Cosmology with Planck T-E correlation coefficient

arXiv:2105.06167

CMB France #1

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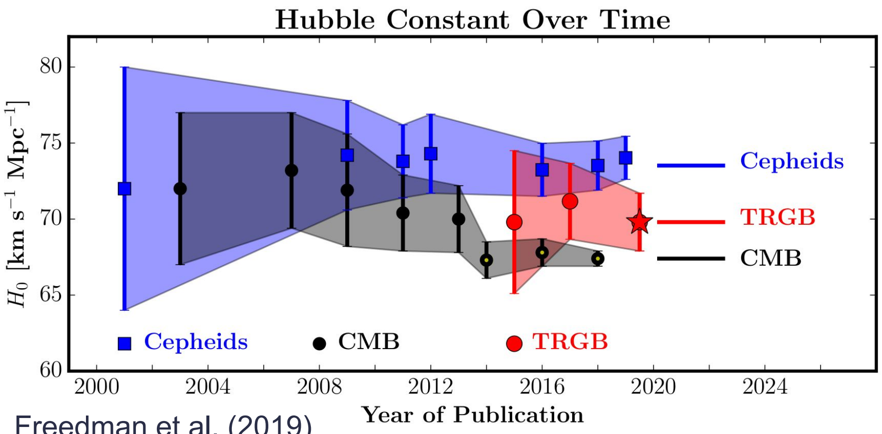
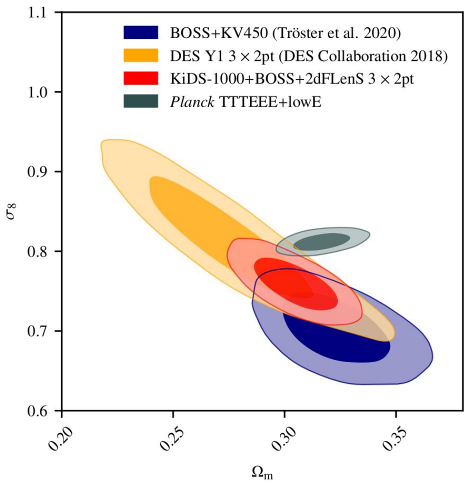
Constraints on ΛCDM



Freedman et al. (2019)
arXiv:1907.05922



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KiDS-1000 results
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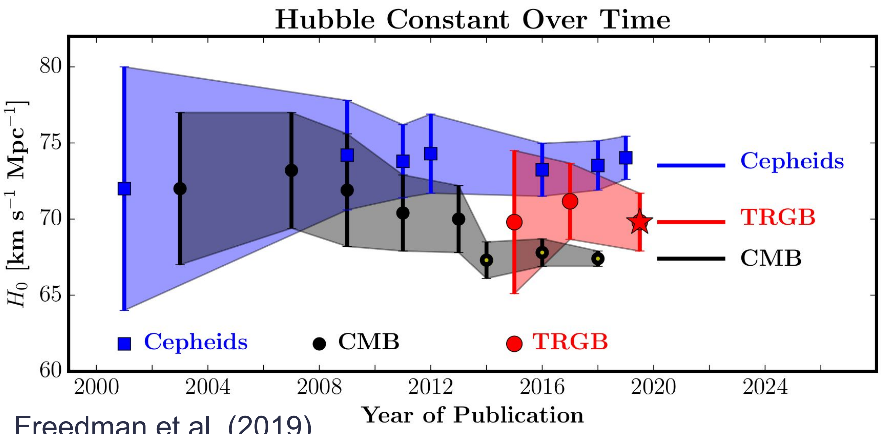

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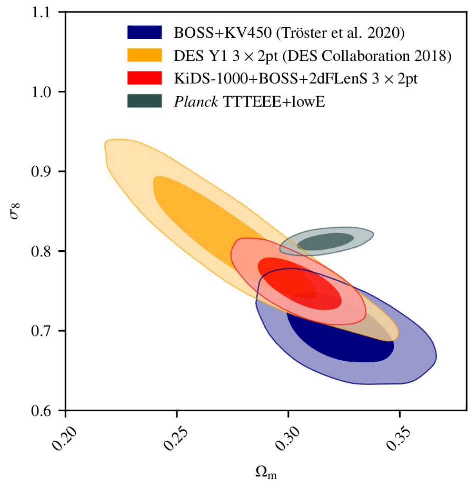

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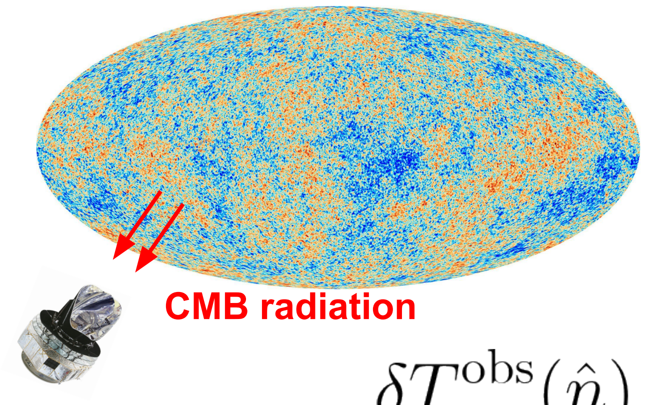
Solution ?

