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Letter

A CMB search for the neutrino mass mechanism and its relation to the Hubble tension

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Abstract The majoron, a pseudo-Goldstone boson arising from the spontaneous breaking of global lepton number, is a generic feature of many models intended to explain the origin of the small neutrino masses. In this work, we investigate potential imprints in the cosmic microwave background (CMB) arising from massive majorons, should they thermalize with neutrinos after Big Bang Nucleosynthesis via inverse neutrino decays. We show that `Planck2018` measurements of the CMB are currently sensitive to neutrino-majoron couplings as small as $\lambda \sim 10^{-13}$, which if interpreted in the context of the type-I seesaw mechanism correspond to a lepton number symmetry breaking scale $v_L \sim \mathcal{O}(100)$ GeV. Additionally, we identify parameter space for which the majoron-neutrino interactions, collectively with an extra contribution to the effective number of relativistic species $N_{\rm eff}$, can ameliorate the outstanding H_0 tension.

1 Introduction

Despite unambiguous evidence that at least two of the known neutrinos have a non-zero mass, the Standard Model (SM) is still lacking of an explanation of their origin. Perhaps more concerning, however, is the question of why neutrino masses are so much smaller than those of charged leptons. While many models have been proposed over the years to explain both the origin and smallness of the neutrino masses (see *e.g.* [1–6]), perhaps the most compelling class of models are those which invoke the so-called seesaw mechanism [7–11]. In such scenarios, the SM is augmented by heavy right-handed neutrinos carrying a Majorana mass term m_N, which

naturally give rise to light neutrino masses m_ν of the order $\sim y_N^2 \, v_H^2/m_N$, where $v_H \simeq 246$ GeV is the vacuum expectation value of the SM Higgs, and y_N is the Dirac Yukawa coupling of the right-handed neutrinos. Generating the Majorana mass term necessary to implement the seesaw mechanism is often accomplished by introducing a new scalar that spontaneously breaks lepton number. Assuming that lepton number is a global symmetry, as in the SM, the spontaneous symmetry breaking (SSB) triggered by the scalar leads to the prediction of a pseudo-Goldstone boson, the so-called majoron [12] (see also [13–15]).

The majoron is notoriously difficult to probe since it interacts very weakly with all SM particles, particularly with charged fermions $\lambda_{\phi e} \sim 10^{-20}$ [12]. However, measurements of the Cosmic Microwave Background (CMB) have reached a level of precision where small modifications to the neutrino sector may be discernible [16–34]. The effect of including majoron-neutrino interactions in the early Universe are twofold [17]: (i) they lead to a non-standard expansion history after Big Bang Nucleosynthesis (BBN) and prior to recombination (generically amounting to $\Delta N_{\rm eff} \sim \mathcal{O}(0.1)$), and (ii) they act to suppress the neutrino anisotropic stress energy tensor, and hence reduce neutrino free-streaming [16]. The idea of identifying features in the CMB arising from the majoron, and thus providing an indirect probe of the neutrino mass mechanism, was proposed at the start of the century [17]. However, until now, no rigorous cosmological implementation of this idea has been performed,[1] nor has there been an analysis using real data.

Using `Planck2018` data [35,36], we analyze a well-motivated region of parameter space in which majorons

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[1] References [20–22] explored the possibility that some component of radiation contained strong self-interactions; this was accomplished by artificially setting to zero the multiples $\ell \geq 2$ in the Boltzmann hierarchy for the interacting radiation. This approach, however, cannot be applied (or mapped) into the scenario of [17], since neutrino-majoron interactions rates are strongly time-dependent and not infinite in strength.

thermalize with neutrinos after BBN via inverse neutrino decay. We show that neutrino-majoron couplings as small as 10^{-13} can be robustly excluded with existing CMB data; future experiments, such as the Simons Observatory [37] and CMB-S4 [38], which are aiming to probe the effective number of relativistic species $N_{\rm eff}$ at the sub-percent level, could have sensitivity to couplings as small as 10^{-14}. If interpreted in the context of the type-I seesaw model, these couplings point toward a lepton number symmetry breaking scale of $\mathcal{O}(100)$ GeV and $\mathcal{O}(1)$ TeV, respectively. Thus, quite remarkably, the CMB is providing an indirect probe of the neutrino mass mechanism at collider energy scales (albeit unaccessible to colliders due to their small couplings), but using feeble interactions with neutrinos in the early Universe.

