Limits on Neutrino-Neutrino Scattering in the Early Universe

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In the standard model neutrinos are assumed to have streamed across the Universe since they last scattered at the weak decoupling epoch when the temperature of the standard-model plasma was $\sim$MeV. The shear stress of free-streaming neutrinos imprints itself gravitationally on the Cosmic Microwave Background (CMB) and makes the CMB a sensitive probe of neutrino scattering. Yet, the presence of nonstandard physics in the neutrino sector may alter this standard chronology and delay neutrino free-streaming until a much later epoch. We use observations of the CMB to constrain the strength of neutrino self-interactions $G_{\rm eff}$ and put limits on new physics in the neutrino sector from the early Universe. Recent measurements of the CMB at large multipoles made by the Planck satellite and high-l experiments are critical for probing this physics. Within the context of conventional ΛCDM parameters cosmological data are compatible with $G_{\rm eff} \lesssim 1/(56\,{\rm MeV})^2$ and neutrino free-streaming might be delayed until their temperature has cooled to as low as $\sim$25 eV. Intriguingly, we also find an alternative cosmology compatible with cosmological data in which neutrinos scatter off each other until $z \sim 10^4$ with a preferred interaction strength in a narrow region around $G_{\rm eff} \simeq 1/(10\,{\rm MeV})^2$. This distinct self-interacting neutrino cosmology is characterized by somewhat lower values of both the scalar spectral index and the amplitude of primordial fluctuations. While we phrase our discussion here in terms of a specific scenario in which a late onset of neutrino free-streaming could occur, our constraints on the neutrino visibility function are very general.

INTRODUCTION Neutrinos are the most elusive components of the standard model (SM) of particle physics. Their tremendously weak interactions with other SM fields render measurements of their fundamental properties very challenging. At the same time, the existence of neutrino mass [1] constitutes one of the most compelling lines of evidence for physics beyond the SM, and makes the neutrino sector a prime candidate for searches for new physics. In recent years, cosmology has provided some of the most stringent constraints on neutrino properties, most notably the sum of their masses and their effective number [2–4]. Can cosmological data inform us about other aspects of neutrino physics?

One assumption that is almost always implicitly made is the free-streaming nature of cosmological neutrinos (for exceptions, see, e.g. Refs. [5–11]). Within the confines of the standard model this assumption is justified since SM neutrinos are expected to have decoupled from the primeval plasma in the very early Universe at a temperature $T \simeq 1.5$ MeV. Yet, this assumption is not a priori driven by cosmological observations, but instead a prior on the models of neutrino physics we choose to compare with data. Abandoning this assumption allows us to answer the important question: *How does cosmology inform us about the interactions of neutrinos with each other?*

Free-streaming neutrinos create anisotropic stress which, through gravity, alters the evolution of the other particle species in the Universe [12, 13]. As cosmological fluctuations in the photon and baryon fluids are particularly sensitive to the presence of a free-streaming component during the radiation-dominated era, we expect the recent measurements of the CMB to provide an interesting constraint on the onset of neutrino free-streaming. We emphasize that while neutrino-neutrino scattering may have been ubiquitous in the early Universe, arranging for and measuring neutrino-neutrino scattering on Earth is particularly difficult given the challenges involved in creating intense neutrino beams (see e. g. [14]).

In this *Letter*, we compute the first purely cosmological constraints on the strength of neutrino self-interactions. We model the interaction as a four-fermion vertex whose strength is controlled by a dimensional constant G_ν, analogous to the Fermi constant. In this scenario, the onset of neutrino free-streaming is delayed until the rate of these interactions fall below the expansion rate of the Universe, hence affecting the evolution of cosmological fluctuations that enter the causal horizon before that epoch. As we discuss below, the cosmological observables are compatible with a neutrino visibility function peaking at a temperature orders of magnitude below that of the standard picture. Furthermore, we unveil here a novel cosmology in which neutrinos are strongly self-interacting until close to the epoch of matter-radiation equality.