→ **Beyond LCDM physics ? (EDE, …)**

→ **Systematics ? (SN calibration, light curves standardization, …)**

CMB anisotropies



$$\delta T^{\rm obs}(\hat{n}) = (\mathcal{F}_T * c * B_T)\delta T^{\rm sky}(\hat{n})$$

$$E^{\rm obs}(\hat{n}) = (\mathcal{F}_E * c_E * c * B_E)E^{\rm sky}(\hat{n})$$

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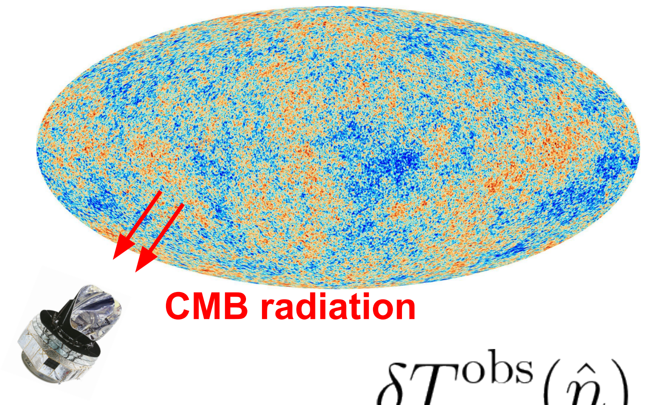

- **Beams**

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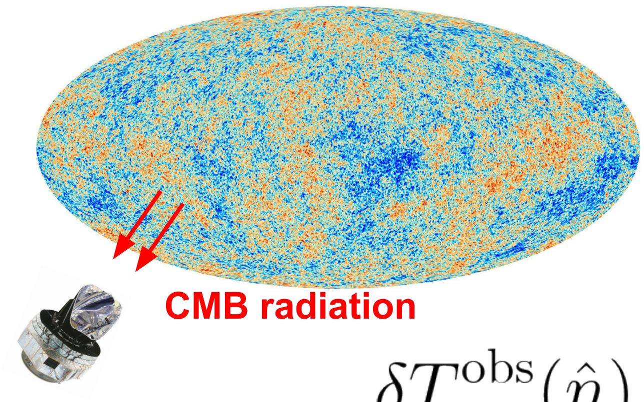
Temperature (Polarization) beam

CMB anisotropies



- **Beams**
- **Calibration**

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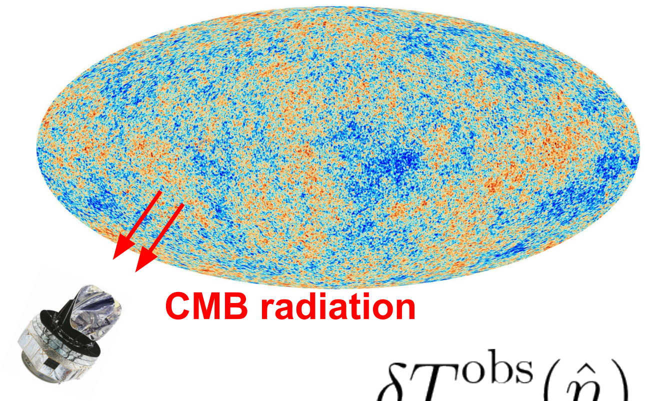
Global calibration

CMB anisotropies



- **Beams**
- **Calibration**
- **Polarization efficiency**

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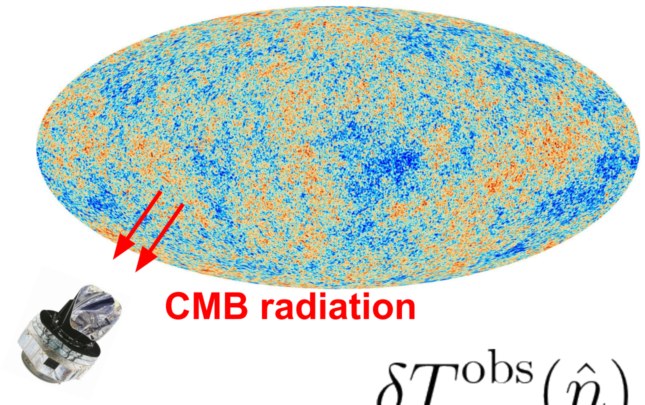
Polarization efficiency

CMB anisotropies



- Beams
- Calibration
- Polarization efficiency
- Transfer functions (?)

$$\delta T^{\rm obs}(\hat{n}) = (\mathcal{F}_T * c * B_T)\,\delta T^{\rm sky}(\hat{n})$$

$$E^{\rm obs}(\hat{n}) = (\mathcal{F}_E * c_E * c * B_E)\,E^{\rm sky}(\hat{n})$$

Temperature (polarization) transfer function

Multiplicative bias at the power spectra level

Goal : look at the impact of **multiplicative biases** on the cosmological parameter constraints

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Bias model

$$\begin{cases} \tilde{C}_\ell^{TT} = (\epsilon_\ell^T)^2 C_\ell^{TT} \\ \tilde{C}_\ell^{TE} = \epsilon_\ell^T \epsilon_\ell^E C_\ell^{TE} \\ \tilde{C}_\ell^{EE} = (\epsilon_\ell^E)^2 C_\ell^{EE} \end{cases}$$

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We study 3 difference biases

1. **Polarization efficiency**

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1. **Polarization efficiency**
2. **Temperature transfer function**

