Nonstandard neutrino cosmology dilutes the lensing anomaly

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Despite the impressive success of the standard cosmological model, several anomalies defy its triumph. Among them is the so-called lensing anomaly: The *Planck* satellite observes stronger cosmic microwave background (CMB) gravitational lensing than expected. The role of neutrinos in this anomaly has been mostly overlooked, despite their key role in CMB lensing, because in the standard scenario they tend to increase the tension. Here, we show that this strongly depends on the assumed neutrino equation of state. We demonstrate that if neutrinos have yet undiscovered long-range interactions, the lensing pattern is significantly affected, rendering the lensing anomaly as a statistical fluctuation. Our results, thus, open up a window to link anomalous CMB lensing with present and future cosmological, astrophysical, and laboratory measurements of neutrino properties.

I. INTRODUCTION

The standard cosmological model, remarkably simple but with profound implications, remains strikingly successful in many diverse environments [1–11]. The precision is such that self-consistency tests are feasible and accurate. These tests check not only if individual datasets are consistent with the model, but also whether the same model *simultaneously* explains all observations or if, on the contrary, new ingredients are needed.

It is in these consistency tests where the standard model may meet its match. Indeed, there exist several anomalies that cannot be fully understood in the minimal cosmological constant plus cold dark matter (ΛCDM) scenario. The most statistically significant one is the discrepancy of the Hubble constant extracted from nearby Universe probes and that derived from cosmic microwave background (CMB) measurements [12–14]. Another one is related to the clustering parameter σ_8, whose values differ for CMB and weak lensing estimates [15]. The third one, the so-called lensing anomaly [7,16], is the focus of this work.

CMB anisotropies get blurred due to gravitational lensing by the large-scale structure of the Universe: Photons from different directions are mixed, and the peaks at large multipoles are smoothed. The amount of lensing is a precise prediction of the ΛCDM model: The consistency of the model can be checked by artificially increasing lensing by a factor A_{lens} [17] (*a priori* an unphysical parameter). If ΛCDM consistently describes all CMB data, observations should prefer $A_{\text{lens}} = 1$.

Intriguingly, Planck CMB data show a *preference* for additional lensing. Indeed, the reference analysis of temperature and polarization anisotropies suggest $A_{\text{lens}} > 1$ at 3σ. CMB lensing also introduces a nontrivial four-point correlation function, and, therefore, it can be independently measured. Adding this information somewhat diminishes the tension, albeit the value of the lensing amplitude is still above the canonical one by about 2σ. The lensing anomaly is robust against changes in the foreground modeling in the baseline likelihood and was already discussed in previous data releases, although it is currently more significant due to the lower reionization optical depth preferred by the Planck 2018 data release. A recent result from the Atacama Cosmology Telescope is compatible with $A_{\text{lens}} = 1$ [11], but the results are consistent with Planck within uncertainties.

Barring systematic errors or a rare statistical fluctuation, the lensing anomaly could have its origin in new physics scenarios. Attempts in the literature have changed either the geometrical or the gravitational sectors of the theory. A closed Universe [18] has been shown to solve the internal tensions in Planck concerning the cosmological parameter values at different angular scales, alleviating the A_{lens} anomaly. However, the positive curvature scenario is strongly rejected by other cosmological observations such as baryon acoustic oscillations (BAOs) [19]. Modified

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gravity theories or a modified primordial perturbation spectrum have also been considered as possible scenarios to solve the A_{lens} anomaly [20–24], but it is also unclear if BAO measurements are compatible with these solutions [23].

Here, we show that nonstandard neutrino properties can lead to unexpected lensing and dilute the preference for $A_{lens} \neq 1$. Neutrinos are key to structure formation in our Universe, but, due to a competition of different effects, in the standard paradigm they *reduce* CMB lensing [25,26]. However, we demonstrate that this dramatically depends on the assumed equation of state for the cosmological neutrino fluid. Under the presence of long-range neutrino interactions [27], largely allowed by other constraints [28–35], the generally assumed ideal gas equation of state no longer holds. This pivotal difference makes neutrinos *increase* CMB lensing, alleviating the A_{lens} anomaly. Crucially, other cosmological datasets such as BAO do not compromise this effect.