While the ΛCDM model has been incredibly successful at describing both high- and low-redshift cosmological observations, a concerning tension has recently emerged between the value of the Hubble constant H_0 inferred using early Universe observations (with data either from the CMB [35], or by combining measurements from BBN with baryonic acoustic oscillations, *i.e.* BAOs [39–41]), and various local late Universe measurements performed using observations of type-Ia supernovae (see *e.g.* [42–47]) and strong lensing [48–51] (see *e.g.* [52] for an overview of the various measurements). The most prolific of these discrepancies is between the value inferred by Planck, $H_0 = 67.4 \pm 0.5$ km/s/Mpc [35], and that observed by SH0ES collaboration, which relies on cepheids to calibrate the distance to type-Ia SN, who find a value of $H_0 = 74.0 \pm 1.4$ km/s/Mpc [43]. Depending both on the choice of distance calibration and how one chooses to combine datasets, the outstanding tension is determined to be at the level of $\sim 4 - 6\,\sigma$ [52,53]. While it is of course possible that this tension is a consequence of unaccounted for systematics in either or both measurements, throughout this work we will take this discrepancy at face value and assume alternatively that this is an indication of new physics beyond the ΛCDM paradigm.

Various groups have attempted to resolve this issue by including additional contributions to $N_{\rm eff}$ [54–58], strong neutrino self-interactions [30,31], hidden neutrino interactions [59–61], exotic dark energy models [62–75], dark sector interactions [76–79], and modified theories of gravity [80–82]. Most of these solutions are either incapable of resolving the tension fully [83–85], are experimentally constrained [86], are highly fine-tuned, or lack theoretical motivation. Perhaps the most simple, and thus theoretically appealing, solution which can ameliorate the H_0 tension to the level of $\sim 3\sigma$ is simply to postulate the existence of non-interacting dark radiation producing a shift in the radiation energy density relative to the value predicted in the Standard Model of $\Delta N_{\rm eff} \sim 0.25$. A more appealing, albeit far more problematic, solution was introduced in [30], where it was shown that strongly interacting 2-to-2 neutrino scatterings together with

a contribution to $\Delta N_{\rm eff} \sim 1$ was able to fully resolve the tension; unfortunately, this solution requires neutrino couplings that are not phenomenologically viable [86], a value of $\Delta N_{\rm eff}$ excluded by BBN [87], and is only successful at reducing the tension if CMB polarization data is neglected. Given that the majoron naturally contributes to $\Delta N_{\rm eff}$ at the level of ~ 0.11 via late-time thermalization and decay, and damps neutrino free-streaming in a manner similar to that of the strongly interacting neutrino solution, it is natural to ask whether 2-to-1 neutrino-majoron interactions are capable of further reducing the H_0 tension, beyond what is simply accomplished with ΛCDM + $\Delta N_{\rm eff}$. Indeed we show that including majoron-neutrino interactions broadens the posterior such that the H_0 tension can be further reduced, albeit only to the level of $2.5\,\sigma$, a level that is comparable with other viable solutions, such as early dark energy (see *e.g.* [70]).

2 Majoron interactions

We parametrize the majoron-neutrino interaction as:

$$\mathcal{L} = i\,\frac{\lambda}{2}\,\phi\,\bar{\nu}\,\gamma_5\,\nu, \tag{1}$$

where ν corresponds to a light neutrino mass eigenstate. The coupling λ, taken here to be universal, is typically intimately related to the mass of the active neutrinos m_ν and the scale at which lepton number is spontaneously broken, v_L. For example, in the type-I seesaw mechanism, λ can be expressed as

$$\lambda = 2\,U^2\,\frac{m_N}{v_L} \simeq 2\,\frac{m_\nu}{v_L}, \tag{2}$$

where U is the mixing between sterile and active neutrinos, and the last line follows from a condition in the type-I seesaw that $U^2 \sim m_\nu/m_N$ [6]. Interestingly, for values of $v_L \sim v_H$ and neutrino masses consistent with current constraints, the value of λ within this model can *e.g.* naturally be of the order of $\lesssim 10^{-12}$, which happens to be around the region where inverse neutrino decays ($\bar{\nu}\nu \rightarrow \phi$) can thermalize light majorons after BBN, but prior to recombination. In what follows we will treat λ as a free parameter to remain as model-independent as possible, and when appropriate, relate v_L to λ by considering the atmospheric mass splitting $m_\nu \sim \sqrt{|\Delta m_{\rm atm}^2|} \simeq 0.05\,{\rm eV}$ [88]. Namely, $v_L \simeq 1\,{\rm TeV}\,(10^{-13}/\lambda)$.

