

External priors for the next generation of CMB experiments.

Alessandro Manzotti,^{1,2,*} Scott Dodelson,^{3,1,2} and Youngsoo Park⁴

¹*Department of Astronomy & Astrophysics, University of Chicago, Chicago IL 60637*

²*Kavli Institute for Cosmological Physics, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*

³*Fermilab Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500*

⁴*Department of Physics, University of Arizona, Tucson, AZ 85721, USA*

(Dated: December 7, 2015)

Planned cosmic microwave background (CMB) experiments can dramatically improve what we know about neutrino physics, inflation, and dark energy. Indeed the low level of noise, together with improved angular resolution, will increase the signal to noise of the CMB polarized signal as well as the reconstructed lensing potential of high redshift large scale structure. Projected constraints on cosmological parameters are extremely tight, but these can be improved even further with information from external experiments. Here, we examine quantitatively the extent to which external priors can lead to improvement in projected constraints from a CMB-Stage 4 (S4) experiment on neutrino and dark energy properties. We find that CMB S4 constraints on neutrino mass could be strongly enhanced by external constraints on the cold dark matter density $\Omega_c h^2$ and the Hubble constant H_0 . If the largest scales ($\ell < 50$) will not be measured, an external prior on the primordial amplitude A_s or the optical depth τ will also be important. Furthermore a CMB constraint on the number of relativistic degrees of freedom, N_{eff} , will benefit from an external prior on the spectral index n_s and the baryon energy density $\Omega_b h^2$. Finally, an external prior on H_0 will help constrain the dark energy equation of state (w).

I. INTRODUCTION

Since their earliest incarnations, Cosmic Microwave Background (CMB) experiments have been crucial in furthering our understanding of the universe. They will maintain their role in the future, thanks to the unprecedented low level of noise and high resolution expected in the planned Stage IV (S4) experiment [1]. The recent past is reassuring. For example, every new generation of satellite experiments improved the level of sensitivity by almost a factor of ten compared to its predecessor, from the first generation instrument COBE to WMAP all the way to the current state of the art represented by Planck [2–6]. These led us from the first detection of anisotropy in the CMB temperature with COBE to a cosmic variance limited measurement of several acoustic peaks with Planck. With the improved sensitivity we have extended our understanding of the universe so that we now have solid evidence for a flat geometry and a well tested model Λ CDM with percent level constraints on its parameters. The same success has characterized ground-based CMB experiments, where, e.g., the first detection of polarization anisotropy by DASI [7] has been followed by a series of precise measurements of the damping tail and maps of the projected gravitational potential by, e.g., SPT [8] and ACT [9]. The planned CMB-S4 experiment will potentially measure the E-mode polarization with cosmic variance limited precision together with an order of magnitude improvement in B-mode measurement and lensing reconstruction. As has happened in the past, this new sensitivity together with the progress in the measurement of other cosmological probes will improve our

understanding of several areas of astrophysics like dark matter, inflation, dark energy, and neutrinos.

The cosmological dependence on neutrinos is two-fold: the number of relativistic species N_{eff} in the early phase of the universe affects the damping tail of the CMB, and sum of the neutrino masses $\sum m_\nu$ affects the late-time growth of cosmic structure. Because relativistic species, like neutrinos, are the main drivers of the cosmic expansion in the early Universe, their number affects the expansion rate $H(z)$. This rate can be powerfully tested using the CMB, by carefully comparing the sound horizon scale, obtained from the CMB peaks positions, and the Silk damping scale (see [1], [10] and references therein). The future experiments, with their high resolution, will probe deep into the damping tale of the CMB power spectrum and will be sensitive to small variations from the canonical, 3-active neutrino prediction of $N_{\text{eff}} = 3.046$. The total mass of neutrinos, on the other hand, has a modest effect on the CMB because, for the range of masses allowed by recent constraints ($\sum m_\nu < 230$ meV from [3]), neutrinos are still relativistic at the last scattering surface. However, massive neutrinos alter the growth of the large scale structure responsible for lensing of the CMB photons. Different neutrino masses consequently lead to different CMB lensing spectra. CMB-S4 will measure small scale temperature and polarization anisotropies with low noise, dramatically improving the lensing reconstruction. This will turn into a precise constraints of the sum of neutrino masses with a possible hint of the hierarchies of the individual masses.

The CMB is sensitive also to the properties of dark energy (see, e.g., [11]). Thanks to the current generation of experiments we know with extraordinary accuracy its energy density. The challenge for the next generation is to reveal the nature of this mysterious component. For ex-

* manzotti.alessandro@gmail.com

ample, a crucial step to identifying the mechanism driving cosmic acceleration will be to investigate any possible deviations in the equation of state, the ratio of pressure and energy density, from the value $w = -1$ predicted by a cosmological constant. Dark energy affects the CMB because it alters the universe's expansion and it consequently changes the distance to the last scattering surface. Furthermore different dark energy models lead to different rates of growth of large scale structure which are tested by CMB lensing. However, dark energy properties are strongly degenerate with other geometrical parameters like H_0 and Ω_k . As with the neutrino sector, dark energy constraints from the CMB will be improved by external experiments.