The structure of the manuscript is as follows. We start in Sec. II by describing the neutrino interaction model and its impact on the equation of state. In Sec. III, we show how different cosmological observables are affected, describing in detail the effect on CMB lensing. Section IV presents our quantitative results on the anomaly. We draw our conclusions and highlight future directions in Sec. V.

II. LONG-RANGE NEUTRINO INTERACTIONS

We consider neutrino self-interactions mediated by a very light scalar field ϕ with mass M_ϕ, so that neutrinos source a classical field making long-range interaction effects relevant [27,36–41]. The corresponding interaction Lagrangian is

$$\mathcal{L}_{int} = -g\phi\bar{\nu}\nu, \tag{1}$$

the standard scenario corresponding to $g = 0$. For simplicity, we consider one scalar field universally coupled to all three neutrino mass eigenstates, that we assume to have a common mass m_ν (cosmological effects of neutrino mass splittings are very challenging to detect [42–44]).

The phenomenology depends on the parameter values (more details are given in Ref. [27]). For $M_\phi \ll m_\nu$, the interaction range is larger than interneutrino distances, and long-range effects are relevant as long as the scalar field is dynamical. This requires $M_\phi \gg H$ (with H the Hubble parameter) at all relevant times, which for CMB observables corresponds to $M_\phi \gtrsim 10^{-25}$ eV. Long-range effects are governed by the ratio gm_ν/M_ϕ. The main constraint, from the observation of neutrino oscillations, is $gm_\nu/M_\phi \lesssim 10^5$ (although this can be evaded if the interaction has flavor structure). Scattering effects depend on g for light mediators, so they can be small even if long-range effects are large (and vice versa). An example of models with extra

scattering are those invoked to alleviate the Hubble tension [29,45–54]. SN1987A and other laboratory constraints [28–35] require $g \lesssim 10^{-7}$. Since we are interested in long-range effects, we focus on the regime where the coupling is tiny, $g \ll 10^{-7}$. This guarantees that scatterings can be neglected and that the scalar field is never produced on shell (so N_{eff} does not change from its standard value [55]).

The impact of long-range interactions on cosmic neutrinos is simple (see Ref. [27] for more details): When the density is large and the typical energy is of the order of the neutrino mass, neutrinos source a classical scalar field. This, in turn, induces an effective neutrino mass $\tilde{m} = m_\nu + g\phi \neq m_\nu$ via the Lagrangian; see Eq. (1). The energy and pressure of the scalar field are also relevant, and they modify the equation of state. Finally, when neutrinos become nonrelativistic, the scalar field induces an attractive force among them. This abruptly condenses all cosmic neutrinos into lumps of size $\lesssim M_\phi^{-1}$ [56–62].

Figure 1 summarizes how long-range interactions affect the evolution of cosmic neutrinos by changing their equation of state (defined as the ratio between pressure and energy density) as a function of redshift z. Under the presence of a long-range interaction, neutrinos behave as radiation for longer times (because $\tilde{m} < m_\nu$ due to scalar interactions being attractive). Later, the negative pressure of the scalar field promptly changes the equation of state to that of dust. This effect is further enhanced by the abrupt formation of lumps.
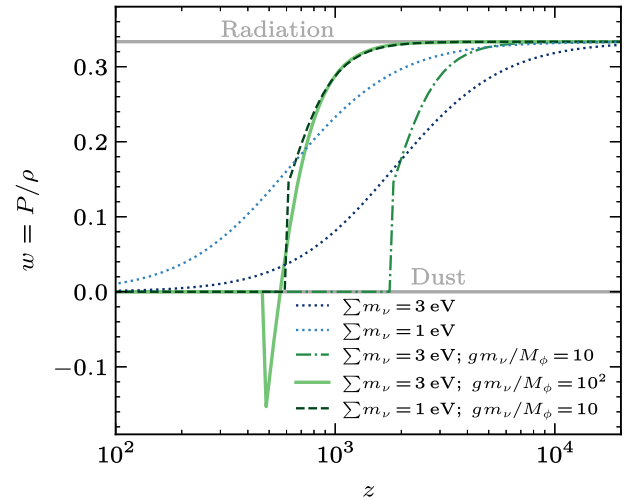

