Updated fundamental constant constraints from Planck 2018 data and possible relations to the Hubble tension

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ABSTRACT
We present updated constraints on the variation of the fine structure constant, $\alpha_{\text{EM}}$, and effective electron rest mass, $m_e$, during the cosmological recombination era. These two fundamental constants directly affect the ionization history at redshift $z \approx 1100$ and thus modify the temperature and polarisation anisotropies of the cosmic microwave background (CMB) measured precisely with Planck. The constraints on $\alpha_{\text{EM}}$ tighten slightly due to improved Planck 2018 polarisation data but otherwise remain similar to previous CMB analysis. However, a comparison with the 2015 constraints reveals a mildly discordant behaviour for $m_e$, which from CMB data alone is found below its local value. Adding baryon acoustic oscillation data brings $m_e$ back to the fiducial value, $m_e = (1.0078 \pm 0.0067) m_e^{\text{fid}}$, and also drives the Hubble parameter to $H_0 = 69.1 \pm 1.2$ [in units of km s$^{-1}$ Mpc$^{-1}$]. Further adding supernova data yields $m_e = (1.0190 \pm 0.0055) m_e^{\text{fid}}$ with $H_0 = 71.24 \pm 0.96$. We perform several comparative analyses using the latest cosmological recombination calculations to further understand the various effects. Our results indicate that a single-parameter extension allowing for a slightly increased value of $m_e$ ($\approx 3.5\sigma$ above $m_e^{\text{fid}}$) could play a role in the Hubble tension.

Key words: recombination – fundamental physics – cosmology – CMB anisotropies

1 INTRODUCTION
In the last few decades, we have achieved unprecedented cosmological results with the CMB anisotropies through various missions (Bennett et al. 2013; Planck Collaboration et al. 2014). The 2015 release of Planck gave us unparalleled precision on the temperature spectra and greatly improved polarisation data at small angular scales (Planck Collaboration et al. 2015a, et. al. 2016). With these modern day developments, we have opened a gateway to various extensions to the standard $\Lambda$CDM model. Several groups have studied cosmological limits on neutrino masses and the number of relativistic degrees of freedom, encoded in the $N_{\text{eff}}$ parameter, leading to further discussion on the makeup of relativistic species in our universe (Gratton et al. 2008; Battye & Moss 2014). Similarly, the advances in CMB anisotropy data have allowed us to explore parameter space of Big Bang Nucleosynthesis as well as other physics beyond the standard model such as magnetic field heating (e.g., Shaw & Lewis 2010) Planck Collaboration et al. 2016), non-standard recombination (e.g., Rubiño-Martín et al. 2010; Farhang et al. 2013) and WIMP dark matter annihilation models (e.g., Galli et al. 2009a; Hütten et al. 2009; Chluba 2010; Planck Collaboration et al. 2015a).

One of the many key physical processes that we can study during the recombination epoch is the possible variations of fundamental constants (Kaplinghat et al. 1999). Comprehensive reviews that motivate the search for variations of fundamental constants have been given in the literature (Uzan 2003; 2011). For instance, constants such as the fine structure constant, $\alpha_{\text{EM}}$, or the effective electron mass, $m_e$, can vary due to the introduction of non-standard electromagnetically-interacting fields (Bekenstein 1982). At low redshifts, these constants have been constrained with quasar absorption lines (Bonifacio et al. 2014; Kotuš et al. 2017). In addition, several papers have studied the variations of these fundamental constants through their effect on the ionization history and the CMB anisotropies (Battye et al. 2001; Avelino et al. 2001; Seočcola et al. 2009; Menegoni et al. 2012; Planck Collaboration et al. 2015a).

In Hart & Chluba (henceforth HC17 2018), we provided the Planck 2015 CMB constraints on constant variations of $\alpha_{\text{EM}}$ and $m_e$ in detail modeling the effects using the cosmological recombination code CosmoRec (Chluba & Thomas 2011). There we also considered explicitly time-dependent variations of $\alpha_{\text{EM}}$ and $m_e$ across the recombination epoch using a phenomenological power-law in redshift (see HC17), that can be motivated with Mota & Barrow (2004). Spatial variations of the fine structure constant have also been discussed (Planck Collaboration et al. 2015b; Smith et al. 2019), as well as variations of the gravitational constant (Galli et al. 2009b; Alvey et al. 2019). So far, no significant departures from the expected values of fundamental constants have been reported.