In the case of both neutrinos and dark energy then, an important lingering question is: What external information can be used to improve projected constraints by breaking degeneracies? Here we study the dependance of projected constraints from CMB on the external priors assumed. For all the parameters of the standard Λ CDM with massive neutrinos ($\Omega_c h^2, \Omega_b h^2, A_s, n_s, \tau, H_0, \sum m_\nu$) together with extensions (N_{eff} and w) to the neutrino and dark energy sectors, we quantify the CMB constraints as a function of external priors. This extends the work of Wu *et al.* [12], which worked with a few fixed external priors, by quantifying the extent to which external information will improve the constraining power of a CMB-S4 experiment.

This paper is organized as follow: in §II we introduce the technique and assumptions we use to derive the effect of external priors on the CMB parameter constraints. In §III we will describe our results and we then conclude with a discussion of them in §IV.

II. ASSUMPTIONS AND METHODS

To measure quantitatively the impact of external priors on the CMB ability to constrain cosmological parameters we use a Fisher matrix formalism. In this section we will quickly review the technique and then present the chosen fiducial cosmological model together with the experimental specifications.

As usual, we define the Fisher matrix elements as the curvature of the likelihood:

$$F_{ij} \equiv - \left\langle \frac{\partial^2 \log \mathcal{L}}{\partial \theta_i \partial \theta_j} \bigg|_{\theta=\theta_0} \right\rangle, \quad (1)$$

where $\theta_{i,j}$ represent the cosmological parameters and θ_0 is the set of fiducial values that, by definition, maximizes the likelihood.

For CMB experiments the Fisher matrix is related to the angular power spectra \mathcal{C}_ℓ by:

$$F_{ij} = \sum_\ell \frac{2\ell+1}{2} f_{\text{sky}} \text{Tr} \left(\mathcal{C}_\ell^{-1}(\theta) \frac{\partial \mathcal{C}_\ell}{\partial \theta_i} \mathcal{C}_\ell^{-1}(\theta) \frac{\partial \mathcal{C}_\ell}{\partial \theta_j} \right) \quad (2)$$

where f_{sky} , the fraction of sky covered, is set to 0.75 throughout. In this work we constrain cosmological parameters with CMB temperature and E-mode polarization together with the reconstructed lensing potential of large scale structure. Therefore, \mathcal{C}_ℓ in Eq. (2) is:

$$\mathcal{C}_\ell \equiv \begin{pmatrix} C_\ell^{TT} + N_\ell^{TT} & C_\ell^{TE} & C_\ell^{T\phi} \\ C_\ell^{TE} & C_\ell^{EE} + N_\ell^{EE} & 0 \\ C_\ell^{T\phi} & 0 & C_\ell^{\phi\phi} + N_\ell^{\phi\phi} \end{pmatrix}. \quad (3)$$

The terms N_ℓ^X represent the instrumental noise power of the specific experiment and will be described at the end of this section. Note that we are neglecting the term $C_\ell^{E\phi}$ since it contains very little information while adding possible numerical issues [10, 12]. Furthermore, as in [12], we use *unlensed* spectra and gaussian covariances in Eq. (2). This means that we neglect eventual imperfect reconstruction of the unlensed spectra (delensing) and the non-gaussian effects described in [13]. However, we expect this approximations to have a small impact on the final results and, for this reason, a more careful modeling is beyond the scope of this work. For example, we checked that using lensed spectra will change the final constraint by less than 10%.

The projected error on the parameter θ_i , marginalized over all the other parameters, σ_i , is then:

$$\sigma_i \equiv \sigma(\theta_i) \geq \sqrt{(\mathbf{F}^{-1})_{ii}}. \quad (4)$$

We can introduce external priors on cosmological parameters. Indeed we simply need to add to the Fisher matrix elements the external priors (before we perform the matrix inversion of Eq. (4)). For example, a 1% prior on the parameter i can be added by:

$$F_{ii} \rightarrow F_{ii} + \frac{1}{(1\% \times \theta_{i,\text{fid}})^2}. \quad (5)$$

We compute the power spectra \mathcal{C}_ℓ in Eq. (2) using CAMB [14, 15] and the derivatives in Eq. (2) using a 5 point finite difference formula: this high order approach allows us to use larger step-sizes around the fiducial parameters to compute derivatives. As a consequence the differences of power spectra corresponding to different values of the parameters are big enough to ensure numerical accuracy. We also test the robustness of this calculation by varying the derivative steps in the range 2 – 7%. The constraints change by at most 10% that should then be considered as a conservative estimate of numerical uncertainties. Our philosophy is to consider as few extensions as possible. Given the current success of the standard models of particle physics and cosmology, one of the primary goals of CMB-S4 will be to find cracks in these models. As such, the key question is: What information is needed to reliably conclude that an additional parameter is required. The natural first baby step is to include massive neutrinos, which (i) are a small extension to the Standard Model and (ii) are known to exist. So our fiducial cosmology is flat $\nu\Lambda$ CDM, with assumed

parameters from Table 2 of the *Planck* best fit [16], i.e. $\Omega_c h^2 = 0.12029$, $\Omega_b h^2 = 0.022068$, $A_s = 2.215 \times 10^{-9}$ at $k_0 = 0.05 \text{ Mpc}^{-1}$, $n_s = 0.9624$, $\tau = 0.0925$, $H_0 = 67.11 \text{ km/s/Mpc}$, supplemented by an choice of $\sum m_\nu \simeq 85 \text{ meV}$ to be consistent with [12]. We then extend the parameter space by introducing N_{eff} and w as free parameters, in each case keeping the other parameter fixed. The fiducial values of these are $N_{\text{eff}} = 3.046$ and a cosmological constant equation of state, $w = -1$. In this same spirit, we keep the curvature fixed to zero, as the level predicted in the vast majority of inflationary models is of order 10^{-5} , much too small to have an impact on the parameters we consider. Similarly, we fix the helium abundance to its canonical value from Big Bang Nucleosynthesis, which depends only on the baryon density.

