck 2015 results XI. [arXiV:1507.02704])

$$\begin{pmatrix} \mathbf{C^{TT}} \\ \mathbf{C^{TE}} \\ \mathbf{C^{EE}} \end{pmatrix} \begin{pmatrix} \Sigma_{TTTT} & \Sigma_{TTTE} & \Sigma_{TTEE} \\ \Sigma_{TETT} & \Sigma_{TETE} & \Sigma_{TEEE} \\ \Sigma_{EETT} & \Sigma_{EETE} & \Sigma_{EEEE} \end{pmatrix} \longrightarrow \begin{pmatrix} \mathbf{C^{T}} \\ \mathbf{C^{P}} \end{pmatrix} \begin{pmatrix} \mathbf{\Sigma}_{T} & \mathbf{\Sigma}_{TP} \\ \mathbf{\Sigma}_{PT} & \mathbf{\Sigma}_{P} \end{pmatrix}$$

Computing the conditional power spectra

This method have already been applied to Planck data
(Planck 2015 results XI. [arXiV:1507.02704])

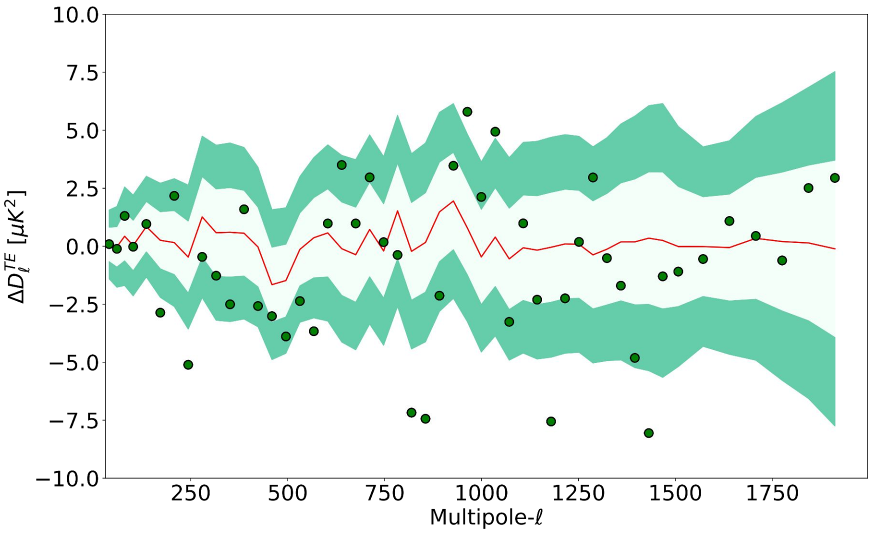
$$\begin{pmatrix} \mathbf{C^{TT}} \\ \mathbf{C^{TE}} \\ \mathbf{C^{EE}} \end{pmatrix} \begin{pmatrix} \Sigma_{TTTT} & \Sigma_{TTTE} & \Sigma_{TTEE} \\ \Sigma_{TETT} & \Sigma_{TETE} & \Sigma_{TEEE} \\ \Sigma_{EETT} & \Sigma_{EETE} & \Sigma_{EEEE} \end{pmatrix} \longrightarrow \begin{pmatrix} \mathbf{C^{T}} \\ \mathbf{C^{P}} \end{pmatrix} \begin{pmatrix} \mathbf{\Sigma}_{T} & \mathbf{\Sigma}_{TP} \\ \mathbf{\Sigma}_{PT} & \mathbf{\Sigma}_{P} \end{pmatrix}$$