In earlier investigations of neutrino properties [15–20], neutrinos were modeled as a fluid-like [21] and constraints were placed on the phenomenological parameters $c_{\rm eff}$ and
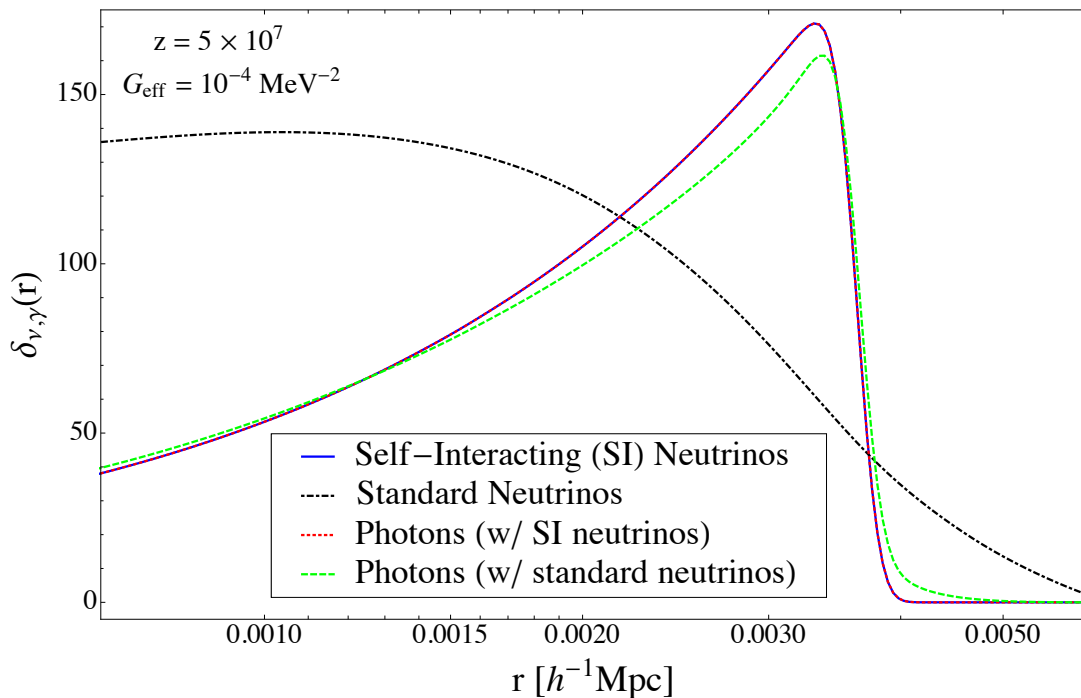
FIG. 1: Evolution of neutrino and photon fluctuations in configuration space for both self-interacting neutrinos (blue solid line) and standard free-streaming neutrinos (black dash-dotted line). Here we have adopted a Planck cosmology [4]. The phase shift and amplitude suppression of the photon fluctuation associated with free-streaming neutrinos are readily noticeable.

$c_{\rm vis}$, the rest-frame sound speed and the viscosity parameter of the neutrino fluid respectively. These analysis found consistency with the free-streaming limit. However, by modeling these parameters as constant throughout the history of the Universe they could not capture the realistic physics of neutrino decoupling. We incorporate here the physics necessary to follow in detail the dynamics of the transition of neutrinos from a tightly-coupled fluid to particles free-streaming across the Universe.

NEUTRINO INTERACTIONS As an example, we consider a scenario in which all neutrinos, in addition to their regular SM interactions, have non-negligible self-interactions due to their coupling g_ν to a new massive mediator particle.[1] When the temperature of the neutrinos falls significantly below the mediator mass, one can integrate the latter out and model the interaction as a four-fermion vertex controlled by a dimensionful coupling constant G_ν. We note that SN1987A only places a weak constraint on neutrino self-interaction, leading to $G_\nu \lesssim 144\,{\rm MeV}^{-2}$ [24].