The instrumental noise power $N_\ell^{T,E}$ and the lensing reconstruction N_ℓ^ϕ in Eq. (2) correspond to the optimistic level for CMB-S4 assumed in [1, 10, 12]. For the temperature and E-mode polarization of the CMB, together with the improved depth and resolution we also assume that large scale foregrounds, like dust, are under control or negligible. This allows us to use all the polarization power spectrum multipoles out to $\ell_{\text{E,max}} = 4500$. We deal with the Poisson noise from point sources in the temperature signal by simply discarding all small scale modes with $\ell > \ell_{\text{T,max}} = 3000$. The remaining source of noise, the instrumental noise, is added to the power spectrum in the usual way:

$$N_\ell^X = s^2 \exp\left(\ell(\ell+1) \frac{\theta_{\text{FWHM}}^2}{8 \log 2}\right), \quad (6)$$

where θ_{FWHM}^2 is the FWHM of the experiment's beam and s represents the instrumental white noise. We use a level of noise $s = 0.58 \mu\text{K-arcmin}$ for $X = T$ and a beam of $\theta_{\text{FWHM}} = 1 \text{ arcmin}$. This corresponds to the $N_{\text{det}} = 10^6$ case of [12]. Note that the quoted noise in temperature and we assume that $s \rightarrow s \times \sqrt{2}$ in the case of polarization $XX' = \{EE, BB\}$. The noise $N_\ell^{\phi\phi}$ associated with the reconstructed ϕ spectrum is modeled assuming an iterative reconstruction technique [17].

We also include information from current Baryon Acoustic Oscillation experiments and projected constraints from low- l Planck polarization. As current BAO data (labeled BAO15), we follow [18] and we take into account 6dFGRS [19], SDSS MGS [20] together with LOW-Z and C-MASS [21]. The noise assumed for Planck corresponds to the ‘‘Planck-pol’’ specifications of [18], where noise levels were approximated by scaling the current sensitivities according to the Planck Blue Book.

III. RESULTS

In this section we present our main results. We will start from $\nu\Lambda\text{CDM}$ and then explore extensions to this model by considering constraints on N_{eff} and then w .

A. Neutrino Masses, $\sum m_\nu$

Small scale structure formation is suppressed if fast-moving neutrinos comprise a significant part of the matter budget. Indeed, below the current free-streaming scale, the matter power spectrum is suppressed in the presence of massive neutrinos by a factor $\Delta P/P \simeq -8f_\nu$, where $f_\nu = \Omega_\nu/\Omega_m$ is the contribution of neutrinos to the total matter density. This effect is probed by CMB lensing and, since the active neutrino number densities are known in the standard model, can be directly transformed into a constraint on the the sum of the neutrino masses $\sum m_\nu$. This is particularly exciting because we now know that neutrinos are massive, with a lower limit $\sum m_\nu > 50 \text{ meV}$ that emerges from oscillation experiments.

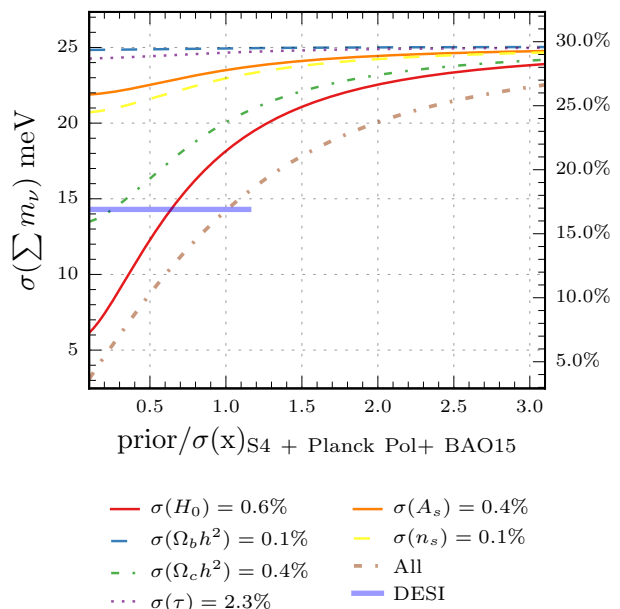


FIG. 1. Constraints on the sum of the neutrino masses as a function of priors on cosmological parameters. Each prior is expressed in units of the error that would be obtained internally from the CMB S4 experiment (+Planck+current BAO); e.g., $\sigma(H_0)_{\text{S4+PlanckPol+BAO15}} = 0.6\%$, so the value of unity on the x-axis corresponds to imposing an external prior on H_0 of 0.6%. The horizontal line correspond to CMB S4 experiment + Planck Pol + DESI. H_0 and $\Omega_c h^2$ are shown to be the most important external priors to improve neutrino mass constraints. We chose a fiducial value $\sum m_\nu = 85 \text{ meV}$ and we impose a Planck-pol prior. The blue horizontal line correspond to the CMB S4+BAO constraint of [12].