FIG. 1. Modified neutrino equation of state w due to long-range interactions (see Ref. [27] for the numerical computation). As w controls the rate of neutrino energy density dilution, $\dot{\rho}/\rho = -3H(1+w)$, the neutrino energy at different redshifts is dramatically affected, which directly impacts many cosmological observables.

III. IMPACT ON CMB OBSERVABLES

The modified equation of state directly impacts the precisely measured CMB anisotropies. As we shall show below, it also increases the observed lensing.

Figure 2 shows how neutrino masses and interactions impact CMB temperature anisotropies. The bottom panel shows the anisotropy ratios to the canonical ΛCDM scenario with massless neutrinos, together with Planck data. In this figure, we have fixed the cosmological parameters $\{\theta_s, \omega_b, \omega_{\rm cdm}, A_s, n_s, \tau_{\rm reio}\}$.

The main effects of long-range interactions arise due to the integrated Sachs-Wolfe effect (for $\ell \lesssim 500$), directly sensitive to the neutrino equation of state; and a reduced Silk damping scale when the neutrino energy density redshifts as dust (visible as an enhancement for large ℓ). These are also the standard effects of neutrino masses on CMB temperature anisotropies [27,63], but, since they can be traced back to how the neutrino equation of state gets modified when they become nonrelativistic, they are directly impacted by long-range interactions. As a consequence, strong long-range interactions completely remove the CMB bound on neutrino masses [27].

Interestingly, we also observe additional wiggles at large ℓ that mimic the scenario with artificially modified lensing $A_{\rm lens} \neq 1$. The effect of noninteracting massive neutrinos is out of phase with $A_{\rm lens} > 1$, indicating that neutrino masses typically reduce CMB lensing as we describe below. However, as we show below, introducing a long-range interaction increases the lensing. This effect is key to our results.

Indeed, the orange shaded region in Fig. 2 corresponds to the massless neutrino case with the value of $A_{\rm lens}$ inferred from a fit to Planck temperature and polarization measurements [7]. As we see, it lies very close to the interacting

neutrino scenario. However, it is not fully degenerate, as long-range interactions introduce additional effects (particularly a reduced Silk damping). This allows future observations to disentangle long-range interactions from other solutions to the lensing anomaly.

Figure 3 shows how neutrino masses and interactions affect the CMB lensing pattern. The bottom panel shows the ratios to the canonical ΛCDM scenario with massless neutrinos. The data points in the upper plot correspond to Planck [64], while in the bottom panel they refer to the errors expected by the next-generation ground-based CMB experiment CMB-S4 [65,66]. The orange band shows the enhanced lensing preferred by a fit to Planck CMB temperature, polarization, and lensing [7].

In the standard scenario, neutrinos reduce CMB lensing, because they are hot thermal relics with a very large velocity dispersion, and, therefore, they suppress clustering at small scales. Furthermore, when they become nonrelativistic, their energy density dilutes slower, enhancing the expansion of the Universe and further suppressing structure formation. However, they also have lensing-enhancing effects. On the one hand, they cluster as matter at large scales, enhancing density perturbations and, thus, the lensing. On the other hand, their modified equation of state before recombination would affect the well-measured CMB sound horizon, which must be compensated by slightly decreasing H_0, and a slower expansion rate of the Universe also enhances structure formation. Without long-range interactions (dotted line in Fig. 3), the last two effects are subdominant, particularly at large ℓ. Overall, neutrino masses tend to reduce CMB lensing.