For the 2018 release of CMB anisotropy results, the Planck team was able to significantly reduce remaining systematic effects in the large-scale data (Planck Collaboration et al. 2018c). Further-
more, polarised foregrounds were even more carefully subtracted in this recent analysis, leading to improved constraints from the CMB polarisation data (e.g., the reionisation optical depth Planck Collaboration et al. 2018a). The updated likelihood has not yet been used to constrain varying fundamental constants.

In this paper, we present the limits on the variations of fundamental constants as an update to the Planck 2015 constraints of HC17. Using the developments from the PR2 to the PR3 release of Planck data and benefitting from the reduction of systematics, especially in the E-mode polarisation, we derive the most stringent limits on the variations of fundamental constants from the CMB to date. These include limits on $\sigma_{\text{EM}}$ and $m_\text{e}$ as well as their redshift-dependence. The general results for $\sigma_{\text{EM}}$ and $m_\text{e}$ and their covariances are unaltered, however, we have expanded our discussion of the parameter degeneracies, and the interplay with the obtained Hubble parameter. This links to the apparent Hubble tension between low- and high-redshift probes (Riess et al. 2016; Bernal et al. 2019; Planck Collaboration et al. 2015a, 2018a), for which previous studies argued that variations of $m_\text{e}$ are unable to help much (Knox & Millea 2019). Similarly, variations of the atomic energy of hydrogen or its two-photon decay rate can only alleviate the Hubble tension when both extensions are included, mainly at the cost of significantly increased uncertainties but without shifting the central value by much (Liu et al. 2019).

Here, we confirm that variations of $\sigma_{\text{EM}}$ indeed can only play minor role for the Hubble tension (see Fig. 1). However, a single-parameter extension that allows for variations of $m_\text{e}$ indeed seems to alleviate the Hubble tension when combining various datasets at the cost of a discordant value for $m_\text{e}$ during recombination and reionization. Indications for this behaviour were already seen for the Planck 2013 release (Planck Collaboration et al. 2015b), however, there the significance for the shift in $m_\text{e}$ was at the $\approx 2\sigma$ level, while here we find a discrepant value of $m_\text{e}$ at $\Delta m_\text{e}/m_\text{e} \approx 3.5\sigma$, thus calling for further investigation.

### 2 UPDATED CONSTRAINTS ON VARYING CONSTANTS

For this paper, the reference dataset is the 2018 baseline Planck data, with low- and high-$\ell$ data for temperature and $E$-mode polarisation power spectra, along with the lensing data from the same release Planck Collaboration et al. 2019a, 2018b. This is also combined with baryon acoustic oscillation (BAO, Alam et al. 2015) and supernova (SN, Riess et al. 2019) data. In this section, we will focus the discussion on Planck and BAO data only and return to the effect of adding SN data in Sect. 3.

As mentioned above, the large-angle polarisation data was slightly improved in the Planck 2018 data release; however, the reference Planck dataset too has changed. In previous Planck analyses the high-$\ell$ temperature and polarisation data was combined with the low-$\ell$ temperature, $E$ and $B$-mode polarisation data, along with the CMB lensing data as well. Here the Planck reference case includes just the high-$\ell$ and low-$\ell$ temperature and $E$-mode polarisation data with CMB lensing. We do not consider this posing an issue given the lack of constraining power from the $B$-modes for these fundamental constant variations.

Here, we examine $\sigma_{\text{EM}}$ and $m_\text{e}$, since these fundamental constants are the ones directly affecting the recombination process and Thomson scattering of the CMB. As illustrated in HC17, the main driving effect from a constant variation of $\sigma_{\text{EM}}$ is a change in the location of the last scattering surface. This originates from the main physical change to recombination from a varying fine structure constant, which modifies atomic transition energies, changing the temperature at which the photons and baryons decouple. Varying constants also affect specific transition rates such as Lyman-$\alpha$ and two-photon processes during recombination, though these modifications lead to far smaller changes (cf. HC17).