3 The majoron mass

Quantum gravity is expected to break all global symmetries [92,93], and hence the majoron should acquire a small but
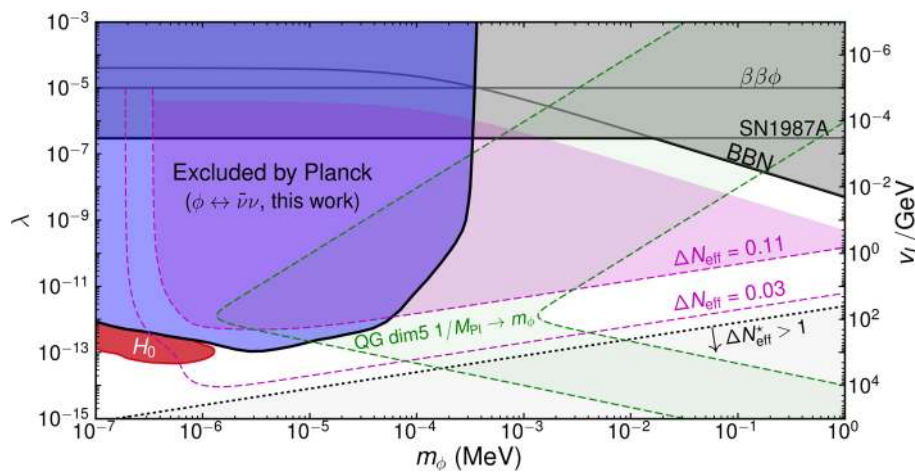
Fig. 1 Majoron parameter space. The left and right vertical axes correspond to the majoron-neutrino coupling and the scale at which lepton number is spontaneously broken in the type-I seesaw model respectively. Current constraints from KamLAND-Zen [89], BBN (see text), and SN1987A [90,91] are shown in grey. The pink region demarcates parameter space for which the majoron fully thermalizes after neutrino decoupling, leading to $\Delta N_{\text{eff}} = 0.11$. The green band highlights the region of parameter space in which the majoron mass could arise from dim-5 Planck suppressed operators (3). Shown in blue is the parameter space excluded in this work using `Planck2018` data at 95% CL. The parameter space below the black dotted line is excluded if there was a small but primordial population of thermal majorons. The region labeled 'H_0' is the preferred 1σ contour for resolving the Hubble tension

non-zero mass. Naively, one might expect the majoron mass to arise from dimension-five (dim-5) Planck scale suppressed operators [94,95]. Should these dim-5 operators involve only the Higgs and the scalar responsible for the SSB of lepton number, the majoron mass is expected to be

$$m_\phi^2 \sim \frac{\beta}{0.1} \frac{v_H}{v_L} \left[1 + 35 \left(\frac{v_L}{v_H} \right)^4 \right] \text{keV}^2 \,, \qquad (3)$$

where β is the coupling constant of a given operator at the Planck scale – which, for concreteness, we have assumed to be the same for all relevant dim-5 operators [95]. Of course, the actual details of the breaking of global symmetries by gravity depend upon the unknown quantum nature of the gravitational theory at the Planck scale [96]; thus we treat m_ϕ as a free parameter in this work, centered approximately around the keV scale, but allowed to vary from 0.1 eV to 1 MeV.

Figure 1 contains a depiction of the majoron parameter space relevant for this work. In addition to highlighting parameter space currently excluded by SN1987A [90,91], BBN (see Supplementary Material, and *e.g.* [97]), and KamLAND-Zen [89], we identify masses and couplings for which the majoron is consistent with arising from dim-5 Planck scale suppressed operators.[2] We defer discussion of the remainder of this plot to later sections.

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[2] This band is constructed by varying β in Eq. (3) between 10^{-6} and 1, where the lower/upper limit has been chosen to be reflect the electron/top Yukawa coupling.