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[1] In this scenario, the possible emission of a (light relative to the decaying species) mediator particle by neutrinos in the final state of Kaon and W decay leads to upper bounds on the value of g_ν. For a vector mediator of mass M_X, we must have $g_\nu < 8 \times 10^{-5}(M_X/{\rm MeV})$ [22], while for a scalar we have $g_\nu < 0.014$ [23].

In the early Universe, self-interactions render the neutrino medium opaque with an opacity $\dot\tau_\nu \equiv -aG_{\rm eff}^2 T_\nu^5$, where all order unity numerical factors have been absorbed in $G_{\rm eff} \propto G_\nu$, T_ν is the temperature of the neutrino bath, and a is the scale factor describing the expansion of the Universe. In this work, we focus our attention on the case where $G_\nu \gg G_{\rm F}$, where $G_{\rm F}$ is the Fermi constant. Therefore, we justifiably neglect the contributions from electroweak processes to the neutrino opacity in what follows. The opacity of the neutrino medium implicitly defines a neutrino visibility function given by $\tilde g_\nu(z) \equiv -\dot\tau_\nu e^{-\tau_\nu}$. As in the photon case, the visibility function can be thought of as a probability density function for the redshift at which a neutrino begins to free-stream. Compared to the standard case, the introduction of a new type of interaction in the neutrino sector can push the peak of the neutrino visibility function to considerably lower redshift.

EVOLUTION OF FLUCTUATIONS To determine the impact of neutrino self-interaction on cosmological observables, we evolve the neutrino fluctuation equations from their early tightly-coupled stage to their late-time free-streaming solution. By prohibiting free-streaming, neutrino self-interactions severely damp the growth of anisotropic stress associated with the quadrupole and higher moments of the neutrino distribution function. Indeed, while the equations for the density and velocity fluctuations of the neutrinos are unaffected by the
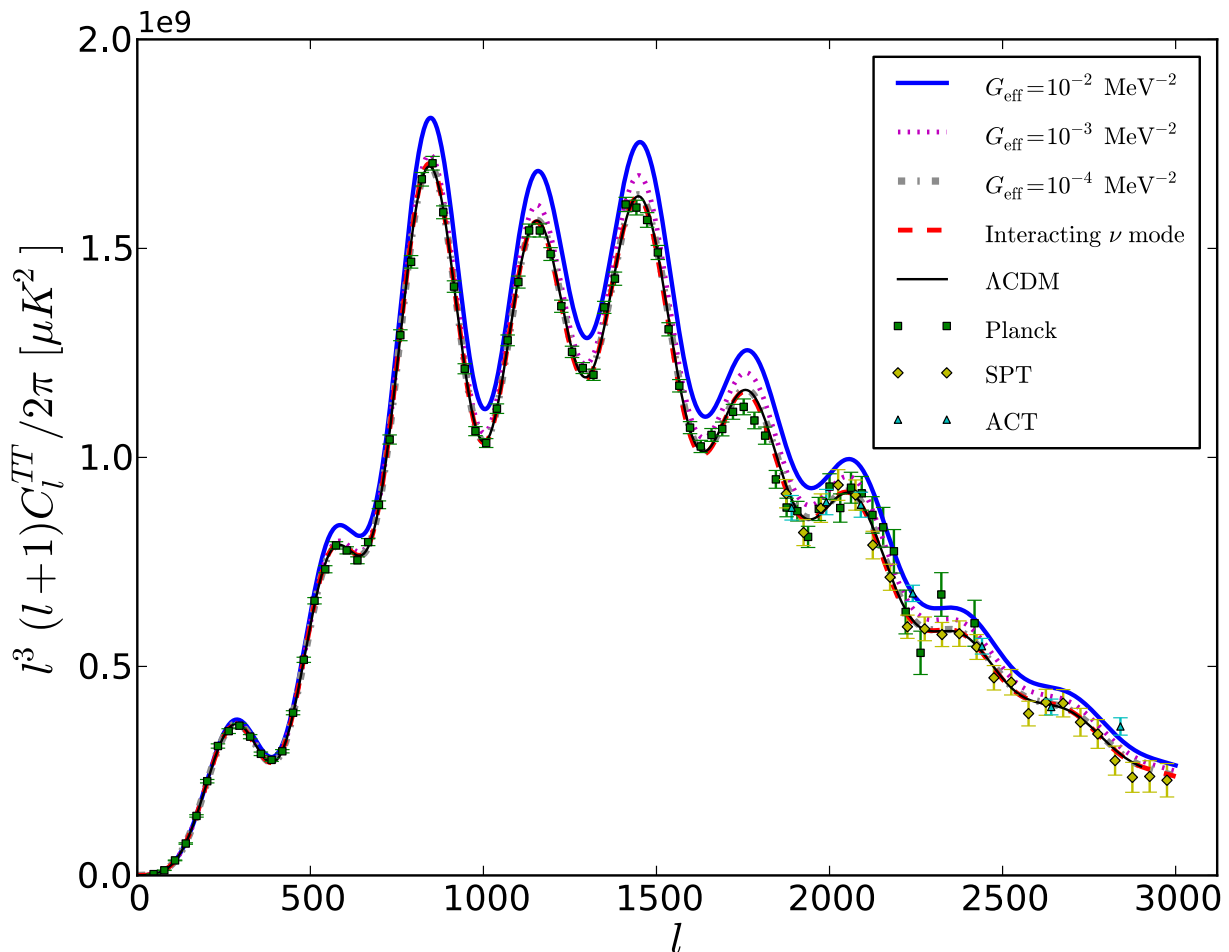
FIG. 2: CMB Temperature power spectra for different values of $G_{\rm eff}$. Here we have adopted a Planck cosmology [4] with three neutrinos and show the corresponding standard ΛCDM spectrum (solid black line) for comparison. We also display the temperature spectrum (dashed red line) for the interacting neutrino cosmology given in Table I.