The effects from $m_\text{e}$ on the recombination history are very similar, even if typically $\approx 2.5$ times smaller than for a similar variation in $\sigma_{\text{EM}}$. Marked differences in the way that the Thomson cross section is changed distinguishes $\sigma_{\text{EM}}$ from $m_\text{e}$ variations. In particular, this effect strongly increases the geometric degeneracies between $m_\text{e}$ and $H_0$ (throughout the paper in units of km s$^{-1}$ Mpc$^{-1}$), leading to a significantly enhanced error on $m_\text{e}$ from CMB data alone (HC17). The latter motivates a more careful consideration of the $m_\text{e}$ constraints when combining CMB with external data, as we especially discuss in Sect. 3 where we present new results for both the Planck 2015 and 2018 releases.

#### 2.1 Variations of the fine structure constant: $\sigma_{\text{EM}}$

We find that the constraints on $\sigma_{\text{EM}}$ remain largely unchanged when moving to the Planck 2018 dataset, albeit yielding slightly improved errors. We summarized the changes through the various Planck data releases in Fig. 1. If we compare with the CMB-only values from our previous paper, we can see a change of the fine structure constant from $\sigma_{\text{EM}}/\sigma_{\text{EM},0} = 0.9993 \pm 0.0025$ to $\sigma_{\text{EM}}/\sigma_{\text{EM},0} = 1.0005 \pm 0.0024$. When we add BAO data, the value drifts slightly away from unity, $\sigma_{\text{EM}}/\sigma_{\text{EM},0} = 1.0019 \pm 0.0022$. This matches the behaviour found for the 2013 and 2015 data, as seen in Fig. 1 where the fiducial value of $\sigma_{\text{EM}}$ shifts to slightly higher values. The errors have not improved substantially due to the addition of higher-precision polarisation data, mainly affecting the reionization optical depth $\tau$, which is largely uncorrelated with $\sigma_{\text{EM}}$.

The values of the standard parameters when adding $\sigma_{\text{EM}}$ are presented in Table 1. The majority of the fiducial parameters’ positions and errors stay the same except for $n_s$ and 100 $\beta_{\text{MC}}$. The error in $n_s$ increases by 0.7$\sigma$, however, the $\beta_{\text{MC}}$ error increases by an order of magnitude due to geometric degeneracies (e.g., Planck Collaboration et al. 2015b). The effect is not as dramatic in $H_0$, where the error is only doubled due to the non-linear contributions from some of the other parameters diluting the increase in the error. This all follows the behaviour of the constraints when $\sigma_{\text{EM}}$ was added in previous works (Planck Collaboration et al. 2015b; Hart & Chluba 2018). Similarly, Table 1 shows that when adding BAO data, the limits do not change qualitatively, except the distance ladder contributions leading to $\sigma_{H_0} = 0.71$ while pulling $H_0$ slightly upwards.

A selection of the most-affected standard parameter posteriors is shown in Fig. 2 where we have compared the CMB-only 2015 (red) and 2018 posteriors (blue), along with respectively coloured bands, showing the fiducial 1$\sigma$ limits of these parameters. The degeneracy with $H_0$ has not changed except that the locations of the contours have shifted to slightly larger marginalised values of $H_0$, from $H_0 = 67.2 \pm 1.0$ in the 2015 release to $H_0 = 67.56 \pm 0.99$ in the 2018 release. This shift marks the main degeneracy of the $\sigma_{\text{EM}}$ parameter, however, we can also clearly see a degeneracy with the tilt of the spectrum, another parameter that slightly differs between the Planck releases. Comparing the fiducial bands in Fig. 2 with the locations of the contours, it is clear that the $\Omega_0 h^2$ and $\Omega_{\text{b}} h^2$ contours have shifted in opposite directions to their 1$\sigma$ bands between the two datasets. Overall, we find consistent results for all the parameters between the two Planck releases. Addition of BAO data to the analysis does not alter the conclusions significantly.
Figure 1. Constraints on the fundamental constants (left) using various combinations of Planck data included with their $H_0$ values and errors (right). The cases without SN data are discussed in Sect. 2, while the addition of SN data is considered in Sect. 3 when alluding to the Hubble tension. Top: results from the fine structure constant $\alpha_{EM}$. Bottom: similar results but from the effective electron mass $m_e$. Here we have redacted the data from CMB data only because the error bars are so large for $H_0$. For the $m_e$ MCMC analysis, we have widened the prior on the Hubble constant such that $H_0 > 20$. 