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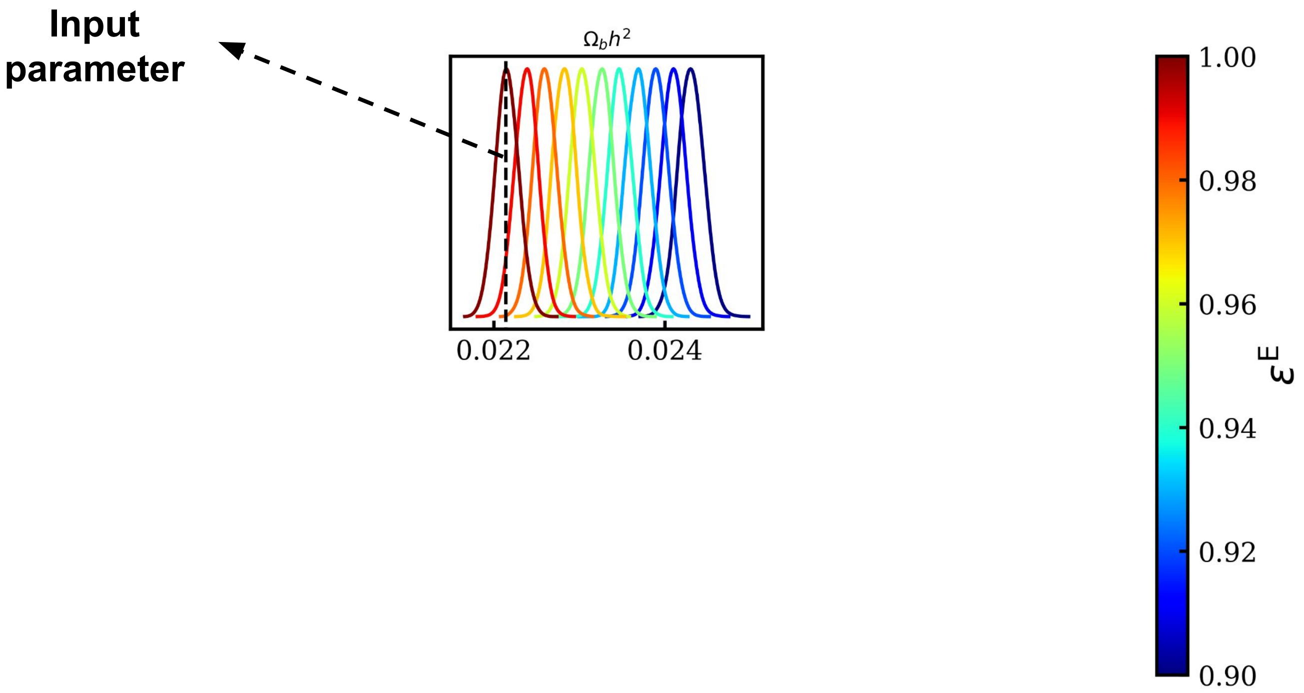
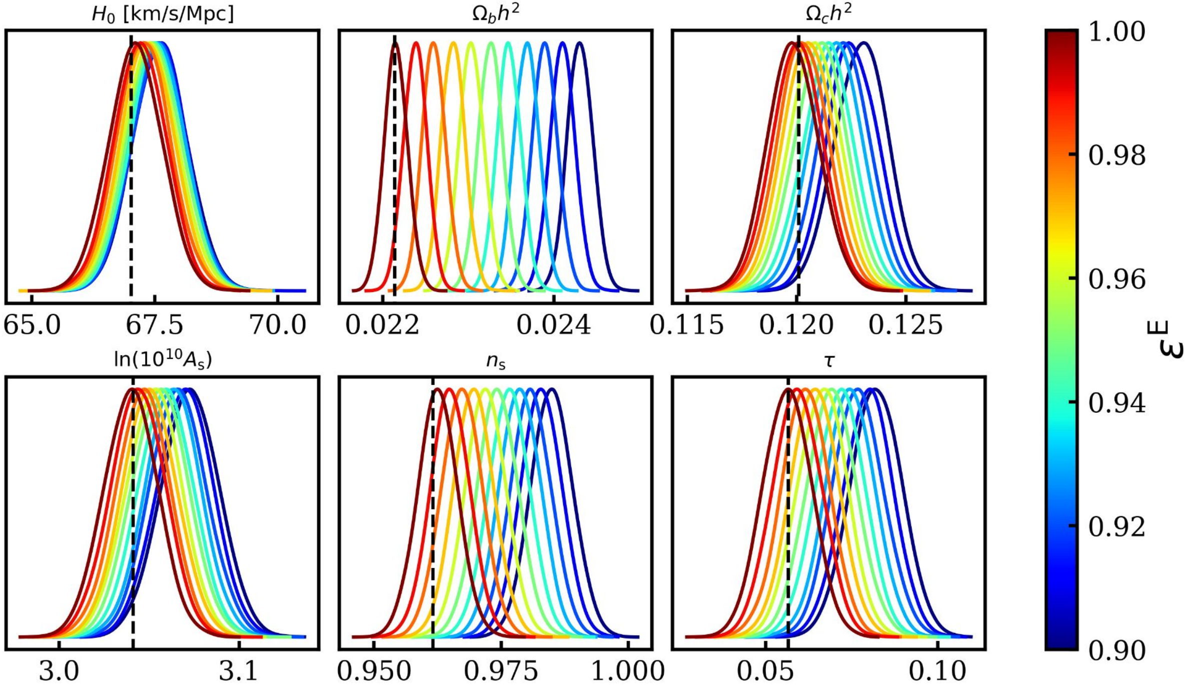
1. **Polarization efficiency**
2. **Temperature transfer function**
3. **Polarization transfer function**