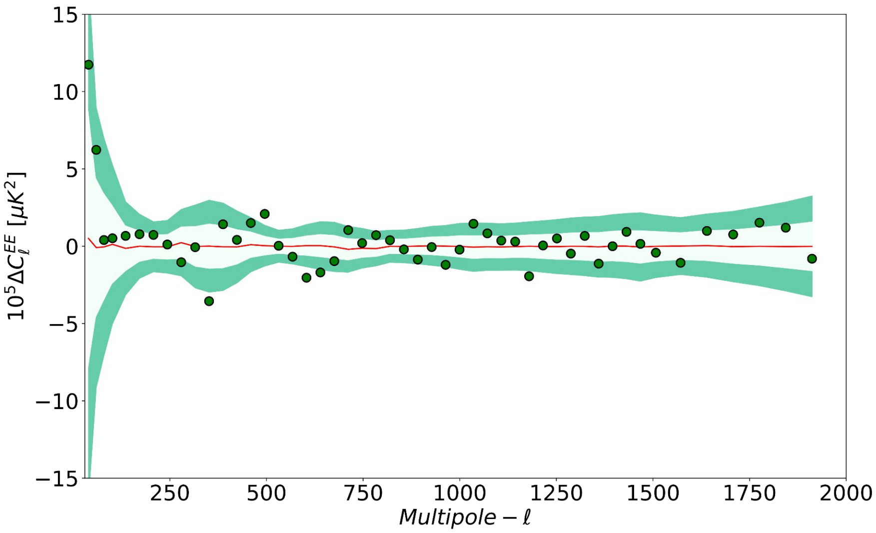
The polarization power spectrum $\mathbf{C^{P}}$ **conditioned** on the temperature power spectrum follows a normal distribution with :

$$\mathbf{C}^{P}_{\mathrm{cond}} = \mathbf{C}^{P}_{\mathrm{th}}(\theta^{T}_{\mathrm{bf}}) + \mathbf{\Sigma}^{\top}_{TP}\mathbf{\Sigma}^{-1}_{T}(\mathbf{C}^{T}_{\mathrm{obs}} - \mathbf{C}^{T}_{\mathrm{th}}(\theta^{T}_{\mathrm{bf}}))$$
$$\mathbf{\Sigma}^{P}_{\mathrm{cond}} = \mathbf{\Sigma}_{P} - \mathbf{\Sigma}^{\top}_{TP}\mathbf{\Sigma}^{-1}_{T}\Sigma_{TP}$$

Planck 2018 conditional residuals

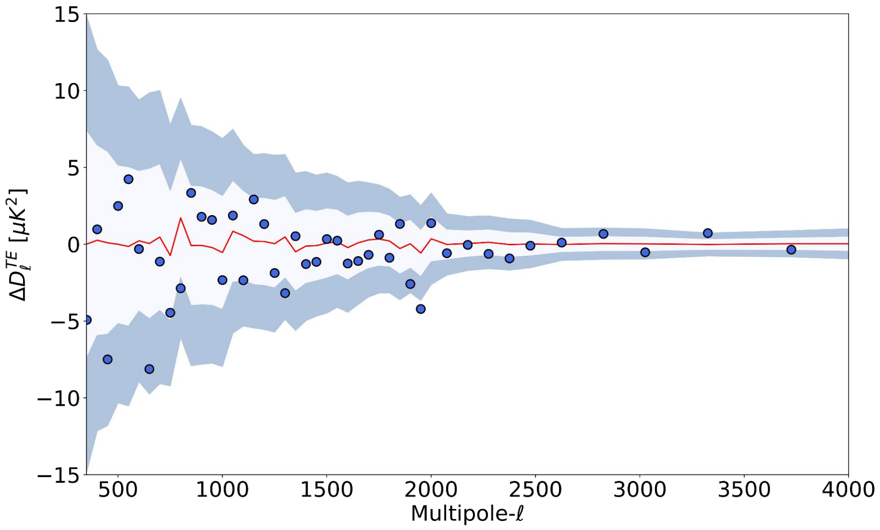
Residual plots : $\mathbf{C}^{P}_{\text{cond}} - \mathbf{C}^{P}_{\text{th}}(\theta^{T}_{\text{bf}})$ **[red line]**