4 Model extensions

Looking forward, it may be interesting to consider the possibility that one of the active neutrinos is exactly massless, as this would decouple the lightest neutrino form the majoron, changing the cosmological evolution of the system. One could also conceive of the possibility of a multi-majoron system resulting from the SSB of a more complex flavor symmetry group in the neutrino sector [17]. In such a scenario, one could produce a more complicated thermalization history which produces step-like features in the evolution of the energy density, and damps the perturbations in a non-trivial manner. While these models are beyond the scope of the current work, they provide a clear extension of the ideas and prospects studied here.

5 Early universe cosmology

The collision terms governing the evolution of the neutrino and majoron phase space distributions are determined by the decay rate of the majoron into two neutrinos $\phi \to \bar\nu\nu$, given by

$$\Gamma_\phi = \frac{\lambda^2}{16\pi} m_\phi \sqrt{1 - \frac{4m_\nu^2}{m_\phi^2}} \simeq \frac{\lambda^2}{16\pi} m_\phi, \qquad (4)$$

where in the last step we have considered $m_\nu \ll m_\phi$. In order to model the time-dependent evolution of the number density and energy density of the system, we follow [98,99] in

assuming that all relevant species are characterized by a temperature T_i and chemical potential μ_i, and solve for their time evolution accounting for all relevant interactions[3] (see Supplementary Material for details). If the majoron is sufficiently heavy and interactions sufficiently strong, the majorons may begin to thermalize prior to or during BBN, leading to an enhanced expansion history of the Universe that would alter the formation of the light elements. For small couplings and masses ($\lambda \lesssim 10^{-5}$ and $\lambda \lesssim 10^{-10}$ MeV$/m_\phi$), majorons thermalize with neutrinos after BBN, and when the majorons become non-relativistic at $T_\nu \sim m_\phi/3$, they decay out of equilibrium to neutrinos leading to a small enhancement in N_{eff}, which asymptotes to $\Delta N_{\text{eff}} = 0.11$. We identify in Fig. 1 a shaded pink region for which full thermalization is achieved after BBN. For yet smaller couplings, partial thermalization can be achieved; the dashed pink line in Fig. 1 identifies majorons that never thermalize, but augment N_{eff} to a level that may be observable with CMB-S4 experiments [100].

We model the phase space perturbations by considering the coupled neutrino-majoron fluid, and approximate the entire system as being massless.[4] Despite the fact that the temperature of the Universe eventually becomes similar to the majoron mass, the majoron contribution to the energy density of the neutrino-majoron system is never larger than 10%. We have explicitly verified that the equation of state $\omega = (p_\phi + p_\nu)/(\rho_\phi + \rho_\nu)$ and the speed of sound $c_s^2 = \delta(p_\phi + p_\nu)/\delta(\rho_\phi + \rho_\nu)$ deviate by less than 3% with respect to that of an ultra-relativistic fluid, *i.e.* $\omega = c_s^2 = 1/3$ (see Supplementary Material). Additionally, we adopt the relaxation time approximation for the collision term [105], which has been shown to accurately reproduce the full solution in similar scenarios [26,27]. The above simplifications allow us to express the density contrast δ, the fluid velocity θ, the shear σ, and the higher anisotropic moments in the synchronous gauge as [105,106]:

$$\dot{\delta}_{\nu\phi} = -\frac{4}{3}\theta_{\nu\phi} - \frac{2}{3}\dot{h}, \tag{5a}$$

$$\dot{\theta}_{\nu\phi} = k^2 \left(\frac{1}{4}\delta_{\nu\phi} - \sigma_{\nu\phi}\right), \tag{5b}$$

$$\dot{F}_{\nu\phi 2} = 2\dot{\sigma}_{\nu\phi} = \frac{8}{15}\theta_{\nu\phi} - \frac{3}{5}k F_{\nu\phi 3}$$
$$+ \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta} - 2 a \Gamma \sigma_{\nu\phi}, \tag{5c}$$

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[3] Reference [98] explicitly demonstrates that this method accurately reproduces a full numerical solution to the Liouville equation for the neutrino and majoron distribution functions within the relevant parameter space considered in this study.