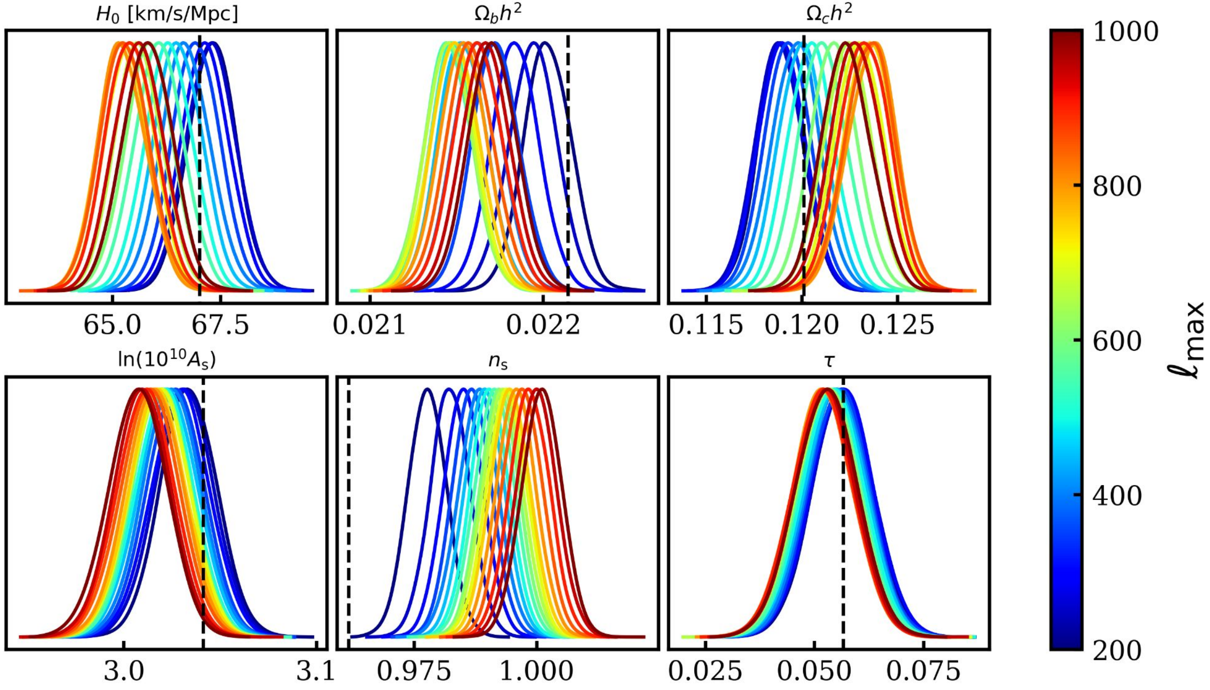
Polarization efficiency



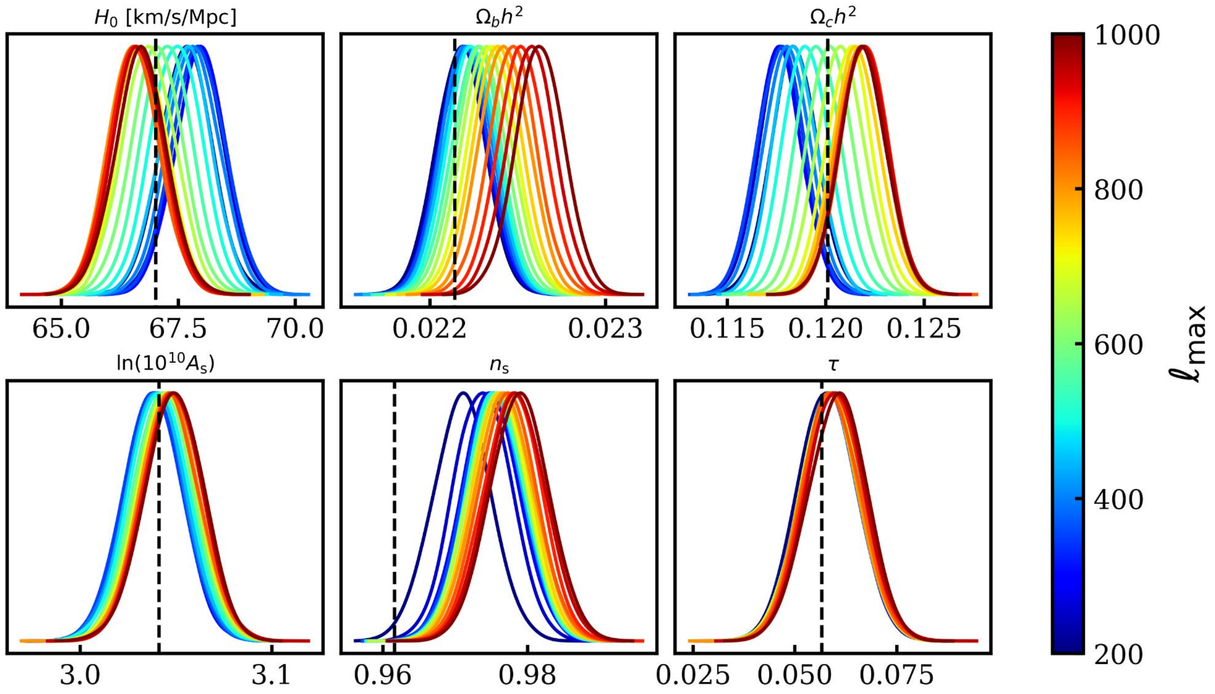
Polarization efficiency



Temperature transfer function



Polarization transfer function



Correlation coefficient of T and E modes

$$\mathcal{R}_\ell^{TE} = \frac{\left\langle a_{\ell m}^{T} a_{\ell m}^{E*} \right\rangle}{\sqrt{\left\langle a_{\ell m}^{T} a_{\ell m}^{T*} \right\rangle \left\langle a_{\ell m}^{E} a_{\ell m}^{E*} \right\rangle}} = \frac{C_\ell^{TE}}{\sqrt{C_\ell^{TT} C_\ell^{EE}}}$$

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Insensitive to multiplicative bias at the power spectra level

Correlation coefficient of T and E modes

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$$\boxed{\tilde{\mathcal{R}}_\ell^{TE}} = \frac{\epsilon_\ell^T \epsilon_\ell^E C_\ell^{TE}}{\sqrt{(\epsilon_\ell^T)^2 C_\ell^{TT} (\epsilon_\ell^E)^2 C_\ell^{EE}}} = \boxed{\mathcal{R}_\ell^{TE}}$$