Fig. 1 shows the projected errors on $\sum m_\nu$ from CMB-S4 (+Planck+current BAO) as a function of external priors. Without any external priors (far right in figure), upcoming CMB experiments are poised to obtain 1-sigma limits on $\sum m_\nu$ of order 25 meV, corresponding to a 2-sigma detection even in the worst case sce-

nario. Adding in external priors helps this significantly though, as discussed, for example, in [1, 18, 22]. There, the added prior was “DESI BAO”, representing a measurement of distances as a function of redshift from the baryon acoustic oscillation feature probed by DESI. This is represented by the blue band in Fig. 1. In addition to showing the implications of introducing this fixed external constraint, Fig. 1 generalizes the extent to which external information will improve the neutrino mass constraints. For example, the red curve shows the improvement as additional information on the Hubble constant is applied. The projected, marginalized constraint on H_0 from just CMB-S4+Planck+BAO15 is 0.5% (and similarly the values for the other parameters are given in the inset). So imposing *external* information with this value of $\sigma_{H_0}/H_0 = 0.005$ corresponds to 1 on the x -axis. This would improve the neutrino mass constraint to 17 meV. Similarly, introducing an external constraint on the dark matter density equal to its internal constraint of 0.3% (so again 1 on the x -axis) improves the projected neutrino mass constraint to 14 meV. It is not surprising that this is equal to the constraint obtained with DESI because the BAO distances in this model depends most sensitively on $\Omega_c h^2$ and H_0 .

The physical reason underlying this improvement is simple: lensing constrains f_ν , the ratio of the neutrino density to the matter density. In order to extract the neutrino density (and therefore the neutrino mass), we need to know the matter density. A prior on H_0 helps for a related, but subtle reason. The position of the CMB peaks, well constrained by measurement, in a flat universe is a function $\Omega_c h^{2.93}$ [3]. For this reason an external prior on H_0 will improve the internal reconstruction of $\Omega_c h^2$, leading back to tighter neutrino mass constraints. As found in [1, 18, 22], the projected error falls below 20 meV with these priors. The left-hand side of Fig. 1 shows that even tighter external constraints on either H_0 or $\Omega_c h^2$ would significantly improve the neutrino mass constraints.

It may be difficult to get the very low- l modes from the ground with CMB-S4, so in Fig. 2 we limit the modes to $\ell > \ell_{\min} = 50$. Together with the importance of H_0 and $\Omega_c h^2$ previously observed in Fig. 1, in this case external priors on A_s and τ are found to be helpful.

Indeed, as recently pointed out by [18], a degeneracy exists between $\sum m_\nu$ and A_s and, as a consequence, between $\sum m_\nu$ and τ . This can be understood as follows. The CMB lensing reconstruction is noisy at scales larger than the neutrino free streaming scale (see Fig. 5 of [1]). For this reason it is hard to measure the unsuppressed CMB lensing power spectra that is then compared to the small scale suppressed one to constrain the values of f_ν . The unsuppressed amplitude of the lensing spectrum is actually better constrained by the primordial amplitude A_s , which is probed by the primordial CMB. Unfortunately, the CMB spectra are sensitive to $A_s \exp^{-2\tau}$, so a measurement of the optical depth is required to infer A_s and therefore to tighten the constraints on $\sum m_\nu$. If CMB S4 will not be designed to measure scales $\ell < 50$

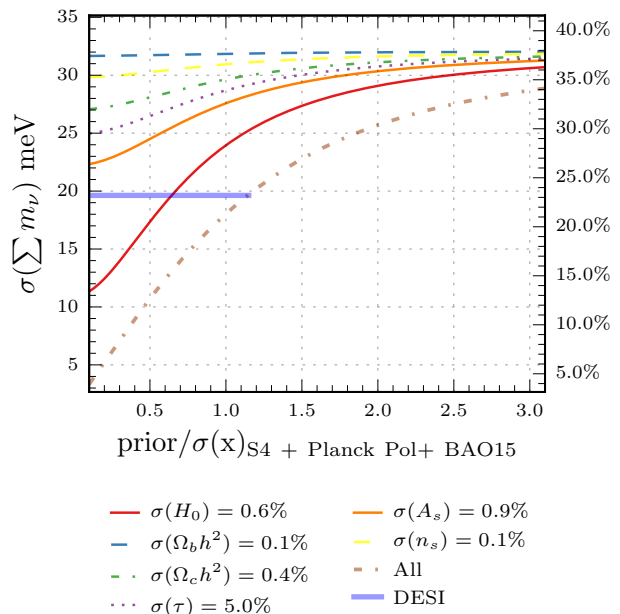


FIG. 2. Same as Fig. 1 but with $\ell_{\min} > 50$. Here A_s and τ priors will also help because of their degeneracy with $\sum m_\nu$.

an external prior on the optical depth from future 21 cm surveys [23] or CMB satellite experiments like PIXIE [24] or balloon like SPIDER [25], will be needed to fully exploit the CMB constraining power.