FIG. 3. Modified CMB lensing power spectrum by massive and interacting neutrinos and the prediction for $A_{\rm lens} \neq 1$. Unlike neutrino masses, neutrino long-range interactions enhance lensing, closely mimicking $A_{\rm lens} > 1$. Future observations could discriminate among these two effects (see the main text for more details).
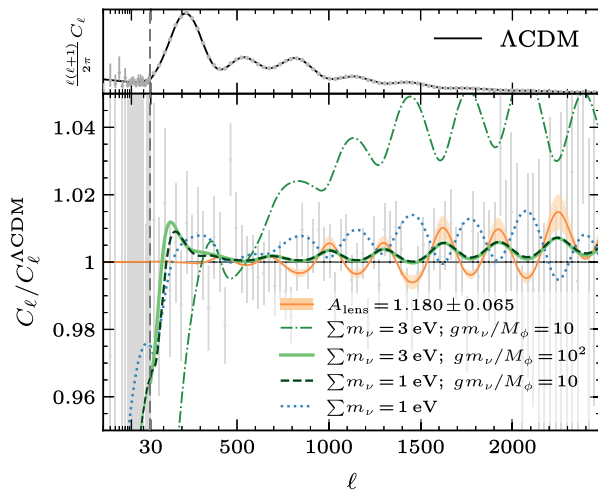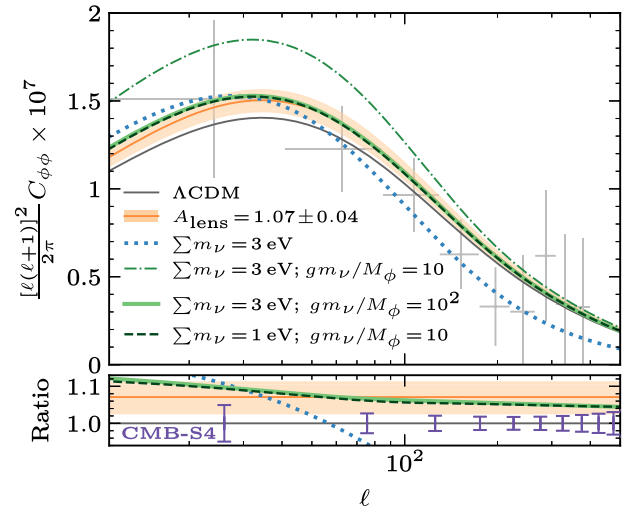

FIG. 2. Modified CMB temperature anisotropies by massive and interacting neutrinos, together with the prediction for $A_{\rm lens} \neq 1$. Neutrino long-range interactions mimic an enhanced lensing contribution, as preferred by the data.

However, long-range interactions flip this effect. The relativistic to nonrelativistic transition is more abrupt: Neutrinos move close to the speed of light for a shorter time (cf. Fig. 1). The energy density in neutrinos is also smaller as scalar interactions are attractive [27]. Therefore, the physical effects that suppress CMB lensing are diminished, and those enhancing it are increased. The overall effect is now the opposite: Neutrino masses and interactions enhance the lensing power spectrum.

Intriguingly, we note from Fig. 3 that the effect of massive neutrinos with $\sum m_\nu = 3$ eV and $gm_\nu/M_\phi = 10^2$ is almost degenerate with the massless neutrino case with $A_{\rm lens} = 1.07 \pm 0.04$. Given current uncertainties, it is always possible to tune the neutrino mass and the interaction strength to produce a CMB lensing pattern very similar to that obtained with $A_{\rm lens} \neq 1$. Since the degeneracy is not perfect, next-generation CMB observations, as those from CMB-S4, might disentangle between these two effects, as the error bars in the bottom panel in Fig. 3 show [67].