Measured correlation coefficient

“True” correlation coefficient

Statistical properties of R^{TE}

Estimator

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

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We define $$\hat{C}_\ell^{XY} = C_\ell^{XY} + \Delta C_\ell^{XY}$$

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$$= \mathcal{R}_\ell^{TE} \frac{1 + \frac{\Delta C_\ell^{TE}}{C_\ell^{TE}}}{\sqrt{(1 + \frac{\Delta C_\ell^{TT}}{C_\ell^{TT}})(1 + \frac{\Delta C_\ell^{EE}}{C_\ell^{EE}})}} = \dots$$

development in the high signal-to-noise limit [□C_ℓ/C_ℓ ≪ 1]

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development in the high signal-to-noise limit [□$C_\ell/C_\ell \ll 1$]

Biased estimator

$$\left\langle \hat{\mathcal{R}}_\ell^{TE} \right\rangle = \mathcal{R}_\ell^{TE}(1 + \alpha_\ell)$$

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

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Biased estimator

$$\left\langle \hat{\mathcal{R}}_\ell^{TE} \right\rangle = \mathcal{R}_\ell^{TE}(1+\alpha_\ell)$$

Covariance matrix

$$\mathrm{cov}(\hat{\mathcal{R}}_\ell^{TE,\nu_1\times\nu_2}, \hat{\mathcal{R}}_\ell^{TE,\nu_3\times\nu_4}) = \left\langle \left(\hat{\mathcal{R}}_\ell^{TE,\nu_1\times\nu_2} - \left\langle \hat{\mathcal{R}}_\ell^{TE,\nu_1\times\nu_2} \right\rangle\right) \left(\hat{\mathcal{R}}_\ell^{TE,\nu_3\times\nu_4} - \left\langle \hat{\mathcal{R}}_\ell^{TE,\nu_3\times\nu_4} \right\rangle\right) \right\rangle$$

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

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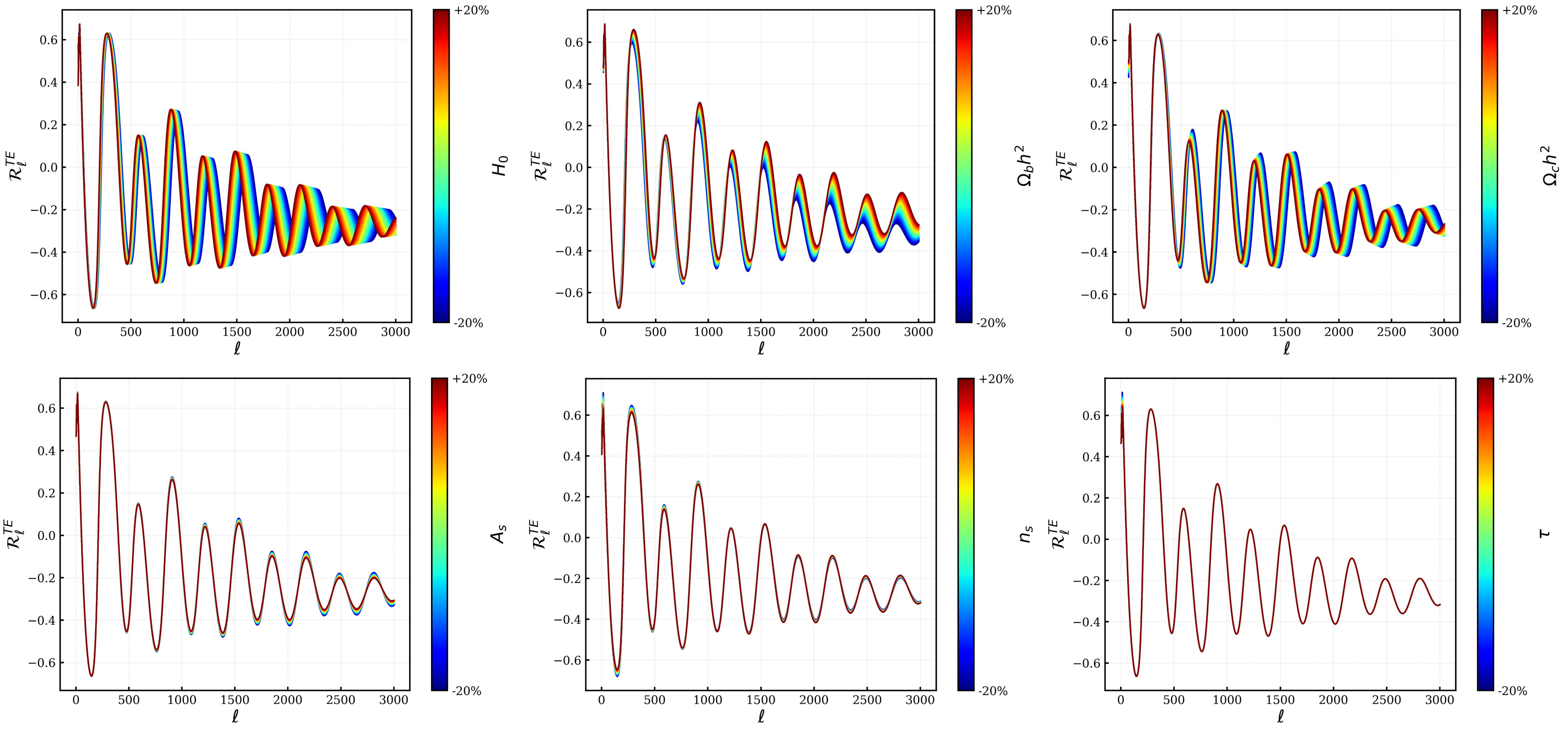
development in the high signal-to-noise limit [□C_ℓ/C_ℓ ≪ 1]