B. Relativistic Degrees of Freedom, N_{eff}

In the standard model of cosmology, three active neutrinos are thermally produced in the early universe. Were they to decouple well before the epoch of electron-positron annihilation, their energy density after their decoupling would be equal to $3 \times (7/8) \times (4/11)^{4/3} \rho_{\text{cmb}}$, with the first factor capturing the contributions from the 3 active species; the second the difference between fermions and bosons; and the last the relative heating of the photons in the CMB by electron-positron annihilation. However, decoupling is not a discrete event and occurs close to the time of electron-positron annihilation, so the neutrinos share a bit in the heating, with the factor of 3 replaced by $N_{\text{eff}} = 3.046$. The additional fraction depends not only on well-known neutrino scattering rates but also on finite temperature quantum corrections. Upcoming experiments have the potential to measure this tiny deviation of N_{eff} from 3. This will be a precision test of our understanding of the Universe when it was about a second old. It also will constrain Beyond the Standard Model physics. For example, as pointed out in [26], tight constraints on N_{eff} will allow us to rule out new particles with couplings that enabled them to thermalize early on but that decoupled when the temperature was above

~ 100 GeV.

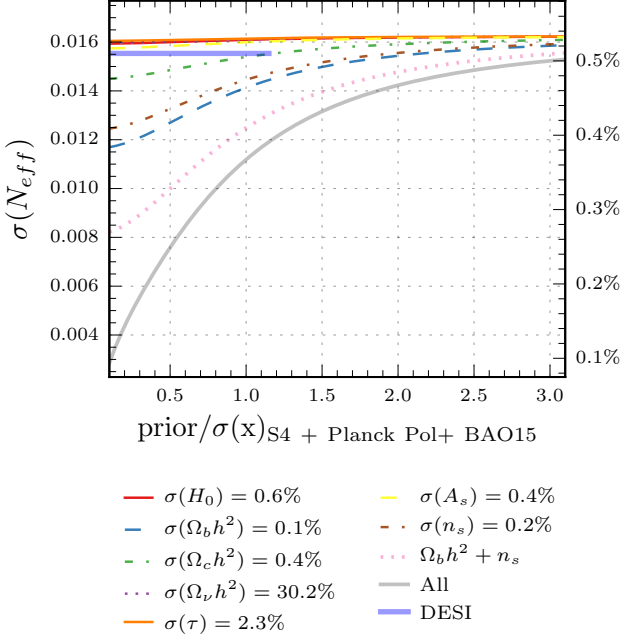


FIG. 3. Projected 1-sigma error on N_{eff} as a function of external priors. The parameters that would be most useful to constrain externally for the purposes of determining N_{eff} are n_s and $\Omega_b h^2$. The bottom-most curve shows the impact of imposing the given prior on *all* the other parameters simultaneously.

Fig. 3 shows projections for how well CMB-S4 will do at measuring N_{eff} as a function of priors on the other seven parameters (the sum of the neutrino masses must be included as a free parameter). With no priors on the other parameters, the projected 1-sigma error is 0.016, close to a 3-sigma detection of the expected deviation from $N_{\text{eff}} = 3$.

The sensitivity to relativistic degrees of freedom comes from the effect of extra species on the damping tail of the CMB anisotropies [10], both in temperature and polarization, so parameters that also strongly affect this part of the spectrum, like the slope n_s and the baryon density $\Omega_b h^2$, are the most relevant to improve N_{eff} constraint. As such, Fig. 3 shows that obtaining external priors on either of these would reduce the errors on N_{eff} to ensure a 3-sigma detection of the partial decoupling prediction. The bottom-most curve shows that if all parameters were constrained externally, then the projected error on N_{eff} would improve significantly.

C. Dark Energy Equation of State, w

The CMB constrains the late-time dark energy equation of state in two ways. The observed CMB spectra

are very sensitive to the distance to the last scattering surface which depends on w . Furthermore CMB lensing probes the growth of structure at late times which is different for different dark energy equations of state.

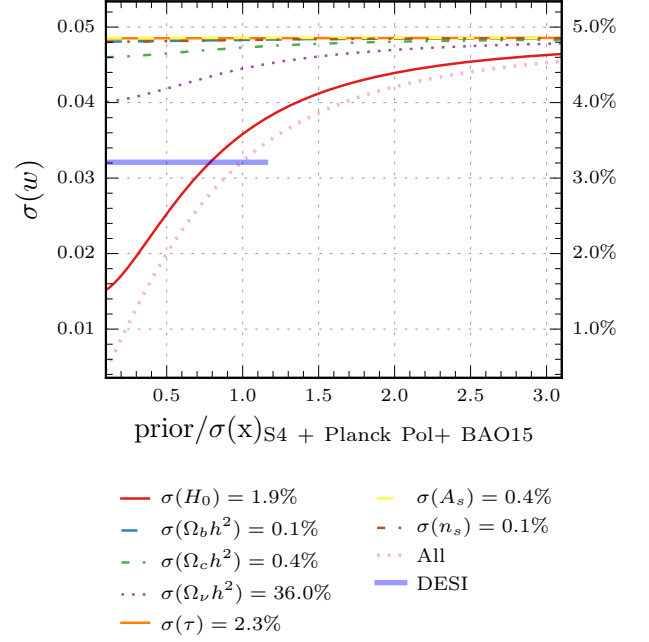


FIG. 4. Constraints on the dark energy equation of state w as a function of external priors on cosmological parameters. An external prior on H_0 will be crucial to improve the constraint.

