Right-Handed Neutrinos as the Dark Radiation: Status and Forecasts for the LHC

Luis A. Anchordoqui, Haim Goldberg, and Gary Steigman

1 Department of Physics, University of Wisconsin-Milwaukee, Milwaukee, WI 53201
2 Department of Physics, Northeastern University, Boston, MA 02115
3 Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210
4 Department of Physics, Ohio State University, Columbus, OH 43210
5 Department of Astronomy, Ohio State University, Columbus, OH 43210

(Dated: November 2012)

Precision data from cosmology (probing the CMB decoupling epoch) and light-element abundances (probing the BBN epoch) have hinted at the presence of extra relativistic degrees of freedom, the so-called “dark radiation.” We present a model independent study to account for the dark radiation by means of the right-handed partners of the three, left-handed, standard model neutrinos. We show that milli-weak interactions of these Dirac states (through their coupling to a TeV-scale $Z'$ gauge boson) may allow the $\nu_R$'s to decouple much earlier, at a higher temperature, than their left-handed counterparts. If the $\nu_R$'s decouple during the quark-hadron crossover transition, they are considerably cooler than the $\nu_L$'s and contribute less than 3 extra “equivalent neutrinos” to the early Universe energy density. For decoupling in this transition region, the $3\nu_R$ generate $\Delta N_{\nu} = 3(T_{\nu_R}/T_{\nu_L})^4 < 3$, extra relativistic degrees of freedom at BBN and at the CMB epochs. Consistency with present constraints on dark radiation permits us to identify the allowed region in the parameter space of $Z'$ masses and couplings. Remarkably, the allowed region is within the range of discovery of LHC14.

Big-bang nucleosynthesis (BBN) is remarkably successful in predicting the relative abundance of light elements as a function of two fundamental parameters: the baryon density of the universe, $\Omega_B h^2$, and the number of “equivalent” light neutrino species, $N_{\nu eff}$. In fact, until recently BBN provided the only constraint on these parameters. Discovery of primordial anisotropies in the cosmic microwave background (CMB) has granted a superior test-bed for precision constraints on fundamental parameters in cosmology. This powerful test-bed can be used to assess whether new physics model predictions are simultaneously consistent with BBN and CMB observations. Of interest here is the capacity to probe right-handed neutrino milli-weak interactions, which are predicted in various extensions of the standard model of particle physics.

In this Letter we construct a model independent template for placing upper and lower bounds on the mass of an extra $Z'$ gauge boson, which allows for milli-weak interactions of the right-handed partner of the Dirac neutrino. A critical input for such an analysis is the relation between the relativistic degrees of freedom and the temperature of the primordial plasma. This relation is complicated because the temperature which is of interest for right-handed neutrino decoupling from the heat bath may lay in the vicinity of the quark-hadron cross-over transition. In a previous publication, use was made of a detailed lattice study to connect the temperature to an effective number of degrees of freedom. Very recently, one of us has provided an analysis in which the decoupling of the extra relativistic degrees of freedom may occur well beyond the cross-over temperature. In that case a general connection between the effective number of degrees of freedom and the right-handed neutrino decoupling temperature is needed. To this end, we employ the results of Ref. [10] to find the $e^+ e^-$ annihilation ratio of the temperatures of the right-handed and left-handed neutrinos, $T_{\nu_R}/T_{\nu_L}$, which is then used to predict the enhancement to the effective number of degrees of freedom in the early Universe, $\Delta N_{\nu} = 3(T_{\nu_R}/T_{\nu_L})^4 < 3$.

The formulation presented here allows for an immediate test for the potential of any model to account for any extra neutrino degrees of freedom. For illustration, we analyze several candidate models. Before proceeding we provide a brief and concise overview of the current observational constraints on the number of light neutrino species.