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We used a wide prior for the marginalised value of departing from its fiducial CMB value. We thus used an even more Planck combined Planck bined Planck in influenced by the prior definition of parameters in coloured bands.

| Parameter | Planck 2018 | Planck 2018 + varying $\alpha_{\text{EM}}$ | Planck 2018 + varying $\alpha_{\text{EM}}$ | Planck 2018 + varying $m_e$ | Planck 2018 + varying $m_e$ |
|-----------|-------------|---------------------------------|---------------------------------|-----------------|-----------------|
| $\Omega_b h^2$ | 0.02237 ± 0.00015 | 0.02236 ± 0.00015 | 0.02240 ± 0.00014 | 0.01970 ± 0.00012 | 0.02255 ± 0.00016 |
| $\Omega_c h^2$ | 0.1199 ± 0.0012 | 0.1201 ± 0.0014 | 0.1199 ± 0.0015 | 0.1058 ± 0.0076 | 0.1208 ± 0.0018 |
| $100^\circ \text{MC}$ | 1.04088 ± 0.00031 | 1.0416 ± 0.0034 | 1.0436 ± 0.0030 | 0.958 ± 0.045 | 1.0464 ± 0.0047 |
| $\tau$ | 0.0542 ± 0.0074 | 0.0540 ± 0.0075 | 0.0553 ± 0.0075 | 0.0512 ± 0.0077 | 0.0549 ± 0.0074 |
| $\ln(10^{10} A_s)$ | 3.044 ± 0.014 | 3.043 ± 0.015 | 3.043 ± 0.015 | 3.029 ± 0.017 | 3.045 ± 0.014 |
| $n_s$ | 0.9649 ± 0.0041 | 0.9637 ± 0.0070 | 0.9621 ± 0.0070 | 0.9640 ± 0.0040 | 0.9654 ± 0.0040 |

| $\alpha_{\text{EM}}/\alpha_{\text{EM,0}}$ | -- | 1.0005 ± 0.0024 | 1.0019 ± 0.0022 | -- | -- |
| $m_e/m_e, p$ | -- | -- | -- | 0.888 ± 0.059 | 1.0078 ± 0.0067 |

Table 1. Marginalised values of the fine structure constant and effective electron mass $\alpha_{\text{EM}}$ and $m_e$ using the Planck 2018 data along with BAO contributions. We used a wide prior for $H_0$ so that the 1$\sigma$ limit is not cut off and therefore avoids biasing the marginalised $m_e$ posterior ($H_0 > 20$).

![Figure 2](image1.png) Figure 2. The posterior contours that illustrate the degeneracies between the fine structure constant $\alpha_{\text{EM}}$ and the most-affected standard parameters $[\Omega_b h^2, \Omega_c h^2, H_0, n_s]$. The $\Lambda$CDM scenario of $\alpha_{\text{EM}}/\alpha_{\text{EM,0}} = 1.0$ is added as a reference, along with the 1$\sigma$ values of Planck 2015 and 2018 standard parameters in coloured bands.

![Figure 3](image2.png) Figure 3. Same as Fig. 2 except here we show the contours for $m_e$. The same $\Lambda$CDM reference marker and fiducial cosmology 1$\sigma$ bands have been added here. In these contours we ensured 20 < $H_0 < 100$.

### 2.2 Variations of the effective electron mass: $m_e$

The difference in constraints for $m_e$ is slightly more complicated than the picture for $\alpha_{\text{EM}}$. Although there are improvements over the Planck 2015 results, the marginalised value of $m_e$ is still heavily influenced by the prior definition of $H_0$. This aspect was covered in our previous work, where we used a prior such that $H_0 > 40$ to conform with the initial CMB analysis with Planck, which combined Planck 2013 and WMAP data [Planck Collaboration et al. 2015b]. However, when considering CMB-only 2018 constraints, the marginalised value of $m_e$ slips further away from unity with $H_0$ departing from its fiducial CMB value. We thus used an even more extended prior 20 < $H_0 < 100$ to avoid prior-domination.