[4] The error introduced by neglecting neutrino masses is the Boltzmann hierarchy is expected to be entirely negligible given current constraints on $\sum m_\nu < 0.12$ eV [35], see also [101–104].

$$\dot{F}_{\nu\phi\ell} = \frac{k}{2\ell+1}\left[\ell F_{\nu\phi(\ell-1)} - (\ell+1)F_{\nu\phi(\ell+1)}\right]$$
$$- a\,\Gamma\,F_{\nu\phi\ell} \quad \text{for} \quad \ell \geq 3. \tag{5d}$$

Here, h and η account for the metric perturbations, k is a given Fourier mode, $F_{\nu\phi\ell}$ represents the ℓth multipole, a the scale factor, and Γ is the interaction rate accounting for inverse neutrino decays and majoron decays, given by

$$\Gamma = \frac{\Gamma_\phi}{2}\frac{m_\phi^2}{T_\nu^2} e^{\frac{\mu_\nu}{T_\nu}} K_1\left(\frac{m_\phi}{T_\nu}\right), \tag{6}$$

where K_1 is the modified Bessel function of the first kind. For convenience one can approximate $e^{\frac{\mu_\nu}{T_\nu}} \simeq 1$, and $T_\gamma/T_\nu \simeq 1.4$ – we have verified that this introduces a negligible error in the final result. In Eq. (5) all derivatives are understood to be with respect to conformal time.

6 Analysis

In order to efficiently scan the parameter space of interest, we define an effective interaction Γ_{eff} in terms of the majoron mass and coupling as

$$\Gamma_{\text{eff}} = \left(\frac{\lambda}{4\times 10^{-12}}\right)^2 \left(\frac{1\,\text{keV}}{m_\phi}\right). \tag{7}$$

This effective interaction is defined such that for $\Gamma_{\text{eff}} \gtrsim 1$ majorons thermalize in the early Universe. We perform runs with two distinct sets of priors: the first is used to place constraints on majoron models producing strong modifications to the neutrino perturbations, and the second is used to identify parameter space for which the H_0 tension can be ameliorated. For both sets of runs, we adopt log-flat priors in λ or Γ_{eff} and m_ϕ spanning

$$\log_{10}(\lambda) = [-15, -6], \tag{8a}$$
$$\log_{10}(m_\phi/\text{eV}) = [-2, 3], \tag{8b}$$

and

$$\log_{10}(\Gamma_{\text{eff}}) = [-4, 4], \tag{9a}$$
$$\log_{10}(m_\phi/\text{eV}) = [-2, 2], \tag{9b}$$

respectively. In addition to these two parameters, we also allow for the possibility of extra relativistic and non-interacting degrees of freedom. We allow ΔN_{eff} to vary linearly between $-2 \leq \Delta N_{\text{eff}} \leq 4$, and treat this additional radiation as free streaming. This additional contribution to N_{eff} should not be considered *ad hoc*, but rather a natural expectation of majoron models. For example, should the

Table 1 Mean (best-fit) values with $\pm 1\sigma$ errors of the cosmological parameters reconstructed from our combined analysis of Planck2018+BAO+SH$_0$ES data in each scenario. For comparison, the best-fit χ^2 we find for ΛCDM using Planck2018+BAO data only with $(R-1)_{min} = 0.007$ is: $\chi^2_{high-\ell} = 2340.25$, $\chi^2_{lowl} = 22.54$, $\chi^2_{lowE} = 395.74$, $\chi^2_{lensing} = 8.92$, $\chi^2_{BAO} = 3.57$, $\chi^2_{CMB} = 2767.45$