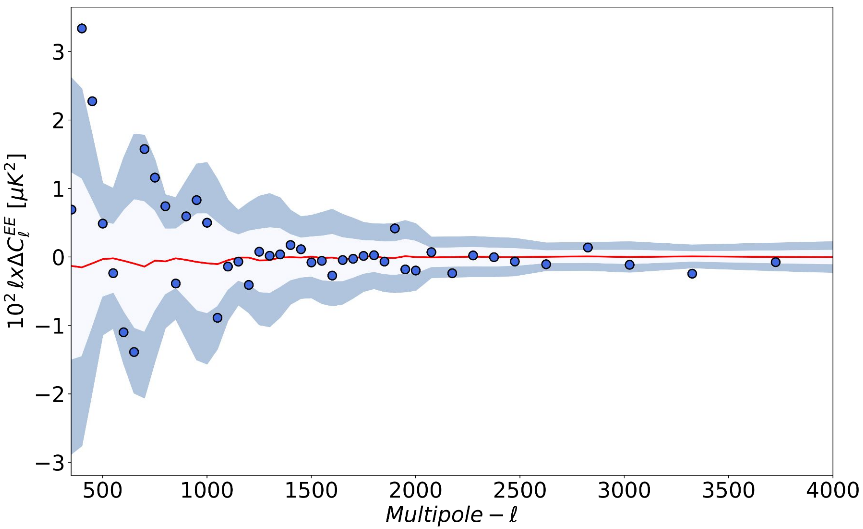




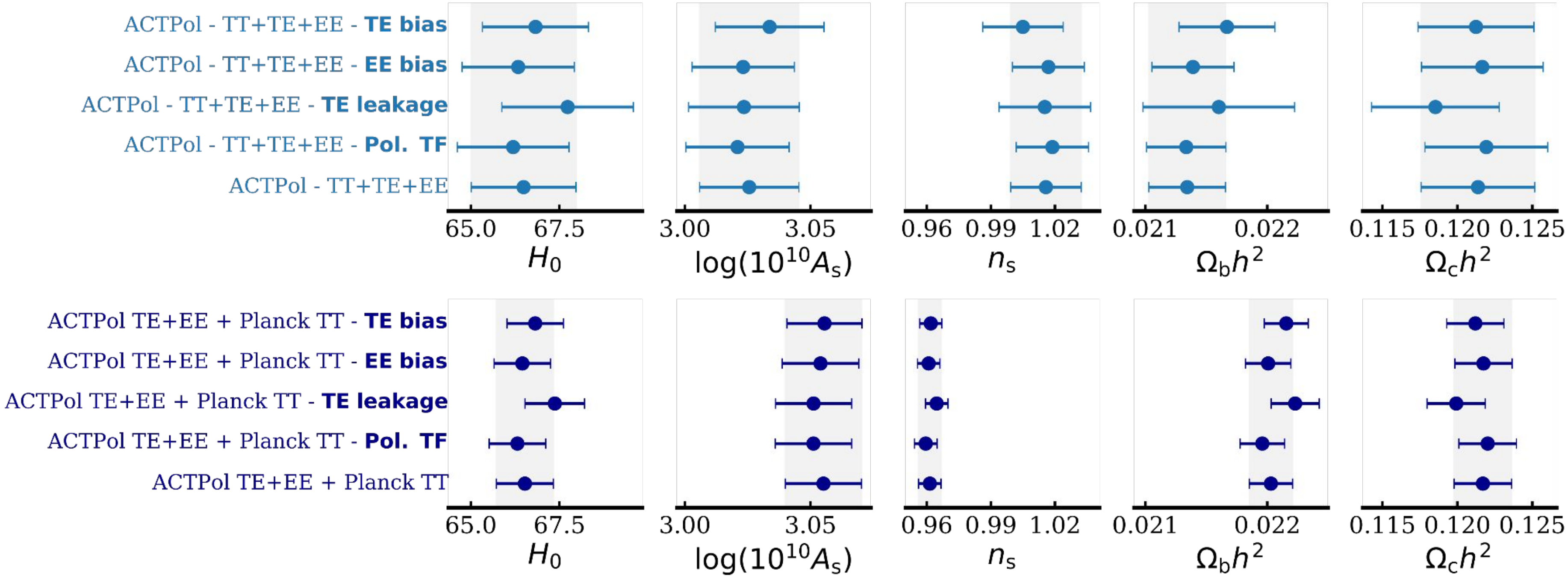
ACT DR4 conditional residuals

Residual plots : $\mathbf{C}^P_{\rm cond} - \mathbf{C}^P_{\rm th}(\theta^T_{\rm bf})$ **[red line]**