For the CMB-only results presented in Table 1 we applied the aforementioned wide prior; however, we have instead shown the narrow prior results in Fig. 1 to better compare with previous works. Further discussion on the prior is found in Sec. 2A where we show the changes in the contours as the prior is adjusted. In 2013 and 2015, the CMB-only constraint for $m_e$ were consistent with the standard value, given the large error bar due to geometric degeneracies. With the 2018 data, $m_e$ drifts further below the local value, indicating a discrepancy of $\Delta m_e/m_e \approx -2\sigma$ level, with extremely low value for $H_0$ (see Table 1). Although for the Planck 2013 and 2015 data, the value was consistent with $m_{e,0}$ to within 1$\sigma$, this behaviour is not surprising given the large degeneracies between $H_0$ and $m_e$ already documented in previous works on Planck data and fundamental constant variations. Adding BAO data brings $m_e$ back to the standard value, restoring concordance at a slightly improved error for the 2018 data.

While parameters like $\tau$, $n_s$, and $A_s$ all stay within 1$\sigma$ of $\Lambda$CDM when adding $m_e$, we must appreciate the drifts in the baryonic and cold matter density parameters, $\Omega_b h^2$ and $\Omega_c h^2$. From Fig. 3 and Table 1 we can see the sharp degeneracies of these parameters leading to $\pm 1.8\sigma$ drifts in $\Omega_b h^2$ and $\pm 2\sigma$ for $\Omega_c h^2$ for CMB-only con-
2.4 Constraints on $\alpha_{\text{EM}}$ and $m_e$ with time dependence

Low redshift probes of fundamental constants have shown that possible variations would have to be as small as $\sim 10^{-8}$ today (see the review in [Uzan 2011] for more details). However explicitly redshift-dependent variations have been motivated by a number of theoretical models such as the string dilaton and runaway dilaton models [Martins et al., 2015]. Here we consider how the fundamental constants $C$ vary with redshift across the recombination epoch, using the phenomenological parametrisation

$$C(z) = C_0 \left(1 + \frac{z}{1100}\right)^p,$$

where $C \in \{\alpha_{\text{EM}}, m_e\}$ for this analysis. Time-independent variations are captured by constant change to $C_0$, just as in the previous sections. Varying $p$ parametrises the time-dependence. It leaves the position of the Thomson visibility function practically unaltered while broadening and narrowing it for negative and positive values of $p$, respectively (see HC17).

When we add a time-dependent variations using the power-law model in Eq. (1) to the MCMC analyses discussed in Sections 2.1 and 2.2 we obtain the results summarized in Table 2.

In comparison to the Planck 2015, the obtained central values and errors change marginally when $p$ is added, showing no indication for departures from $p = 0$. Whilst $\alpha_{\text{EM}} = 0.9998 \pm 0.0036$ and $p = 0.0007 \pm 0.0036$ for the Planck 2015 release, the fundamental constant marginalised values are $\alpha_{\text{EM}} = 0.9997 \pm 0.0035$ and $p = -0.0011 \pm 0.0035$ for the Planck 2018 data. The index of the power law $p$, is consistent with zero to within $\sim 0.3\sigma$, suggesting that this parameter is tightly constrained by the current CMB anisotropies. Adding BAO data, we obtain $p = 0.0007 \pm 0.0031$, agreeing with the value for $\Lambda$CDM to within $\sim 0.2\sigma$. The overall posteriors remain extremely close to those presented in the Planck 2015 analysis, so that we do not repeat them here.

Turning to the case of time-varying $m_e$, we again find that $p$ is consistent with zero at a fraction of a $\sigma$ (see Table 2). Even with the large geometric degeneracies between $H_0$ and $m_e$ described in Sec. 2.2, the only differences are small shifts of the central parameter values, which derive from the subtle differences in the effects between $\alpha_{\text{EM}}$ and $m_e$ on the recombination and reionization visibilities mentioned above (see Sect. 2.2.1).

Our findings again highlight that explicitly time-varying $\alpha_{\text{EM}}$ and $m_e$ can be constrained independently of their constant variations using CMB data. A more in depth study is thus expected to lead constraints on at least two independent model parameters if the recombination physics of the $z \approx 1100$ Universe is indeed affected.