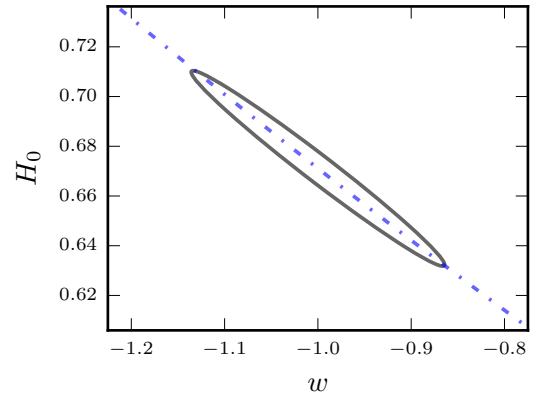


FIG. 5. Two dimensional constraint (CMB S4 + Planck) 1σ ellipse for w, H_0 space. The dashed (red) line correspond to values in the plane corresponding to the same distance to the last scattering surface.

Fig. 4 shows that without any priors, CMB experiments will do better than current constraints, which hover around 10%. However, an external constraint on the Hubble constant would improve the CMB constraints

on w by a factor of 2. This is primarily due to the fact that CMB constrains w through a precise measurement of the comoving distance to the last scattering surface. However that can be kept fixed while varying w by accordingly changing the value of H_0 (and Ω_Λ to keep the universe flat). Indeed in a two dimensional (H_0, w) space the CMB constraint approximately lies on the region of constant large scattering surface distance as shown in Fig. 5. Notice that an external prior on H_0 two times more accurate than CMB S4 can improve the CMB constraint almost by a factor of 2 from a 4% error to a 2% level.

IV. CONCLUSIONS

A CMB-S4 experiment will measure the sum of the neutrino masses, constrain extra relativistic degrees of freedom predicted in many extensions of the Standard Model, and measure the dark energy equation of state at the few percent level. These results can be improved even further by combining them with information from external experiments. Understanding the impact of such external information is crucial in determining the experimental specifications and requirements needed for CMB-S4, and ultimately in maximizing the scientific impact of the future CMB experiments.

Toward that goal, we investigated here how these constraints depend on external priors:

$\sum m_\nu$: To improve the CMB constraint on the sum of neutrino masses by a factor of two, low-redshift measurements will be needed. Indeed an external prior on $\Omega_c h^2$ and H_0 at the level attained by CMB-S4 (sub-percent) can reduce the $1\text{-}\sigma$ uncertainty by almost a factor of two. Furthermore, if the final design of CMB S4 will not include measurements

on large scales ($\ell < 50$), external constraints on the primordial amplitude A_s will also be useful.

N_{eff} : The constraint on the relativistic degrees of freedom will benefit from external priors on parameters that affect the shape of the damping tail, such as the spectral index n_s and the baryon energy density $\Omega_b h^2$.

w : In this case the improvement will mainly come from external priors on H_0 . For example a 1% prior from an external experiment will reduce the error on w by a factor of two.

Much of the improvement that would come on neutrino masses and w from H_0 or $\Omega_c h^2$ priors is anticipated to be provided by distance measurements made by DESI. But, additional H_0 measurements beyond DESI would help, as evidenced by the sharply falling curves in the left-most regions of Fig. 1 and Fig. 5. Indeed, perhaps the most tantalizing finding is that future surveys beyond DESI and LSST that would tighten the constraints on, say, the baryon density and n_s could indirectly lead to constraints in N_{eff} much less than a percent. Given the power of these constraints to probe physics beyond the Standard Model, such surveys seem particularly interesting to pursue.

ACKNOWLEDGMENTS

We thank Wayne Hu for useful discussions. AM wants to thank Zhen Pan who allowed a careful cross-check of our results. This work was partially supported by the Kavli Institute for Cosmological Physics at the University of Chicago through grants NSF PHY-1125897 and an endowment from the Kavli Foundation and its founder Fred Kavli. The work of SD is supported by the U.S. Department of Energy, including grant DE-FG02-95ER40896.

-
- [1] K. N. Abazajian, K. Arnold, J. Austermann, B. A. Benson, C. Bischoff, J. Bock, J. R. Bond, J. Borrill, E. Calabrese, J. E. Carlstrom, C. S. Carvalho, C. L. Chang, H. C. Chiang, S. Church, A. Cooray, T. M. Crawford, K. S. Dawson, S. Das, M. J. Devlin, M. Dobbs, S. Dodelson, O. Dore, J. Dunkley, J. Errard, A. Fraisse, J. Gallicchio, N. W. Halverson, S. Hanany, S. R. Hildebrandt, A. Hincks, R. Hlozek, G. Holder, W. L. Holzapfel, K. Honscheid, W. Hu, J. Hubmayr, K. Irwin, W. C. Jones, M. Kamionkowski, B. Keating, R. Keisler, L. Knox, E. Komatsu, J. Kovac, C.-L. Kuo, C. Lawrence, A. T. Lee, E. Leitch, E. Linder, P. Lubin, J. McMahon, A. Miller, L. Newburgh, M. D. Niemack, H. Nguyen, H. T. Nguyen, L. Page, C. Pryke, C. L. Reichardt, J. E. Ruhl, N. Sehgal, U. Seljak, J. Sievers, E. Silverstein, A. Slosar, K. M. Smith, D. Spergel, S. T. Staggs, A. Stark, R. Stompor, A. G. Vieregg, G. Wang, S. Watson, E. J. Wollack, W. L. K. Wu, K. W. Yoon, and O. Zahn, ArXiv e-prints (2013), arXiv:1309.5383.
- [2] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, and et al., ArXiv e-prints (2015), arXiv:1502.01589.
- [3] Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, and et al., *A&A* **571**, A16 (2014), arXiv:1303.5076.
- [4] D. N. Spergel, L. Verde, H. V. Peiris, E. Komatsu, M. R.olta, C. L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, L. Page, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright, *ApJS* **148**, 175 (2003), astro-ph/0302209.
- [5] S. Hanany, P. Ade, A. Balbi, J. Bock, J. Borrill, A. Boscaleri, P. de Bernardis, P. G. Ferreira, V. V. Hristov, A. H. Jaffe, A. E. Lange, A. T. Lee, P. D. Mauskopf, C. B. Netterfield, S. Oh, E. Pascale, B. Rabbii, P. L. Richards,