self-interaction, the moments with $l \geq 2$ are corrected by a damping term proportional to $\dot{\tau}_\nu$ which effectively suppresses their growth,

$$\dot{F}_{\nu 2} = \frac{8}{15}\theta_\nu + \frac{8}{15}k\sigma - \frac{3}{5}kF_{\nu 3} + \frac{9}{10}\alpha_2\dot{\tau}_\nu F_{\nu 2}, \quad (1)$$

$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right] + \alpha_l\dot{\tau}_\nu F_{\nu l}, \quad (2)$$

where we follow closely the notation of [25] in synchronous gauge. The α_ls are order unity l-dependent coefficients that depends on the specific model used for neutrino interactions. In our analysis, we set these coefficients to unity; in practice, any change to α_2 can be reabsorbed into $G_{\rm eff}$ while changes to α_l for $l \geq 3$ have very little impact on the CMB. We solve these equations numerically together with the standard perturbation equations for the photons, baryons and dark matter using a modified version of the code CAMB [26]. At early times, the tightly-coupled neutrino equations are very stiff and we use a tight-coupling approximation which

sets $F_{\nu 2} = 16(\theta_\nu + k\sigma)/(27\alpha_2\dot{\tau}_\nu)$ and $F_{\nu l} = 0$ for $l \geq 3$ [27]. We note that the neutrino opacity is related to the commonly used viscosity parameter $c_{\rm vis}^2$ though the relation $c_{\rm vis}^2 = (1/3)(1 - (27/16)\dot{\tau}_\nu\alpha_2 F_{\nu 2}/(\theta_\nu + k\sigma))$. As long as neutrinos form a tightly-coupled fluid, the second term is very close to unity and $c_{\rm vis}^2$ approaches zero. After, the onset of neutrino free-streaming, the second term becomes vanishingly small and $c_{\rm vis}^2 \to 1/3$.