Covariance matrix

$$\begin{aligned}
\frac{\mathrm{cov}(\mathcal{R}_b^{TE,\nu_1\times\nu_2}, \mathcal{R}_b^{TE,\nu_3\times\nu_4})}{\mathcal{R}_b^{TE,\nu_1\times\nu_2}\mathcal{R}_b^{TE,\nu_3\times\nu_4}} &= \frac{\mathrm{cov}(C_b^{TE,\nu_1\times\nu_2}, C_b^{TE,\nu_3\times\nu_4})}{C_b^{TE,\nu_1\times\nu_2}C_b^{TE,\nu_3\times\nu_4}} \\
&+ \frac{1}{4}\left[\frac{\mathrm{cov}(C_b^{TT,\nu_1\times\nu_2}, C_b^{TT,\nu_3\times\nu_4})}{C_b^{TT,\nu_1\times\nu_2}C_b^{TT,\nu_3\times\nu_4}} + \frac{\mathrm{cov}(C_b^{EE,\nu_1\times\nu_2}, C_b^{EE,\nu_3\times\nu_4})}{C_b^{EE,\nu_1\times\nu_2}C_b^{EE,\nu_3\times\nu_4}}\right] \\
&- \frac{1}{2}\left[\frac{\mathrm{cov}(C_b^{TE,\nu_1\times\nu_2}, C_b^{TT,\nu_3\times\nu_4})}{C_b^{TE,\nu_1\times\nu_2}C_b^{TT,\nu_3\times\nu_4}} + \frac{\mathrm{cov}(C_b^{TT,\nu_1\times\nu_2}, C_b^{TE,\nu_3\times\nu_4})}{C_b^{TT,\nu_1\times\nu_2}C_b^{TE,\nu_3\times\nu_4}}\right. \\
&+ \left.\frac{\mathrm{cov}(C_b^{TE,\nu_1\times\nu_2}, C_b^{EE,\nu_3\times\nu_4})}{C_b^{TE,\nu_1\times\nu_2}C_b^{EE,\nu_3\times\nu_4}} + \frac{\mathrm{cov}(C_b^{EE,\nu_1\times\nu_2}, C_b^{TE,\nu_3\times\nu_4})}{C_b^{EE,\nu_1\times\nu_2}C_b^{TE,\nu_3\times\nu_4}}\right] \\
&+ \frac{1}{4}\left[\frac{\mathrm{cov}(C_b^{TT,\nu_1\times\nu_2}, C_b^{EE,\nu_3\times\nu_4})}{C_b^{TT,\nu_1\times\nu_2}C_b^{EE,\nu_3\times\nu_4}} + \frac{\mathrm{cov}(C_b^{EE,\nu_1\times\nu_2}, C_b^{TT,\nu_3\times\nu_4})}{C_b^{EE,\nu_1\times\nu_2}C_b^{TT,\nu_3\times\nu_4}}\right]
\end{aligned}$$

LCDM parameter dependance of R^{TE}



HiLLiPoP likelihood for R^{TE}

HiLLiPoP : High-L Likelihood Polarized for Planck (https://github.com/planck-npipe)

likelihood and foregrounds model are described in details in Couchot et al. (2017) (arXiv:1609.09730)

multi-frequency likelihood for the Planck channels **100**, **143** and **217** GHz

 6 cross-frequency spectra (**TT**, **TE**, **EE**)

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R^{TE}-likelihood

$$\Delta\mathcal{R}_\ell^{TE,\nu_1\times\nu_2} = \hat{\mathcal{R}}_\ell^{TE,\nu_1\times\nu_2}(1-\alpha_\ell) - \mathcal{R}_\ell^{TE,\nu_1\times\nu_2,\mathrm{model}}$$

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Unbiased estimator (data)

$$\frac{C_\ell^{TE,\nu_1\times\nu_2,\mathrm{model}}(p_{\mathrm{cosmo}},p_{\mathrm{fg}})}{\sqrt{C_\ell^{TT,\nu_1\times\nu_2,\mathrm{model}}(p_{\mathrm{cosmo}},p_{\mathrm{fg}})\,C_\ell^{EE,\nu_1\times\nu_2,\mathrm{model}}(p_{\mathrm{cosmo}},p_{\mathrm{fg}})}}$$