The presence of a long-range interaction in the neutrino sector, thus, generates very rich physics. Its effects turn on at a specific time (when neutrino masses start to be relevant) and make neutrinos behave as radiation even if they have *large* masses, at the same time enhancing CMB lensing as neutrinos increase perturbation growth in a different way than they would do in the noninteracting case. This makes long-range neutrino interactions a very attractive and predictive scheme to solve the $A_{\rm lens}$ anomaly.

IV. METHODOLOGY AND RESULTS

Below, we quantify how neutrino long-range interactions alleviate the $A_{\rm lens}$ anomaly. For this, we use the temperature and polarization CMB anisotropies from Planck 2018 [68] (at both high and low multipoles with the reference PLIK and alternative CamSpec likelihoods, which among other differences use different polarization masks, dust subtraction, and calibration) that we refer to as TTTEEE+lowl; the Planck CMB lensing reconstruction from the four-point correlation function [69], that we refer to as lensing; and the BAO observations from 6dFGS [1], SDSS-DR7 MGS [2], and BOSS DR12 [4], that we refer to as BAO.

We compute cosmological observables by varying all parameters (that is, the standard ΛCDM parameters, the lensing parameter $A_{\rm lens}$, the total neutrino mass $\sum m_\nu$, and the interaction strength gm_ν/M_ϕ) using the extension of the code CLASS [70,71] from Ref. [27] (publicly available [72]). We compute $\Delta\chi^2_{\rm eff}$ by modifying the MontePython [73] code, and we carry out all our minimizations with the BOBYQA minimizer [74] and its PYTHON implementation [75]. This minimizer is robust against nonsmooth likelihoods, making it ideal for the problem studied here [76,77].
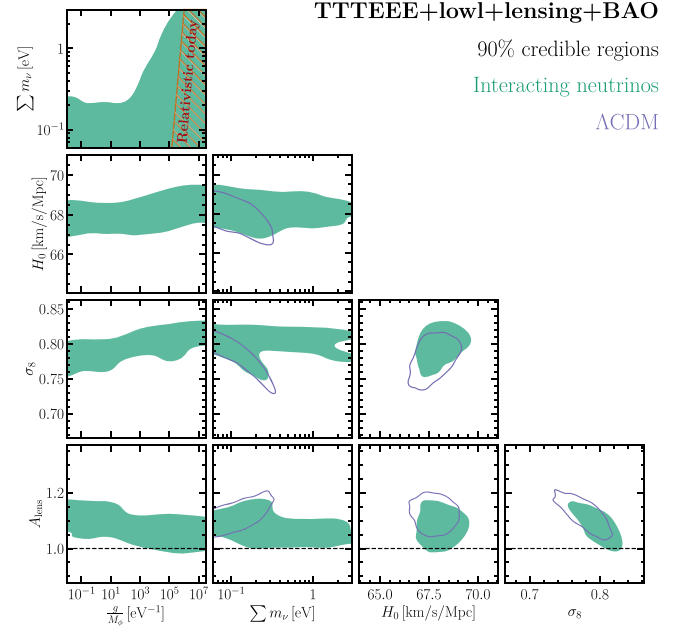

FIG. 4. Allowed parameter values and correlations after including all relevant datasets. The significance of the $A_{\rm lens}$ anomaly as read from this figure is prior dependent and subject to Bayesian volume effects (see the text); hence, we do *not* draw our main quantitative conclusions from here. Allowing for neutrino long-range interactions dilutes the anomalous preference for $A_{\rm lens} > 1$. The shift in other parameters is mild.