We compare in Fig. 1 the evolution in configuration space of self-interacting and free-streaming neutrino fluctuations. Since it can establish gravitational potential perturbation beyond the sound horizon of the photon-baryon plasma, free-streaming radiation suppresses the amplitude and shift the phase of photon density fluctuations [12]. For each Fourier mode of the photon fluctuations, the magnitude of these two effects is directly proportional to the free-streaming fraction of the total radiation energy density when the Fourier mode enters the Hubble horizon. If neutrino free-streaming is delayed

due to their self-interaction until redshift $z_{\nu*}$, Fourier modes of photon fluctuations entering the horizon before $z_{\nu*}$ would not be affected by the standard shift in amplitude and phase. On the other hand, the amplitude of photon fluctuations becoming sub-horizon at a redshift $z_{eq} < z < z_{\nu*}$ would be suppressed and their phase would be shifted toward larger scales (smaller l). Therefore, the impact of delayed neutrino free-streaming on the temperature and polarization power spectra of the CMB is a l-dependent shift in their amplitude and phase. Multipoles with $l_{eq} < l < l_{\nu*}$ are largely unaffected by neutrino self-interaction while multipoles with $l > l_{\nu*}$ are expected to gradually display more power and have their phase shifted toward smaller angular scales as l is increased. We illustrate these signatures of neutrino self-interaction for different values of G_{eff} in Fig. 2.

DATA To constrain neutrino self-interaction, we use the CMB data from the Planck satellite [4]. We utilize both the low-multipole and high-multipole temperature data, incorporating the required "nuisance" parameters describing foregrounds and instrumental effects, and also include the WMAP low-l polarization data. We refer to this dataset as "Planck+WP". We also incorporate the high-resolution temperature data from the South Pole Telescope (SPT) and the Atacama Cosmology Telescope (ACT). As in the original Planck analysis, we only include the ACT 148×148 spectra for $l \geq 1000$, the ACT 148×218 and 218×218 spectra for $l \geq 1500$ [28, 29], and the SPT data described in [30] for $l \geq 2000$. We fully incorporate the nuisance parameters describing foregrounds and calibration uncertainties for both SPT and ACT. We collectively refer to this dataset as "High-l". We also include in our analysis baryon acoustic oscillation (BAO) data from a reanalysis of the Sloan Digital Sky Survey DR7 [31], from the 6-degree Field survey [32], and from the Baryon Oscillation Spectroscopic Survey [33]. For our cosmological parameter estimation, we use the publicly available Markov Chain Monte Carlo code `CosmoMC` [34]. We also obtain a pre-Planck era constraint on neutrino self-interaction by using WMAP9 temperature and polarization data [35] in addition to the high-resolution temperature data from SPT and ACT. For this analysis, we use the ACT temperature data from the equatorial patch for $500 < l < 3500$ and SPT temperature data for $650 < l < 3000$ as described in [36]. In both cases, these spectra are pre-calibrated to WMAP and pre-marginalized over foregrounds. We collectively refer to this dataset as "WMAP9 + ACT + SPT". While the cosmological results from this last combination of datasets are somewhat in tension with those determined by Planck, we will see that our results are robust and only weakly depend on the specific datasets considered.

RESULTS AND DISCUSSION We run Markov Chain Monte Carlo analyses with the above-mentioned data, letting the standard six parameters of ΛCDM vary ($\Omega_c h^2$, $\Omega_b h^2$, θ_*, τ, n_s and $\ln(10^{10} A_s)$) in addition to vary-

ing G_{eff} and the nuisance parameters. We set the prior distributions to those described in [4], and use a flat prior on $\log_{10}(G_{eff}\mathrm{MeV}^2) \in [-6, 0]$. To ensure that we fully explore the posterior distribution, we generate Markov chains at high temperature and obtain our final posterior by importance sampling. In our analysis, we fix the effective number of neutrinos to the standard value of 3.046 and focus on massless neutrinos. We will expand our analysis to massive neutrinos in future work.