Over the past few years, the Wilkinson Microwave Anisotropy Probe (WMAP) [11], the Atacama Cosmology Telescope (ACT) [12], and the South Pole Telescope (SPT) [13] have each provided evidence for a “dark” relativistic background (a.k.a. dark radiation). Parameterized in terms of the number of relativistic degrees of freedom the data seem to favor the existence of roughly one extra effective neutrino species. Specifically, the parameter constraint from the combination of WMAP 7-year data, the latest distance measurements from the baryon acoustic oscillations (BAO) in the distribution of galaxies [13], and precise measurements of $H_0$ [15] lead...
related to possible dark matter candidates \[25, 30\]: (ii) models based on active-sterile mixing of neutrinos in a heat bath \[31, 32\]; (iii) models based on milli-weak interactions of right-handed partners of three Dirac neutrinos \[5\]. In this work we confine our discussion to case (iii).

We begin by first establishing, in a model independent manner, the range of decoupling temperatures implied by the BBN or CMB observations. The effective number of neutrino species contributing to r.d.o.f. can be written as \(N_{\text{eff}} = 3[1 + (T_{\nu R}/T_{\nu L})^4]\); therefore, taking into account the isentropic heating of the rest of the plasma between \(T_{\nu R}^{\text{dec}}\) and \(T_{\nu L}^{\text{dec}}\) decoupling temperatures we obtain

\[
\Delta N_{\nu} = 3 \left( \frac{g(T_{\nu R}^{\text{dec}})/g(T_{\nu L}^{\text{dec}})}{4/3} \right),
\]

where \(g(T)\) is the effective number of interacting (thermally coupled) r.d.o.f. at temperature \(T\); for example, \(g(T_{\nu R}^{\text{dec}}) = 43/4\) \[33\]. For the particle content of the standard model, there is a maximum of \(g(T_{\nu R}^{\text{dec}}) = 427/4\) (with \(T_{\nu R}^{\text{dec}} \gg m_{\text{top}}\)), which corresponds to a minimum value of \(\Delta N_{\nu} = 0.14\). For the subsequent study, we adopt the determination of \(g(T)\) given in \[3\] based on the results of \[10\]. Then using Eq. \[2\] we obtain a relation between \(\Delta N_{\nu}\) vs. \(T_{\nu R}^{\text{dec}}\), which is shown in Fig. \[2\]. From this curve we determine the range of decoupling temperature: \(T_{\nu R}^{\text{dec}} = 0.174^{+0.53}_{-0.030}\) GeV.

The physics of interest then will be taking place at energies in the region of the quark-hadron crossover transition, so that we will restrict ourselves to the following fermionic fields, and their contribution to r.d.o.f.: \([3u_R] + [3d_R] + [3s_R] + [3u_L + e_L + \mu_L] + [e_R + \mu_R] + [3u_L + 3d_L + 3s_L] + [3\nu_R]\). This amounts to 28 Weyl fields, translating to 56 fermionic r.d.o.f.\[4\].

The right-handed neutrino decouples from the plasma when its mean free path becomes greater than the Hubble radius at that time. To determine \(T_{\nu R}^{\text{dec}}\), we first calculate the \(\nu_R\) interaction rate

\[
\Gamma(T) = K \frac{1}{8} \left( \frac{g}{M_Z^2} \right)^4 T^5 \sum_{i=1}^{6} N_i ,
\]

where \(N_i\) is the number of chiral states,

\[
g = \left( \frac{\sum_{i=1}^{6} N_i g_i^2}{\sum_{i=1}^{6} N_i} \right)^{1/4}.
\]

\[2\] If relativistic particles are present that have decoupled from the photons, it is necessary to distinguish between two kinds of \(g\): \(g_\nu\) which is associated with the total energy density, and \(g_\rho\) which is associated with the total entropy density. For our calculations we use \(g = g_\nu = g_\rho\).

\[3\] In principle, the contributions to the \(\nu_R\) interaction rate \(\Gamma(T)\) from the \(c\) quark and \(\tau\) lepton should be included for the lowest value of \(\Delta N_{\nu}\), which in this paper corresponds to a decoupling temperature of 1.5 GeV. However, one can easily verify that this inclusion will not be visible in Fig. \[2\].
The latter two are interesting because they provided a test basis for Z' searches at ATLAS [34] and CMS [35]. For each of the $E_6$ models we may write $g_i$ in (3) as $g_i = g_0 Q_I$, where in conformity with grand unification we follow [6] and choose

$$g_0 = \sqrt{\frac{5}{3}} g_2 \tan \theta_W \sim 0.46,$$

with $g_2$ the $SU(2)_L$ coupling. The charges $Q_i$ for the different fermions are conveniently tabulated in [6].