- G. F. Smoot, R. Stompor, C. D. Winant, and J. H. P. Wu, *ApJL* **545**, L5 (2000), [astro-ph/0005123](#).
- [6] P. de Bernardis, P. A. R. Ade, J. J. Bock, J. R. Bond, J. Borrill, A. Boscaleri, K. Coble, B. P. Crill, G. De Gasperis, P. C. Farese, P. G. Ferreira, K. Ganga, M. Giacometti, E. Hivon, V. V. Hristov, A. Iacoangeli, A. H. Jaffe, A. E. Lange, L. Martinis, S. Masi, P. V. Mason, P. D. Mauskopf, A. Melchiorri, L. Miglio, T. Montroy, C. B. Netterfield, E. Pascale, F. Piacentini, D. Pogosyan, S. Prunet, S. Rao, G. Romeo, J. E. Ruhl, F. Scaramuzzi, D. Sforza, and N. Vittorio, *Nature (London)* **404**, 955 (2000), [astro-ph/0004404](#).
- [7] N. W. Halverson, E. M. Leitch, C. Pryke, J. Kovac, J. E. Carlstrom, W. L. Holzapfel, M. Dragovan, J. K. Cartwright, B. S. Mason, S. Padin, T. J. Pearson, A. C. S. Readhead, and M. C. Shepherd, *Astrophys. J.* **568**, 38 (2002), [astro-ph/0104489](#).
- [8] R. Keisler, C. L. Reichardt, K. A. Aird, B. A. Benson, L. E. Bleem, J. E. Carlstrom, C. L. Chang, H. M. Cho, T. M. Crawford, A. T. Crites, T. de Haan, M. A. Dobbs, J. Dudley, E. M. George, N. W. Halverson, G. P. Holder, W. L. Holzapfel, S. Hoover, Z. Hou, J. D. Hrubes, M. Joy, L. Knox, A. T. Lee, E. M. Leitch, M. Lueker, D. Luong-Van, J. J. McMahon, J. Mehl, S. S. Meyer, M. Millea, J. J. Mohr, T. E. Montroy, T. Natoli, S. Padin, T. Plagge, C. Pryke, J. E. Ruhl, K. K. Schaffer, L. Shaw, E. Shirokoff, H. G. Spieler, Z. Staniszewski, A. A. Stark, K. Story, A. van Engelen, K. Vanderlinde, J. D. Vieira, R. Williamson, and O. Zahn, *Astrophys. J.* **743**, 28 (2011), [arXiv:1105.3182](#).
- [9] J. Dunkley, R. Hlozek, J. Sievers, V. Acquaviva, P. A. R. Ade, P. Aguirre, M. Amiri, J. W. Appel, L. F. Barrientos, E. S. Battistelli, J. R. Bond, B. Brown, B. Burger, J. Chervenak, S. Das, M. J. Devlin, S. R. Dicker, W. Bertrand Doriese, R. Dünner, T. Essinger-Hileman, R. P. Fisher, J. W. Fowler, A. Hajian, M. Halpern, M. Hasselfield, C. Hernández-Monteagudo, G. C. Hilton, M. Hilton, A. D. Hincks, K. M. Huffenberger, D. H. Hughes, J. P. Hughes, L. Infante, K. D. Irwin, J. B. Juin, M. Kaul, J. Klein, A. Kosowsky, J. M. Lau, M. Limon, Y.-T. Lin, R. H. Lupton, T. A. Marriage, D. Marsden, P. Mauskopf, F. Menanteau, K. Moodley, H. Moseley, C. B. Netterfield, M. D. Niemack, M. R. Nolte, L. A. Page, L. Parker, B. Partridge, B. Reid, N. Sehgal, B. Sherwin, D. N. Spergel, S. T. Staggs, D. S. Swetz, E. R. Switzer, R. Thornton, H. Trac, C. Tucker, R. Warne, E. Wollack, and Y. Zhao, *Astrophys. J.* **739**, 52 (2011), [arXiv:1009.0866](#).
- [10] Z. Hou, R. Keisler, L. Knox, M. Millea, and C. Reichardt, *Phys. Rev. D* **87**, 083008 (2013), [arXiv:1104.2333 \[astro-ph.CO\]](#).
- [11] H. K. Jassal, J. S. Bagla, and T. Padmanabhan, *MNRAS* **405**, 2639 (2010), [astro-ph/0601389](#).
- [12] W. L. K. Wu, J. Errard, C. Dvorkin, C. L. Kuo, A. T. Lee, P. McDonald, A. Slosar, and O. Zahn, *Astrophys. J.* **788**, 138 (2014), [arXiv:1402.4108](#).
- [13] A. Benoit-Lévy, K. M. Smith, and W. Hu, *Phys. Rev. D* **86**, 123008 (2012), [arXiv:1205.0474 \[astro-ph.CO\]](#).