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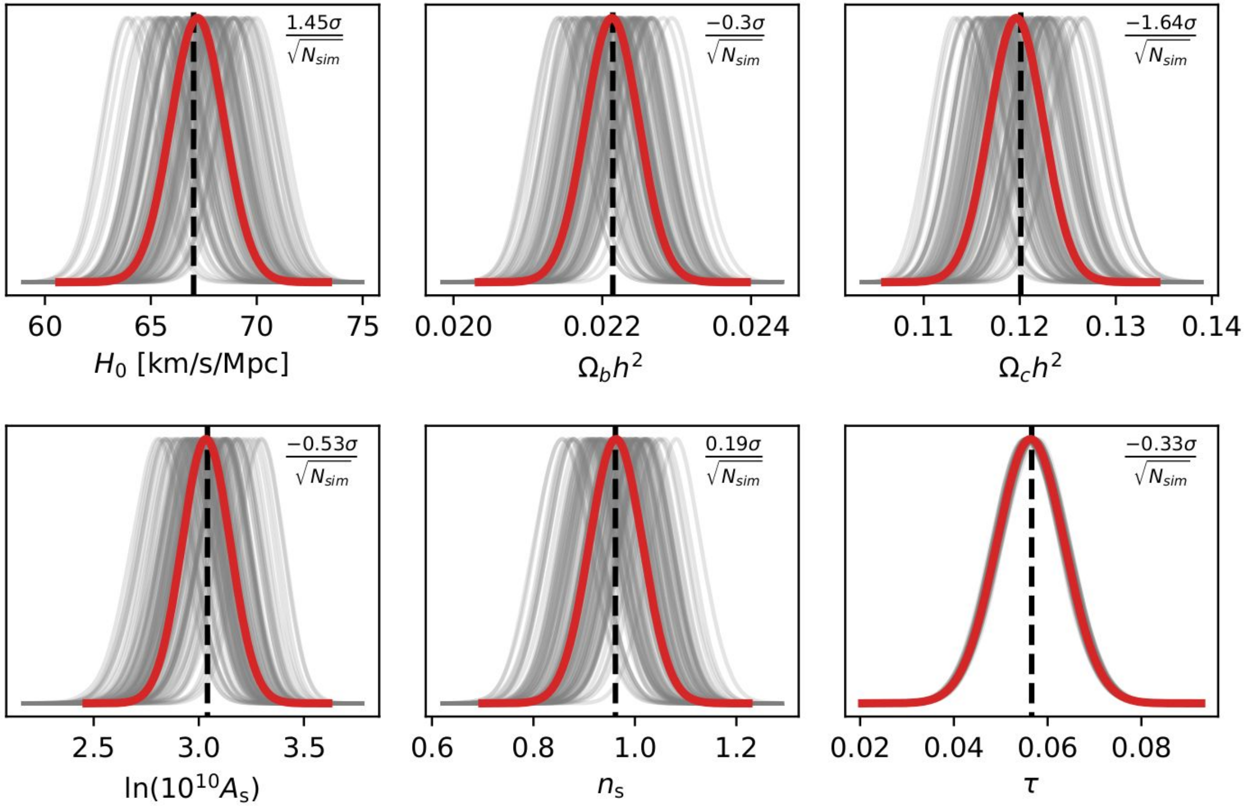
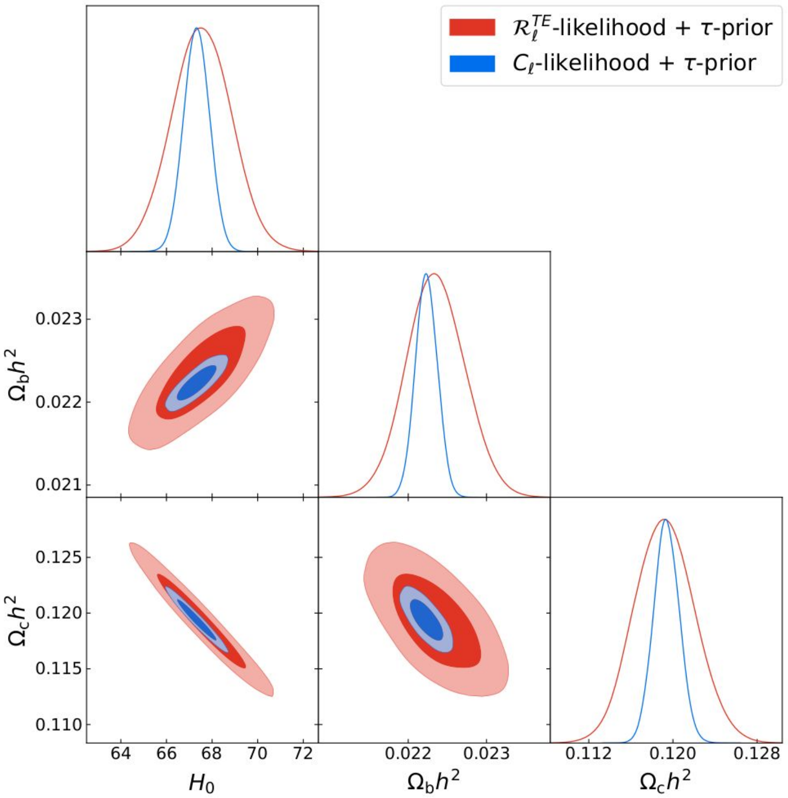
$$\ln\mathcal{L} \simeq -\frac{1}{2}\left(\Delta\mathcal{R}^{\mathrm{vec}}\right)^{\mathrm{T}}\mathbf{\Xi}^{-1}\left(\Delta\mathcal{R}^{\mathrm{vec}}\right)$$

Gaussian likelihood validation

N_{sim} = 100



Cosmological results from R^{TE}

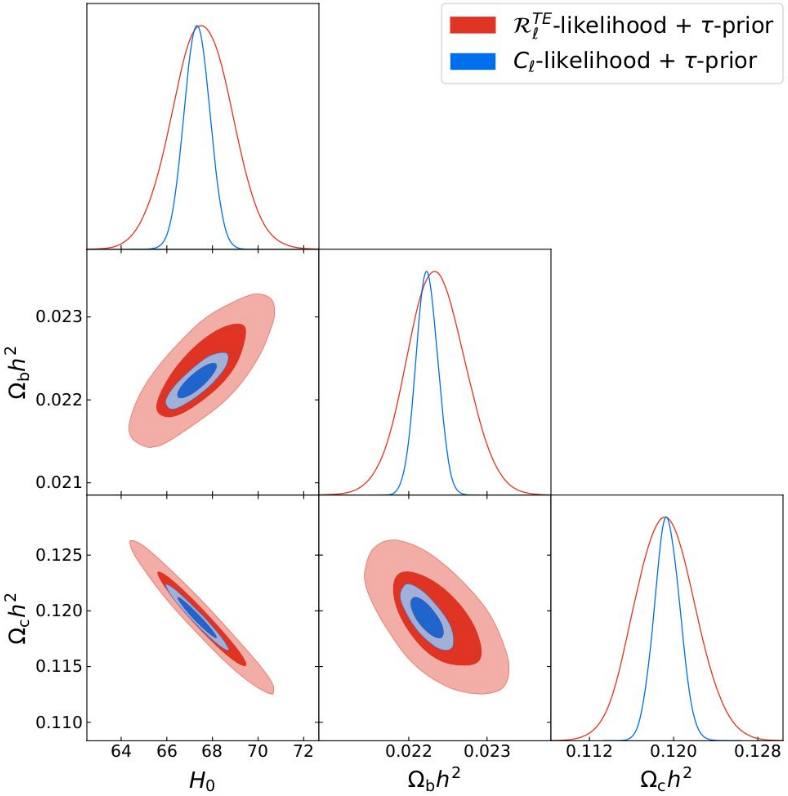


H_0 = 67.5 +/- 1.3 [km/s/Mpc]