In the D-brane construction, the Weyl fermions live at the brane intersections of a particular 4-stack quiver configuration: $U(3)_C \times SU(2)_L \times U(1)_I \times U(1)_L$ [36]. The resulting $U(1)$ content gauges the baryon number $B$ [with $U(1)_B \subset U(3)_C$], the lepton number $L$, and a third additional abelian charge $I_R$ which acts as the third isospin component of an $SU(2)_R$. Contact with gauge structures at TeV energies is achieved by a field rotation to couple diagonally to hypercharge $Y$. Two of the Euler angles are determined by this rotation and the third one is chosen so that one of the $U(1)$ gauge bosons couples only to an anomaly free linear combination of $I_R$ and $B - L$ [37]. Of the three original abelian couplings, the baryon number coupling is fixed to be $\sqrt{1/6}$ of the QCD coupling at the string scale. The orthogonal nature of the rotation imposes one additional constraint on the remaining couplings [38]. Since one of the two extra gauge bosons is coupled to an anomalous current, its mass is $O(M_z)$, as generated through some St"uckelberg mechanism. The other gauge boson is coupled to an anomaly free current and therefore (under certain topological conditions) it can remain massless and grow a TeV-scale mass through ordinary Higgs mechanisms [39]. We consider two extreme possibilities in which the TeV-scale Z' gauge boson is mostly $I_R$ or mostly $B - L$. The chiral couplings ($g_i$) of these gauge boson are tabulated in [37]. We also consider a D-brane construct with TeV-scale string compactification (the chiral couplings of this model are given in Table IV of [38]). Details of these assignments are given in the figure caption. Termination of the lines on the left reflects the LHC experimental limits on the mass of the gauge boson, using null signals for enhancements in dilepton [34, 35] and dijet [40, 41] searches.

The cosmology results from the Planck satellite would allow determination of $N_{\text{eff}}$ with a standard deviation of about 0.2 [42, 43], whereas the future Large Synoptic Survey Telescope (LSST) could determine $N_{\text{eff}}$ with a standard deviation of about 0.1 [44]. With this enhanced sensitivity the hatched region will collapse to a line and intersect for any given model its horizontal curve at the mass of the Z'.

**Note added:** After this work was finished a paper appeared on the arXiv with a comprehensive study on dark radiation of $E_6$ models [45]. Our results are completely consistent with those of Ref. [45].

\[ \Gamma(T_{\nu R}) = H(T_{\nu R}) \, , \]

where

$$H(T_{\nu R}) = 1.66 \sqrt{g(T_{\nu R})} \frac{(T_{\nu R})^2}{M_{\text{Pl}}} \left( \frac{3}{\Delta N_\nu} \right)^{3/8} \, . \quad (6)$$

Substituting (3) and (6) into (5) we obtain

$$\overline{\bar{g}} = \left( \frac{3}{\Delta N_\nu} \right)^{3/32} \left( \frac{13.28 \sqrt{g(T_{\nu R})}}{M_{\text{Pl}} K (T_{\nu R})^3} \right)^{1/4} \, . \quad (7)$$

For a given value of $\Delta N_\nu$, (7) conveniently yields a straight line plot of $\bar{g}$ vs. $M_{Z'}$. In Fig. 3 we provide graphs corresponding to the central value and $1\sigma$ limits for the values of $\Delta N_\nu$ given in [1]. The hatched region between the highest and lowest lines represents the $\overline{\bar{g}} - M_{Z'}$ parameter space consistent with the $\Delta N_\nu$ measurement.