We show in Fig. 3 the marginalized posterior distribution of $\log_{10}(G_{eff}\mathrm{MeV}^2)$ for all the combinations of datasets considered. We surprisingly observe that the marginalized posterior is *multimodal*. To avoid quoting misleading bounds, we provide below confidence intervals for each mode separately. It is important to emphasize that the posterior distribution of nuisance parameters is not affected by the introduction of G_{eff}, indicating that the effect of neutrino interaction is not degenerate with foreground contamination and calibration uncertainties.

The principal mode of the distribution, which connects continuously with the standard cosmological scenario with $G_\nu = G_F$, spans the range $G_{eff} \leq 10^{-2.6}\mathrm{MeV}^{-2}$. For this mode, the exact confidence intervals strongly depend on the lower limit of the flat prior on $\log_{10}(G_{eff}\mathrm{MeV}^2)$ since $G_{eff} \lesssim 10^{-5}\,\mathrm{MeV}^{-2}$ has little impact on the CMB. For our choice of prior, we obtain $\log_{10}(G_{eff}\mathrm{MeV}^2) < -3.5$ (95% C.L.) for "Planck+WP+High-l+BAO". Within this mode, the range of allowed G_{eff} values is remarkably large, implying that the onset of neutrino free-streaming could have been significantly delayed beyond weak decoupling without affecting cosmological observables. Recasting the above limit into a model-independent lower bound on the peak of the neutrino visibility function, we obtain $z_{\nu*} \gtrsim 1.5 \times 10^5$. This in turns implies that the temperature of the cosmological neutrino bath at the onset of free-streaming could have been as low as ~ 25 eV. It is important to emphasize that this number is almost *5 orders of magnitude* below the standard value of $T_{\nu,dec} \simeq 1.5$ MeV. While this observation *does not* imply the presence of new physics in the neutrino sector, it *does* show that there is considerable room for new physics to turn up in the way neutrinos interact.

The secondary mode of the posterior distribution, which spans $10^{-2.6} < G_{eff}\mathrm{MeV}^2 < 10^{-1.3}$, represents a truly novel cosmological scenario. In this "interacting neutrino" cosmology, neutrinos are tightly-coupled until $z_{\nu*} \sim 10^4$ such that most of the CMB multipoles do not receive the usual phase shift and amplitude suppression associated with the presence of free-streaming radiation. The presence of this new mode with $\log_{10}(G_{eff}\mathrm{MeV}^2) = -2.0 \pm 0.2$ (68% C.L.) indicates that the absence of these "free-streaming" effects can be compensated by adjusting the other cosmological parameters, especially the scalar spectral index and the amplitude of primordial fluctuations (see Table I). This points to a previously unknown degeneracy between the spectrum of primordial fluctu-
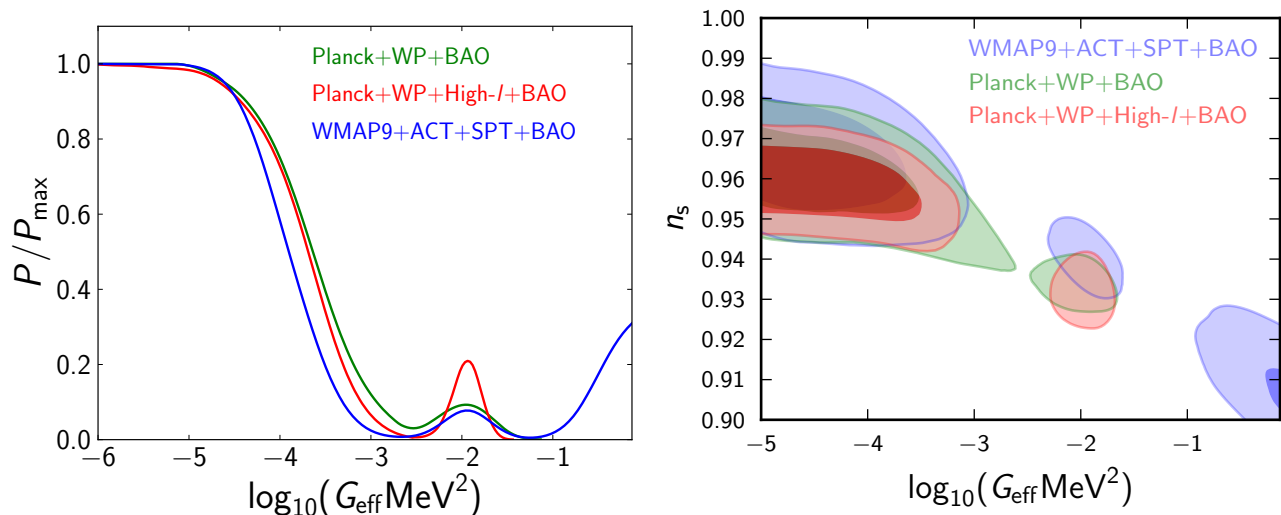
FIG. 3: *Left panel:* Marginalized posterior distribution of $\log_{10}(\mathrm{G_{eff}MeV^2})$ for different combinations of datasets. *Right Panel:* 2D marginalized constraints in the n_s and $\log_{10}(\mathrm{G_{eff}MeV^2})$ plane.