Figure 4 shows that neutrino long-range interactions dilute the preference toward extra lensing. We show the Bayesian 90% credible regions in two-parameter spaces of $\sum m_\nu, H_0, \sigma_8, A_{\rm lens}$, and gm_ν/M_ϕ for the ΛCDM plus $A_{\rm lens}$ model and for the interacting long-range scenario after marginalizing over all other parameters. We combine Planck temperature, polarization, and lensing data with BAO measurements, and we perform a Bayesian Markov chain Monte Carlo sampling that we have checked to converge as all Gelman-Rubin parameters satisfy $R - 1 < 0.02$. In the hatched region, cosmological neutrinos would still be relativistic today, with potential impact on other observables depending on the flavor structure of the interaction [27]. This figure illustrates the shift induced in the different parameters by the presence of a long-range force: The value of $A_{\rm lens}$ is lowered, as CMB lensing is reduced in the presence of these long-range interactions. As the interaction strength increases, the parameter $A_{\rm lens}$ becomes more consistent with the canonical $A_{\rm lens} = 1$. In this model, the cosmological neutrino mass bound is largely relaxed. The other cosmological parameters suffer a mild shift in their best-fit values. In addition, the H_0 and σ_8 tensions are not worsened.

Precisely quantifying the significance of the lensing anomaly through Fig. 4 is subject to prior dependence and Bayesian volume effects. There is infinite parameter space where long-range interactions are degenerate with

ΛCDM: for very large gm_ν/M_ϕ, where neutrinos behave as a massless ideal gas (see Fig. 1); for small gm_ν/M_ϕ, where the interaction is negligible; and for small $\sum m_\nu$, where interaction effects turn on very late (see Fig. 1). Thus, Bayesian inferences that integrate over $\sum m_\nu$ and/or g/M_ϕ will receive large contributions from parameter regions with no new effects and large A_{lens}. Even if some parameter region with beyond-ΛCDM effects and $A_{\text{lens}} \sim 1$ provided an equally good fit—hence alleviating the anomaly—its small relative volume would bias conclusions toward no new effects and a significant lensing anomaly. Moreover, the relative volume of these regions depends on the chosen priors (e.g., linear vs logarithmic) and parameter limits.

Hence, to draw our quantitative conclusions we follow the Planck Collaboration [7], and we quantify the significance of the lensing anomaly by computing

$$\Delta\chi^2_{\text{eff}} = \chi^2_{\text{eff}}(A_{\text{lens}} = 1) - \chi^2_{\text{eff}}(A_{\text{lens}} \neq 1), \qquad (2)$$

where χ^2_{eff} is the value of χ^2 after minimizing over all cosmological and nuisance parameters. A larger $\Delta\chi^2_{\text{eff}}$ corresponds to a more significant anomaly. As no integral is performed, this figure of merit avoids any Bayesian volume effect.

Table I shows our main results. As described above, we compute $\Delta\chi^2_{\text{eff}}$ for different datasets and for the two Planck likelihoods, the reference PLIK and the alternative CamSpec, for ΛCDM and with long-range neutrino interactions. In the former case, we follow the Planck analysis and assume $\sum m_\nu = 0.06$ eV [7]. In the latter, both the total neutrino mass $\sum m_\nu$ and the interaction strength gm_ν/M_ϕ are free parameters to be determined by data. We also show the frequentist p values for excluding $A_{\text{lens}} = 1$. (Below, we further quantify the tension with the Akaike information criterion.)

We first note that, when no long-range forces are present in the neutrino sector, the fit to CMB temperature and polarization anisotropy data greatly improves if we introduce the extra parameter A_{lens}. From a frequentist point of view, there is a 3σ preference for $A_{\text{lens}} \neq 1$ if we use the PLIK likelihood and somewhat smaller for CamSpec. Interestingly, this preference drops drastically when considering additional datasets, indicating some internal inconsistency.

The preference for $A_{\text{lens}} \neq 1$ dilutes when we include neutrino long-range interactions. Its statistical significance merely reaches the $\sim 1.5\sigma$–2σ level (or $< 1\sigma$ if we consider Planck temperature, polarization, and lensing data), and, therefore, it can be interpreted as a simple statistical fluctuation. Furthermore, the values of $\Delta\chi^2_{\text{eff}}$ become more uniform and consistent among the different datasets. This is unlike other proposed solutions to the lensing anomaly such as curvature, where BAO data fully restore the preference toward $A_{\text{lens}} \neq 1$.