3 ADDING SN DATA AND THE HUBBLE TENSION

Although the degeneracy between distance measures such as $H_0$ and $\alpha_{\text{EM}}$ is already evident, the geometric effects due to the scaling of the Thomson cross section creates an even larger degeneracy between $m_e$ and $H_0$, as well as the baryonic and cold dark matter densities ($\Omega_m h^2$ and $\Omega_c h^2$). We should thus check if the widening error bars of $H_0$ and $m_e$, as explained in Sec. 2.2.2 allow us to alleviate some of the recently discussed tensions with supernovae data (e.g. [Riess et al., 2016] [Bernal et al., 2016] [Knox & Millea, 2019]).

In this section, we add SN data to the analysis using a prior of $H_0 = 74.03 \pm 1.42$ [Riess et al., 2019]. Our results are summarized in Fig. 1 and Table 4. When varying $\alpha_{\text{EM}}$, a slight shift towards $\alpha_{\text{EM}}/\alpha_{\text{EM}0} > 1$ is seen both for the Planck 2015+BAO+SN and Planck 2018+BAO+SN data. In addition, the derived value for $H_0$...
of-fit is not severely sacrificed when we add $\alpha_{EM}$ and $m_e$. For the CMB + BAO case, adding $\alpha_{EM}$ gives a slightly worse fit but $m_e$ gives a marginally better fit. When we add SN data, the $\chi^2$ drops

| Parameter | Planck 2018 | Planck 2018 + BAO | Planck 2018 + $\alpha_{EM}$ | Planck 2018 + $m_e$ | Planck 2018 + SN | Planck 2018 + $\alpha_{EM}$ + SN | Planck 2018 + $m_e$ + SN |
|-----------|-------------|------------------|-----------------------------|----------------------|-----------------|---------------------------------|-----------------------------|
| $\Omega_m h^2$ | 0.02244 ± 0.00013 | 0.02240 ± 0.00014 | 0.02255 ± 0.00016 | 0.02255 ± 0.00013 | 0.02244 ± 0.00014 | 0.02277 ± 0.00015 | 0.02277 ± 0.00015 |
| $\Omega_b h^2$ | 0.11895 ± 0.00092 | 0.1199 ± 0.0015 | 0.1208 ± 0.0018 | 0.11791 ± 0.00090 | 0.1204 ± 0.0014 | 0.1229 ± 0.0017 | 0.1229 ± 0.0017 |
| $\Omega_{b0}$ | 1.04100 ± 0.00029 | 1.0436 ± 0.0030 | 1.0464 ± 0.0047 | 1.04116 ± 0.00029 | 1.0475 ± 0.0027 | 1.0543 ± 0.0038 | 1.0543 ± 0.0038 |
| $\sigma_8$ | 0.5071 ± 0.0076 | 0.5553 ± 0.0075 | 0.5049 ± 0.0074 | 0.5002 ± 0.0071 | 0.5051 ± 0.0074 | 0.5033 ± 0.0074 | 0.5033 ± 0.0074 |
| $\ln(10^{10} A_s)$ | 3.048 ± 0.015 | 3.043 ± 0.015 | 3.045 ± 0.014 | 3.052 ± 0.017 | 3.039 ± 0.015 | 3.044 ± 0.014 | 3.044 ± 0.014 |
| $n_s$ | 0.9674 ± 0.0037 | 0.9621 ± 0.0070 | 0.9654 ± 0.0040 | 0.9700 ± 0.0036 | 0.9567 ± 0.0066 | 0.9640 ± 0.0041 | 0.9640 ± 0.0041 |

| $\alpha_{EM}/\alpha_{EM,0}$ | -- | 1.0019 ± 0.0022 | -- | -- | 1.0047 ± 0.0020 | -- | -- |
| $m_e/m_e,0$ | -- | -- | 1.0078 ± 0.0067 | -- | -- | 1.0190 ± 0.0055 | -- | -- |
| $H_0$ | 67.81 ± 0.42 | 68.32 ± 0.71 | 69.1 ± 1.2 | 68.32 ± 0.41 | 69.48 ± 0.65 | 71.24 ± 0.96 | 71.24 ± 0.96 |
| $\Delta \chi^2_{min}$ | -- | 0.21 | -- | 0.39 | -- | 4.71 | -- | 10.92 |