Parameter	ΛCDM	ΛCDM + ΔN_{eff}	Majoron + ΔN_{eff}
ΔN_{eff}	–	0.43 (0.358) $\pm$ 0.18	0.52 (0.545) $\pm$ 0.19
m_ϕ/eV	–	–	(0.33)
Γ_{eff}	–	–	(8.1)
$100\,\Omega_b h^2$	2.252 (2.2563) $\pm$ 0.016	2.270 (2.2676) $\pm$ 0.017	2.280 (2.2765) $\pm$ 0.02
$\Omega_{cdm}h^2$	0.1176 (0.11769) $\pm$ 0.0012	0.125 (0.1243) $\pm$ 0.003	0.127 (0.1279) $\pm$ 0.004
$100\,\theta_s$	1.0421 (1.04223) $\pm$ 0.0003	1.0411 (1.04125) $\pm$ 0.0005	1.0410 (1.04102) $\pm$ 0.0005
$\ln(10^{10}A_s)$	3.09 (3.1102) $\pm$ 0.03	3.10 (3.072) $\pm$ 0.03	3.11 (3.116) $\pm$ 0.03
n_s	0.971 (0.9690) $\pm$ 0.004	0.981 (0.9780) $\pm$ 0.006	0.990 (0.99354) $\pm$ 0.010
τ_{reio}	0.051 (0.0500) $\pm$ 0.008	0.052 (0.0537) $\pm$ 0.008	0.052 (0.0576) $\pm$ 0.008
H_0	68.98 (69.04) $\pm$ 0.57	71.27 (70.60) $\pm$ 1.1	71.92 (71.53) $\pm$ 1.2
$(R-1)_{min}$	0.009	0.009	0.03
χ^2_{min} high-ℓ	2341.56	2345.39	2338.84
χ^2_{min} lowl	22.45	21.56	20.81
χ^2_{min} lowE	395.72	395.89	396.40
χ^2_{min} lensing	9.91	9.21	10.69
χ^2_{min} BAO	4.74	4.5	4.69
χ^2_{min} SH$_0$ES	12.34	5.82	3.10
χ^2_{min} CMB	2769.6	2772.1	2766.7
χ^2_{min} TOT	2786.7	2782.4	2774.5
$\chi^2_{min} - \chi^2_{min}\vert^{\Lambda CDM}$	0	−4.3	−12.2

reheating temperature be above the mass of right handed neutrinos, a thermal population of majorons produced in the early Universe may come to dominate the energy density of the Universe, producing nearly arbitrarily large contributions to ΔN_{eff}. Such an effect becomes increasingly important for feeble interactions, such that an effective lower bound can be placed on the the neutrino-majoron interaction – needless to say, however, this bound is inherently dependent on pre-BBN cosmology. We include in Fig. 1 a line, labeled ΔN^*_{eff}, that identifies parameter space for which the contribution to ΔN_{eff} from a primordial population of majorons would be excluded by `Planck` and measurements of large scale structure. We include a more comprehensive discussion of this effect in the Supplementary Material.

7 Results and conclusions

After implementing the above modifications to both the energy density and neutrino-majoron perturbations in `CLASS` [107,108], we perform an MCMC with `Montepython` [109,110] using the `Planck-2018` TTTEEE+lowlTT+lowE+lensing likelihood [36], including data on BAOs from the 6DF galaxy survey [111], the MGS galaxy sample of

SDSS [112], and from the CMASS and LOWZ galaxy samples of BOSS DR12 [113], both including and excluding a Gaussian contribution to the likelihood on H_0 from SH$_0$ES [43], taken to have a mean value and standard deviation of 74.0 and 1.4 km/s/Mpc. All MCMCs have been run until the largest Gelman-Rubin coefficient was $R-1 < 0.03$ or better. In Table 1 we outline all relevant cosmological parameters for the analyses of Planck 2018 + BAO + SH$_0$ES data.

In Fig. 1 we show the 95% exclusion contours derived in this work, and the 1σ contour for parameter space preferred from the fit including the SH$_0$ES likelihood. We derive the 95% CL exclusion contours using only `Planck` data in order to remain conservative, and note that including *e.g.* BAO data leads to a minor strengthening of this contour. Interestingly, the results obtained here illustrate that `Planck` has already begun to significantly probe well-motivated regions of parameter space in which the majoron mass arises from dim-5 Planck scale suppressed operators. If interpreted in terms of the type-I seesaw model, current CMB observations are now probing lepton symmetry breaking scales $\mathcal{O}(100)$ GeV, with future CMB experiments potentially reaching the level of ~ 10 TeV. Before continuing, we would like to emphasize that the constraints derived in this work are both stringent and robust over wide regions of parameter space.
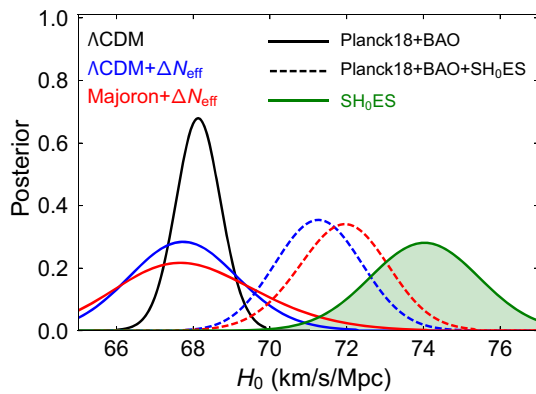
Fig. 2 H_0 posteriors for ΛCDM (black), ΛCDM + $\Delta N_{\rm eff}$ (blue), and majoron + $\Delta N_{\rm eff}$ (red), using `Planck2018` + BAO (solid) and including a gaussian likelihood for SH$_0$ES (dashed). SH$_0$ES posterior shown for comparison in green. See Table 1 for best-fit values and 1σ uncertainties. The red solid line roughly corresponds to $H_0 = 68.0 \pm 1.9$ km/s/Mpc and hence is in 2.5σ tension with the SH$_0$ES measurement