In order to further assess the impact of our results, we also use one of the information criteria widely exploited in astrophysical and cosmological studies to discriminate between competing models (see, e.g., Refs. [78,79])—the frequentist Akaike information criterion (AIC):

$$\text{AIC} \equiv \chi^2_{\text{eff}} + 2k, \qquad (3)$$

where k is the number of free parameters in the model; the second term penalizes models with more free parameters. The best model is the one with the smallest AIC. Following Jeffreys' scale, we rate a difference $\Delta\text{AIC} > 5$ or > 10 as strong or decisive evidence, respectively, against the disfavored model [78].

This statistical criterion also reflects that neutrino long-range interactions dilute the lensing anomaly. Focusing on the TTTEEE + lowl dataset and the PLIK likelihood, $\Delta\text{AIC} = 7.66$, and, therefore, $A_{\text{lens}} = 1$ is penalized in a strong-to-decisive manner with respect to the case in which the lensing amplitude is a free parameter. For the very same dataset and likelihood, $\Delta\text{AIC} < 5$ when long-range interactions are switched on, and, therefore, no significant claim can be stated concerning a preference for $A_{\text{lens}} \neq 1$. Similar results hold for other datasets and the CamSpec likelihood. A nonminimal neutrino sector, thus, dilutes the preference for

TABLE I. Significance of the lensing anomaly without and with neutrino long-range self-interactions, for the two official Planck likelihoods (see the text for details). Introducing long-range interactions removes the significant preference for extra lensing, rendering the CMB data self-consistent with the assumed cosmology.

	$\Delta\chi^2_{\text{eff}} = \chi^2_{\text{eff}}(A_{\text{lens}} = 1) - \chi^2_{\text{eff}}(A_{\text{lens}} \neq 1)$		
	TTTEEE + lowl	TTTEEE + lowl + lensing	TTTEEE + lowl + lensing + BAO
PLIK (reference): ΛCDM	9.66 $p = 0.2\%$	3.43 $p = 6\%$	4.26 $p = 4\%$
PLIK (reference): self-interactions	4.87 $p = 3\%$	0.76 $p = 38\%$	2.71 $p = 10\%$
CamSpec (alternative): ΛCDM	4.82 $p = 3\%$	2.01 $p = 16\%$	1.96 $p = 16\%$
CamSpec (alternative): self-interactions	2.06 $p = 15\%$	1.39 $p = 24\%$	1.79 $p = 18\%$

TABLE II. Neutrino mass and long-range interaction strength preferred by different datasets. These values alleviate the lensing anomaly.

		TTTEEE + lowl	TTTEEE + lowl + lensing	TTTEEE + lowl + lensing + BAO
PLIK	$\sum m_\nu$ (eV)	0.8	2.9	0.08
(reference)	gm_ν/M_ϕ	13	317	2×10^3
CamSpec	$\sum m_\nu$ (eV)	0.7	0.07	0.06
(alternative)	gm_ν/M_ϕ	16	7	15

extra artificial lensing, making CMB data consistent with the assumed cosmological history of the Universe.

Table II shows the neutrino parameters that alleviate the lensing anomaly. We show the best-fit values for the total neutrino mass $\sum m_\nu$ and the long-range interaction strength gm_ν/M_ϕ assuming a canonical lensing amplitude $A_{\text{lens}} = 1$, for both likelihoods and for the three possible datasets here exploited. We note that, in general, CMB data prefer moderate interaction rates $gm_\nu/M_\phi \sim 10\text{--}10^3$. The preferred neutrino masses, still lying in the sub-eV region compatible with laboratory data [80], typically exceed the current cosmological limits for noninteracting neutrinos. More precise measurements of the neutrino mass in the laboratory, which are more model independent [27], could thus shed complementary light onto these models and their early Universe phenomenology. Although the precise best fit changes from one dataset to another, we notice from the contours in Fig. 4 that a wide parameter range points toward $A_{\text{lens}} = 1$. No fine-tuning of the best-fit values is needed to alleviate the A_{lens} tension.