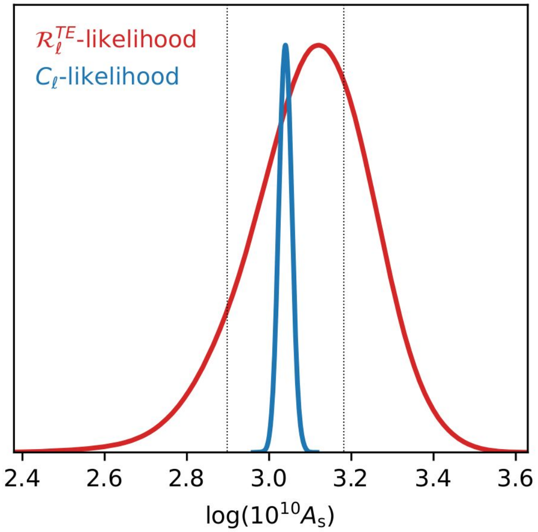
$\Omega_b h^2$ = 0.02235 +\- 0.00037

$\Omega_c h^2$ = 0.1192 +\- 0.0028

Cosmological results from R^{TE}



Constraints on A_s from lensing



CMB only correlation coefficient

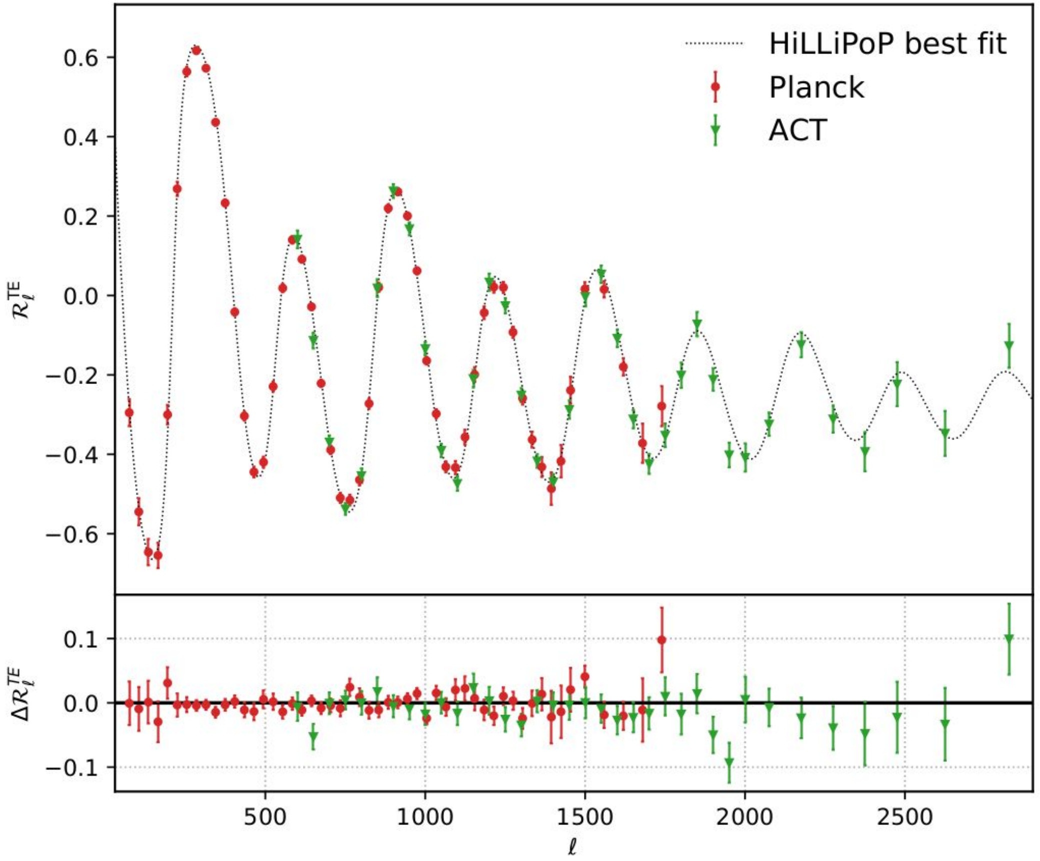
Joint sampling of **CMB bandpowers** and foregrounds parameters

□^{2} / dof = 52.7 / 52

□^{2} / dof = 39.0 / 36

Good agreement between the correlation coefficients and the Planck NPIPE C_ℓ cosmology

https://github.com/ACTCollaboration/pyactlike



Conclusion

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Conclusion

- We analyze Planck NPIPE data using an observable robust against multiplicative instrumental systematics

  ⇒ No evidence for such a bias in the data

- We obtain a constraint on $\mathbf{H_0}$ **= 67.5 +/- 1.3 km/s/Mpc** (**3.1σ** away from Riess et al. 2020)

- Upcoming precise measurements of CMB polarization will increase the constraining power of the correlation coefficient. R^{TE} provides a good consistency check against multiplicative instrumental systematics.