For example, a majoron of $m_\phi = 1\,{\rm eV}$ and $\lambda = 10^{-11}$ is excluded by more than 5σ.

In Fig. 2 we show the posterior distributions for ΛCDM, ΛCDM with a floating value of $\Delta N_{\rm eff}$, and the majoron + $\Delta N_{\rm eff}$, each including and excluding the SH$_0$ES likelihood. The SH$_0$ES posterior is shown for comparison. Including the majoron broadens the posterior and induces a minimal shift of the central value to large H_0, an effect which is more visible when the SH$_0$ES likelihood is included. While the difference induced by including the majoron is not enormous, the H_0 tension can be reduced from $4.4\,\sigma$ to $2.5\,\sigma$ when neutrino-majoron interactions, and an additional contribution to dark radiation, are included.

By performing a MCMC including the SH$_0$ES likelihood, we find that a scenario with $\Delta N_{\rm eff} = 0.52 \pm 0.19$, $0.1\,{\rm eV} < m_\phi < 1\,{\rm eV}$, and coupling strengths $\lambda \sim (10^{-14} - 10^{-13})\,({\rm eV}/m_\phi)$ – as highlighted in red in Fig. 1 – would render a posterior for H_0 of 71.9 ± 1.2 km/s/Mpc and an overall improvement of $\Delta\chi^2 \simeq -12.2$ with respect to ΛCDM. We remind the reader here that, because of the residual 2.5σ tension, it may not be entirely meaningful to combine the partially discrepant datasets, and thus care should be given in the interpretation of this region. Notice that the improvement in the χ^2 does not *exclusively* arise from the shift in H_0; this can be seen from the fact that the contribution of the CMB likelihood in the Majoron+$\Delta N_{\rm eff}$ is less than that of ΛCDM. Interestingly, this region of parameter space corresponds to lepton number symmetry breaking scales in the type-I seesaw near the electroweak scale. Furthermore, it is worth emphasizing that unlike the strongly interacting neutrino solution proposed in [30] (defined by a 2-to-2 neutrino contact interaction), the solution proposed here is robust to the inclusion of polarization data, is phenomenologically viable, and is theoretically motivated.

An important comment on the consistency of this type of solution is necessary. If the contribution to $N_{\rm eff}$ is of primordial origin, then successful BBN excludes values of $\Delta N_{\rm eff} \gtrsim 0.4$ at $T \sim$ MeV [87,114,115]. In addition, including a floating value of $\Delta N_{\rm eff}$ in the CMB analysis can induce a shift in the preferred value of $\Omega_b h^2$, which is also constrained by BBN. In the Supplementary Material, we address the extent to which the parameter space in the $\Delta N_{\rm eff} - \Omega_b h^2$ plane preferred by the CMB fit is compatible with expectations of BBN.

Evidence for the existence of the majoron, arising from the spontaneous breaking of global lepton number, would provide a strong clue to the origin of the neutrino masses. In this work we have looked at the extent to which CMB measurements have probed the existence of such a particle through its impact on the expansion history of the Universe and its interactions with neutrinos. We show that there exists a broad range of well-motivated parameter space that is now excluded using `Planck2018` measurements of the CMB power spectrum. Furthermore, we identify a region in which the majoron interactions help ameliorate the outstanding H_0 tension to a level that is beyond what is simply accomplished by including $\Delta N_{\rm eff}$. If confirmed, the H_0 tension could be providing the first insight into the origin of the small neutrino masses.

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