- [14] C. Howlett, A. Lewis, A. Hall, and A. Challinor, *JCAP* **1204**, 027 (2012), [arXiv:1201.3654 \[astro-ph.CO\]](#).
- [15] A. Lewis, A. Challinor, and A. Lasenby, *Astrophys. J.* **538**, 473 (2000), [astro-ph/9911177](#).
- [16] Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, and et al., *A&A* **571**, A16 (2014), [arXiv:1303.5076](#).
- [17] U. Seljak and C. M. Hirata, *Phys. Rev. D* **69**, 043005 (2004), [astro-ph/0310163](#).
- [18] R. Allison, P. Caucal, E. Calabrese, J. Dunkley, and T. Louis, *ArXiv e-prints* (2015), [arXiv:1509.07471](#).
- [19] F. Beutler, C. Blake, M. Colless, D. H. Jones, L. Staveley-Smith, L. Campbell, Q. Parker, W. Saunders, and F. Watson, *MNRAS* **416**, 3017 (2011), [arXiv:1106.3366](#).
- [20] A. J. Ross, L. Samushia, C. Howlett, W. J. Percival, A. Burden, and M. Manera, *MNRAS* **449**, 835 (2015), [arXiv:1409.3242](#).
- [21] L. Anderson, É. Aubourg, S. Bailey, F. Beutler, V. Bhardwaj, M. Blanton, A. S. Bolton, J. Brinkmann, J. R. Brownstein, A. Burden, C.-H. Chuang, A. J. Cuesta, K. S. Dawson, D. J. Eisenstein, S. Escoffier, J. E. Gunn, H. Guo, S. Ho, K. Honscheid, C. Howlett, D. Kirkby, R. H. Lupton, M. Manera, C. Maraston, C. K. McBride, O. Mena, F. Montesano, R. C. Nichol, S. E. Nuza, M. D. Olmstead, N. Padmanabhan, N. Palanque-Delabrouille, J. Parejko, W. J. Percival, P. Petitjean, F. Prada, A. M. Price-Whelan, B. Reid, N. A. Roe, A. J. Ross, N. P. Ross, C. G. Sabiu, S. Saito, L. Samushia, A. G. Sánchez, D. J. Schlegel, D. P. Schneider, C. G. Scoccola, H.-J. Seo, R. A. Skibba, M. A. Strauss, M. E. C. Swanson, D. Thomas, J. L. Tinker, R. Tojeiro, M. V. Magaña, L. Verde, D. A. Wake, B. A. Weaver, D. H. Weinberg, M. White, X. Xu, C. Yèche, I. Zehavi, and G.-B. Zhao, *MNRAS* **441**, 24 (2014), [arXiv:1312.4877](#).
- [22] Z. Pan and L. Knox, *ArXiv e-prints* (2015), [arXiv:1506.07493](#).
- [23] A. Liu, J. R. Pritchard, R. Allison, A. R. Parsons, U. Seljak, and B. D. Sherwin, *ArXiv e-prints* (2015), [arXiv:1509.08463](#).
- [24] A. Kogut, D. J. Fixsen, D. T. Chuss, J. Dotson, E. Dwek, M. Halpern, G. F. Hinshaw, S. M. Meyer, S. H. Moseley, M. D. Seiffert, D. N. Spergel, and E. J. Wollack, *JCAP* **7**, 025 (2011), [arXiv:1105.2044](#).
- [25] J. P. Filippini, P. A. R. Ade, M. Amiri, S. J. Benton, R. Bihary, J. J. Bock, J. R. Bond, J. A. Bonetti, S. A. Bryan, B. Burger, H. C. Chiang, C. R. Contaldi, B. P. Crill, O. Doré, M. Farhang, L. M. Fissel, N. N. Gandilo, S. R. Golwala, J. E. Gudmundsson, M. Halpern, M. Hasselfield, G. Hilton, W. Holmes, V. V. Hristov, K. D. Irwin, W. C. Jones, C. L. Kuo, C. J. MacTavish, P. V. Mason, T. E. Montroy, T. A. Morford, C. B. Netterfield, D. T. O’Dea, A. S. Rahlin, C. D. Reintsema, J. E. Ruhl, M. C. Runyan, M. A. Schenker, J. A. Shariff, J. D. Soler, A. Trangsrud, C. Tucker, R. S. Tucker, and A. D. Turner, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7741 (2010) p. 1, [arXiv:1106.2158 \[astro-ph.CO\]](#).
- [26] D. Baumann, D. Green, J. Meyers, and B. Wallisch, *ArXiv e-prints* (2015), [arXiv:1508.06342](#).