Table 3. Planck 2018 marginalised results for varying $\alpha_{EM}$ and $m_e$ along with BAO and SN datasets. Reference cases for CMB+BAO and CMB+BAO+SN are included. We also show the change in fit, $\Delta \chi^2_{min}$, for the results compared to their reference cases.
for both $\alpha_{\text{EM}}$ and $m_e$. We also find that the CMB-only component of the total $\chi^2$ decreases when adding $m_e$ to CMB+BAO+SN such that $\Delta\chi^2_{\text{CMB}} = -1.17$. This means the goodness-of-fit improves for the CMB+BAO+SN when $m_e$ variations included. A detailed comparison of the $\chi^2$ values is given in Table 4.

The tendency to allow for larger values of $m_e$ and $H_0$ is even more clear in the Planck 2013 data release (Planck Collaboration et al. 2013) when combined with the 2011 SN data (Riess et al. 2011). Though the migration of both $m_e$ and $H_0$ is larger for Planck 2013 (see Fig. 1), the value of $m_e$ is only 2.3$\sigma$ away from ADM and no significant Hubble tension was yet identified back then. We find a similar constraint on $m_e$ as for Planck 2018 when we consider a combination of Planck 2015+BAO+SN data, $m_e/m_{e,0} = 1.0191 \pm 0.0059$ ($\Delta m_e/m_e \approx 3.2\sigma$); however, the movement of $H_0$ remains more restricted, leaving a $\approx 3.4\sigma$ tension with the SN data (cf. Fig. 1). This indicates that for the Planck 2018 data the geometric degeneracy line is opened more strongly when allowing $m_e$ to vary.

In Fig. 6 we show the contours of some of the most affected standard parameters. A full set of parameter contours is shown in Appendix A. The contours shift away from the CMB-only posteriors (blue bands) as BAO (red) and SN (green) data are added. The $H_0 - m_e$ contour is narrower as SN data is added and as described above, weighted more towards the SN only value. We can see similar effects in $\Omega_b h^2$ and $\Omega_c h^2$, which move by $\approx 2.5\sigma$ and $\approx 1.8\sigma$, respectively. All this indicates that a discordant value of $m_e$ can be traded in for an alleviation of the $H_0$ tension while affecting the standard parameters at the level of $\lesssim 2.3\sigma$.

Finally, the analysis with both $m_e$ and $\alpha_{\text{EM}}$ varying can be extended to include SN data as shown in Fig. 7. Here we have redone the analysis from Fig. 4; however the Planck-only contours have been removed for clarity. Though there is a small drift in $\alpha_{\text{EM}}$, the main effect from adding SN constraints is a migration of $m_e$ away from the standard value. This is also expected from Fig. 5 and further supports the perspective that variations of $m_e$ could indeed play a direct role in explaining the Hubble tension.

### 4 Conclusion

We provided updated constraints on the variation of the fundamental constants $\alpha_{\text{EM}}$ and $m_e$, closely following the discussion of HC17 for Planck 2015 data. When omitting SN data, we find no significant difference between the results of the 2015 and the present analysis for variations of $\alpha_{\text{EM}}$ and $m_e$ (see Fig. 1). As expected, the addition of improved polarisation information from Planck 2018 leads to slightly improved errors on $\alpha_{\text{EM}}$ and $m_e$ with shifts between the values from the 2015 and 2018 data combinations remaining below $\approx 1\sigma$ (see Table 1 and 2 for summary of the parameter values).

In addition to the update of the Planck 2015 analyses, we also extended the discussion to combinations including SN data (Sect. 1). SN data pulls both $\alpha_{\text{EM}}$ and $m_e$ above their standard values; however, only for the combination Planck 2018+BAO+SN does the migration exceed the $3\sigma$ threshold (see Fig. 1 and Table 3). Simultaneously, we find the value for $H_0$ to move closer to that obtained from SN data. Improvements in the $\chi^2$-values further

| Planck 2018 + BAO | $\Lambda$CDM | $+ \Delta\alpha_{\text{EM}}$ | $+ \Delta m_e$ |
|-------------------|---------------|----------------|----------------|
| Planck (high-ℓ+low-ℓ) | 2789.36 | 2790.04 | 2789.50 |
| BAO | 8.61 | 8.14 | 8.08 |
| $\Delta\chi^2$ | -- | 0.21 | -0.39 |