ations and the gravitational effect of the neutrinos on the CMB. We note in passing that the error bars of the WMAP 9-year data allows for an additional mode of non-vanishing probability at large G_{eff} values. This region is disfavoured by current Planck data and we do not further consider this region of parameter space.

How significant is the interacting neutrino cosmology? From Fig. 3, it is clear that the weight of the interacting neutrino mode in the posterior is smaller compared to that of the principal mode. This is however the result of our choice of prior: a uniform prior on $\log_{10}(G_{eff}\mathrm{MeV^2})$ is equivalent to setting a non-uniform prior on G_{eff} which scales as $1/G_{eff}$. Our choice of prior thus gives larger weights to small values of G_{eff}, hence favoring the standard ΛCDM model. However, if we instead impose (an arguably equally reasonable) uniform prior on G_{eff}, then the interacting neutrino cosmology becomes favored over the standard cosmological model. Therefore, it is clear that additional datasets will have to be considered to determine whether the interacting neutrino cosmology is a plausible scenario. It is nevertheless intriguing that this alternate cosmology is only viable for a narrow range of the neutrino interaction strength.

In conclusion, we have shown that the CMB allows for a neutrino self-interaction strength that is orders of magnitude larger than the standard Fermi constant. Moreover, we have determined that strongly self-interacting neutrinos with $G_{eff} \simeq 1/(10\,\mathrm{MeV})^2$ can lead to a CMB spectrum that is in very good agreement with the data. Given the relatively large interaction strengths discussed here, it is interesting to consider whether tests of self-interacting neutrino physics might be made with extensions of existing neutrino beam experiments (see, e. g.,

Parameters	Standard Mode	Interacting-ν Mode
$\Omega_b h^2$	0.0221 ± 0.0002	0.0222 ± 0.0003
$\Omega_c h^2$	0.119 ± 0.002	0.120 ± 0.002
τ	0.09 ± 0.01	0.09 ± 0.01
H_0	68.1 ± 0.8	69.0 ± 0.8
n_s	0.959 ± 0.006	0.932 ± 0.006
$10^9 A_s$	2.19 ± 0.02	2.07 ± 0.02
$\log_{10}(\mathrm{G_{eff}MeV^2})$	$< -3.5\,(95\%\,\mathrm{C.L.})$	-2.0 ± 0.2

TABLE I: Marginalized constraints on cosmological parameters for the two main modes of the distribution. Unless otherwise indicated, we quote 68% confidence level for Planck + WP + High-l + BAO.

Refs. [14, 37]), a rather exciting possibility.

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