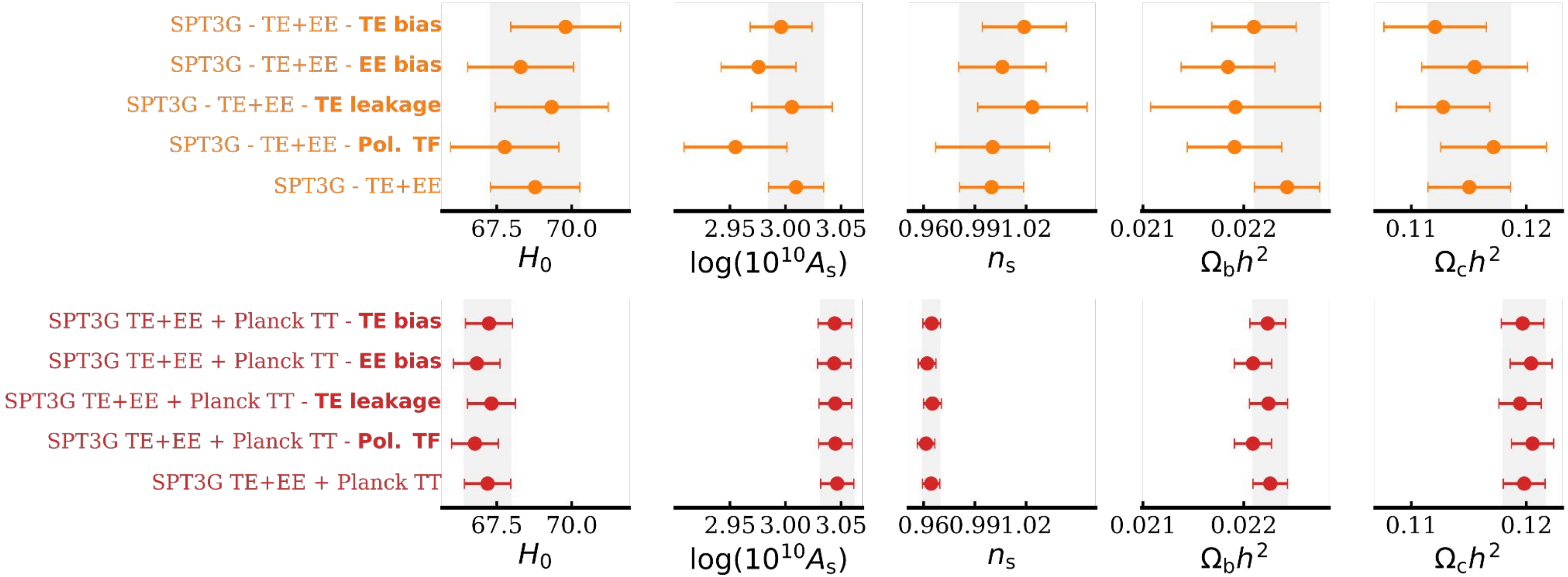




ACTPol DR4 cosmology



SPT3G cosmology



Temperature transfer function

Cosmology is fixed with the EE power spectrum $\tilde{C}_\ell^{EE} = C_\ell^{EE}$

$$\tilde{C}_\ell^{TT} = \epsilon_\ell^2 C_\ell^{TT}$$
$$\tilde{C}_\ell^{TE} = \epsilon_\ell C_\ell^{TE}$$

χ^2 / dof = 10.3 / 10 (PTE = 0.42) [ACT]

χ^2 / dof = 16.2 / 20 (PTE = 0.7) [PLANCK]