To illustrate we calculate $\overline{\bar{g}}$ for two candidate models. The first is a set of variations on D-brane constructions which do not have coupling constant unification. The second are two $U(1)$ models ($U(1)_\psi$ and $U(1)_\chi$) which are embedded in a grand unified exceptional $E_6$ group, with breaking pattern

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\psi \times U(1)_\chi \, . \quad (8)$$
FIG. 3. The green cross-hatched areas show the region allowed from decoupling requirements to accommodate BBN and CMB eras. Each of the horizontal lines refers to a particular model: from the top the $E_6 Z'$, a D-brane model in which $Z'$ is mostly $B - L$, a D-brane model in which $Z'$ couples mostly to the third component of a right-handed isospin, a D-brane model with TeV-scale strings, the $E_6 Z_\nu$. Termination of the lines on the left reflects the LHC experimental limits on the mass of the gauge boson. The left and right figures show the condition on decoupling for loss of chemical and thermal equilibrium, respectively.

We thank the Galileo Galilei Institute for Theoretical Physics for the hospitality and the INFN for partial support during the completion of this work. L.A.A. is supported by the U.S. National Science Foundation (NSF) under CAREER Grant PHY-1053663. H.G. is supported by NSF Grant PHY-0757959. G.S. is supported by the Department of Energy (DOE) Grant DE-FG02-91ER40690. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF or DOE.

[1] G. Steigman, D. N. Schramm and J. E. Gunn, Phys. Lett. B 66, 202 (1977).
[2] J. Beringer et al. [Particle Data Group Collaboration], Phys. Rev. D 86, 010001 (2012).
[3] J. R. Ellis, K. Enqvist, D. V. Nanopoulos and S. Sarkar, Phys. Lett. B 167, 457 (1986).
[4] M. C. Gonzalez-Garcia and J. W. F. Valle, Phys. Lett. B 240, 163 (1990).
[5] J. L. Lopez and D. V. Nanopoulos, Phys. Lett. B 241, 392 (1990).
[6] V. Barger, P. Langacker and H. S. Lee, Phys. Rev. D 67, 075009 (2003) [arXiv:hep-ph/0302066].
[7] L. A. Anchordoqui and H. Goldberg, Phys. Rev. Lett. 108, 081805 (2012) [arXiv:1111.7264 [hep-ph]].
[8] G. Steigman, arXiv:1208.0032 [hep-ph].
[9] G. Steigman, B. Dasgupta and J. F. Beacom, Phys. Rev. D 86, 023506 (2012) [arXiv:1204.3622 [hep-ph]].
[10] M. Laine and Y. Schröder, Phys. Rev. D 73, 085009 (2006) [hep-ph/0603048].
[11] E. Komatsu et al. [WMAP Collaboration], Astrophys. J. Suppl. 192, 18 (2011) [arXiv:1001.4538 [astro-ph.CO]].
[12] J. Dunkley et al., Astrophys. J. 739, 52 (2011) [arXiv:1009.0866 [astro-ph.CO]].
[13] R. Keisler et al., Astrophys. J. 743, 28 (2011) [arXiv:1105.3132 [astro-ph.CO]].
[14] W. J. Percival et al. [SDSS Collaboration], Mon. Not. Roy. Astron. Soc. 401, 2148 (2010) [arXiv:0907.1660 [astro-ph.CO]].
[15] A. G. Riess, L. Macri, S. Casertano, M. Sosey, H. Lampeitl, H. C. Ferguson, A. V. Filippenko and S. W. Jha et al., Astrophys. J. 699, 539 (2009) [arXiv:0905.0695 [astro-ph.CO]].
[16] V. Simha and G. Steigman, JCAP 0806, 016 (2008) [arXiv:0803.3465 [astro-ph]].
[17] Y. I. Izotov and T. X. Thuan, Astrophys. J. 710, L67 (2010) [arXiv:1001.4440 [astro-ph.CO]].
[18] E. Aver, K. A. Olive and E. D. Skillman, JCAP 1005, 003 (2010) [arXiv:1001.3218 [astro-ph.CO]].
[19] Z. Hou, R. Keisler, L. Knox, M. Millea and C. Reichardt, arXiv:1104.2333 [astro-ph.CO].
[20] M. Archidiacono, E. Calabrese and A. Melchiorri, Phys. Rev. D 84, 123008 (2011) [arXiv:1109.2767 [astro-ph.CO]].
[21] J. Hamann, JCAP 1203, 021 (2012) [arXiv:1110.4271 [astro-ph.CO]].
[22] K. M. Nollett and G. P. Holder, arXiv:1112.2683 [astro-ph.CO].
[23] M. Moresco, L. Verde, L. Pozzetti, R. Jimenez and A. Cimatti, JCAP 1207, 053 (2012) [arXiv:1201.6658].
[astro-ph.CO]].