| Planck 2018 + BAO + SN | $\Lambda$CDM | $+ \Delta\alpha_{\text{EM}}$ | $+ \Delta m_e$ |
|------------------------|---------------|----------------|----------------|
| Planck (high-ℓ+low-ℓ) | 2791.65 | 2792.65 | 2790.48 |
| BAO | 7.59 | 7.65 | 9.77 |
| SN | 16.25 | 10.48 | 4.31 |
| $\Delta\chi^2$ | -- | -4.71 | -10.92 |

Table 4. Changes in the goodness-of-fit $\chi^2$ when $\alpha_{\text{EM}}$ or $m_e$ is added to the $\Lambda$CDM model. Here the $\Lambda$CDM cases are references to compare the $\Delta\chi^2$ from each of the added fundamental constant variations. All the quoted $\chi^2$ values are the fits from the final marginalised results quoted in Table 3.

![Figure 6](image_url) Marginalised contours from $m_e$ with the standard parameters ($\Omega_c h^2, \Omega_b h^2, H_0$). The other parameters have been omitted as they do not vary with the $m_e$ changes and we have shown this in Fig. A1. The blue bands represent the standard $\Lambda$CDM limits for these parameters. The orange band represents the SN constraint on $H_0$ (Riess et al. 2019).

![Figure 7](image_url) Probability contours between $\alpha_{\text{EM}}$ and $m_e$ for Planck and BAO, with added SN constraints as well.
indicate that variations of $\sigma_8$ could indeed play a role in the low-versus high-redshift Hubble tension. As already alluded to in HC17, the distinct role of $\sigma_8$ in the value of $\sigma_{200}$ opens the geometric degeneracy line to enable SN data to overcome the tight grip of Planck data on $H_0$. When neglecting the rescaling of $\sigma_{8}$ with $m_\text{r}$ this degree of freedom closes. Our analysis thus suggests that a delicate interplay between the low- and high-redshift ionization history could indeed influence our interpretation of the cosmological datasets. A shift of $m_\text{r}$ away from the standard value appears to enable this. More general alternatives could be a modified recombination history and simultaneously altered reionization history. Future works should thus investigate a possible integration of the reionization and recombination processes to more accurately model fundamental constant variations across cosmic time.

Models with explicit time-dependence of $\sigma_{8m}$ and $m_\text{r}$ should furthermore be more carefully studied. As pointed out in Poulin et al. (2019), models of early-dark energy could also play a role in the Hubble tension. Similar physical mechanisms could give rise to varying constants, potentially linking the effects to the same underlying scalar field. Recently, models with positive spatial curvature have too enriched the discussion on the Hubble tension (Di Valentino et al. 2019). Including fundamental constant variations may alleviate the discrepancies in lensing in a similar way to that of a closed Universe. Also, spatial variations of fundamental constants could be present, potentially linking the CMB anomalies seen at large-angular scales (Planck Collaboration et al. 2019). We look forward to exploring these possibilities in the future.

Finally, we stress that there seems to be a marked difference between the Planck 2015 and 2018 data. For Planck 2015, we find similar constraints on $m_\text{r}$, but the shift in the Hubble parameter is more mild and unable to reconcile $H_0$ (see Fig. [1]). This indicates that improvements to the Planck 2018 polarization data opened the aforementioned geometric degeneracy more strongly. This calls for further investigations of systematic effects to clearly identify the origin our findings regarding the Hubble tension.

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APPENDIX A: EXTRA MARGINALISED RESULTS

For transparency, in Fig. [A1] we show the full parameter constraints for $\Lambda$CDM parameters and $m_\text{r}$ when BAO and SN data is added.
Figure A1. Fully marginalised results from Planck + BAO and Planck + BAO + SN and variations of $m_e$ with CMB only as a reference (blue-dashed). This figure includes contributions from $\{\tau, n_s, \ln(10^{10} A_s)\}$ which are effectively decorrelated from $m_e$. The $\Lambda$CDM value of $m_e = 1$ is added as a dashed line.