V. CONCLUSIONS AND FUTURE PROSPECTS

The ΛCDM picture has provided an extremely good explanation of present cosmological observations. Nevertheless, it relies on very simplistic assumptions on the different ingredients, reflecting our ignorance on the microphysics of the different components of the Universe. Namely, dark energy is simply described by a cosmological constant representing the vacuum energy, dark matter is merely assumed to be a noninteracting dust, and neutrinos are relativistic species that transition into dust as an ideal gas.

Deviations from this simple and economical scenario are, thus, natural as data get more precise. These may show up in self-consistency tests that start out as anomalies and then evolve into incontrovertible evidence pointing to either uncontrolled uncertainties or new physics. The fact that cosmology probes extreme densities also implies that phenomena beyond the Standard Model of particle physics could first appear there.

In this work, we have explored if the simplistic and minimal ΛCDM scenario could alleviate some of its current anomalies if the neutrino sector is richer, leading to unexpected effects. This is somewhat expected, as neutrinos have

provided so far the only laboratory evidence for physics beyond the Standard Model [81–89].

An especially rich cosmological observable is the CMB lensing. Neutrinos substantially affect it, to the extent that present and future CMB constraints on neutrino masses strongly rely on measuring it [90]. And, as we have shown, deviations from the minimal ideal gas scheme notably modify the canonical expectations.

A nonideal neutrino equation of state, thus, *naturally* provides a physical framework to solve the so-called lensing (A_{lens}) anomaly. We have shown that the presence of a long-range interaction in the neutrino sector makes CMB observations consistent with the canonical value $A_{\text{lens}} = 1$. In addition, the interaction strength required to decrease the lensing anomaly down to a statistical fluctuation is consistent with other existing bounds.

Our scenario can be easily explored with other cosmological observations. Future CMB measurements will have superb precision, and they could discriminate between neutrino interactions and uniformly enhanced lensing [65,67]. Furthermore, current surveys are rapidly improving our precision of the matter power spectrum [10,91], to the extent that they could start being sensitive to effects induced by neutrino self-interactions [27]. In Ref. [27], it was explicitly shown that long-range neutrino interactions remove the power spectrum enhancement at scales $k \sim 10^{-3} h/\text{Mpc}$ due to nonrelativistic neutrinos falling in the dark matter gravitational wells and contributing to structure growth. As shown there, the future EUCLID survey will significantly improve the current sensitivity to long-range interacting neutrino scenarios. The light new scalar responsible for the long-range interaction could also give rise to observable departures from standard cosmology [36–41].

More interestingly, due to the direct link to particle physics, neutrino long-range interactions can leave imprints on astrophysical and laboratory probes. Environments with a large neutrino density such as the Sun or core-collapse supernovae might get affected [92], and the precise data that future neutrino observatories will gather open exciting prospects [93–99]. Our scenario also predicts that the entire cosmic neutrino background should be condensed in relatively dense lumps that could give additional signals, for instance, through their effect on astrophysical neutrinos. Furthermore, in minimal realizations of our model, laboratory neutrino mass constraints are not affected [27].

Thus, the relatively large neutrino masses required to alleviate the lensing anomaly could generate unexpected signals in beta decay [80,100] or neutrinoless double-beta decay [101] searches. Additionally, variations of our model could also induce neutrino decay [34,45,102–115].

Finally, we have considered only the phenomenology induced by the minimal Lagrangian (1). Electroweak gauge invariance, or a mechanism that ensures the lightness of the mediator, can be achieved only in a UV-complete model with extra ingredients (see, e.g., Refs. [29,116–118]). This may bring up additional phenomenology in other cosmological, astrophysical, or laboratory observations.

We are living in exciting times for cosmology. The ΛCDM paradigm will be profoundly scrutinized, and any inconsistency will shed light onto the most elusive part of our Universe. Neutrinos, ordinarily ghostly particles, may be the path to new cosmological models, with intriguing links to astrophysics and particle physics observations.

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