[24] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti and P. D. Serpico, Nucl. Phys. B 729, 221 (2005) hep-ph/0506164.

[25] K. Ichikawa, M. Kawasaki, K. Nakayama, M. Senami and F. Takahashi, JCAP 0705, 008 (2007) hep-ph/0703034 [HEP-PH]].

[26] J. Hasenkamp, Phys. Lett. B 707, 121 (2012) arXiv:1107.4319 [hep-ph].

[27] J. L. Menestrina and R. J. Scherrer, Phys. Rev. D 85, 047301 (2012) arXiv:1111.0605 [astro-ph.CO]].

[28] J. L. Feng, V. Rentala and Z. e. Surujon, Phys. Rev. D 85, 055003 (2012) arXiv:1111.4479 [hep-ph].

[29] D. Hooper, F. S. Queiroz and N. Y. Gnedin, Phys. Rev. D 85, 063513 (2012) arXiv:1111.6599 [astro-ph.CO]].

[30] O. E. Bjaelde, S. Das and A. Moss, JCAP 1210, 017 (2012) arXiv:1205.0553 [astro-ph.CO]].

[31] J. Hamann, S. Hannestad, G. G. Raffelt, I. Tamborra and Y. Y. Wong, Phys. Rev. Lett. 105, 181301 (2010) arXiv:1006.5276 [hep-ph].

[32] L. M. Krauss, C. Lunardini and C. Smith, arXiv:1009.4666 [hep-ph].

[33] E. W. Kolb and M. S. Turner, Front. Phys. 69, 1 (1990).

[34] G. Aad et al. [ATLAS Collaboration], arXiv:1209.2535 [hep-ex].

[35] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 714, 158 (2012) arXiv:1208.1849 [hep-ex]].

[36] D. Cremades, L. E. Ibanez and F. Marchesano, JHEP 0307, 038 (2003) hep-th/0308210]

[37] L. A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lust, T. R. Taylor and B. Vlcek, Phys. Rev. D 86, 066004 (2012) arXiv:1206.2537 [hep-ph]].

[38] L. A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lust and T. R. Taylor, Phys. Rev. D 85, 086003 (2012) arXiv:1107.4309 [hep-ph]].

[39] M. Cvetic, J. Halverson and P. Langacker, JHEP 1111, 058 (2011) arXiv:1110.5187 [hep-ph]].

[40] G. Aad et al. [ATLAS Collaboration], arXiv:1210.1718 [hep-ex].

[41] S. Chatrchyan et al [CMS Collaboration], arXiv:1210.2387 [hep-ex].

[42] J. Hamann, J. Lesgourgues and G. Mangano, JCAP 0803, 004 (2008) arXiv:0712.2826 [astro-ph]].

[43] S. Galli, M. Martinelli, A. Melchiorri, L. Pagano, B. D. Sherwin and D. N. Spergel, Phys. Rev. D 82, 123504 (2010) arXiv:1005.3808 [astro-ph.CO]].

[44] S. Joudaki and M. Kaplinghat, Phys. Rev. D 86, 023526 (2012) arXiv:1106.0299 [astro-ph.CO]].

[45] A. Solaguren-Beascoa and M. C. Gonzalez-Garcia, arXiv:1210.6350 [hep-ph].