Scenario of light sterile neutrinos with a heavy tau neutrino in a supersymmetric model post-print

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Abstract

Three light sterile neutrinos (#23;se , #23;s and #23;s) are introduced to accommodate all the available neutrino data: the atmospheric neutrino anomaly is explained by #23; − #23;s oscillation with maximal mixing; the solar one is due to #23;e − #23;se oscillation of small angle Mikheyev-Smirnov-Wolfenstein type; the Liquid Scintillation Neutrino Detector data is from #23;e − #23; oscillations, so that the neutrinos can be the hot component of the dark matter. The big bang nucleosynthesis constraint is satisfied by taking the tau neutrino to be 10 MeV heavy. The #23;#28; decay is discussed in a model of gauge mediated supersymmetry breaking. The decay mode #23;#28; → ˜G with ˜G being the gravitino is proposed. The #23;#28; has a rather long lifetime 103 − 1013 sec. Its implication to the Gamma-ray Burst is discussed.

Full Text

Preamble

Scenario of Light Sterile Neutrinos with a Heavy Tau Neutrino in a Supersymmetric Model

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Abstract

Three light sterile neutrinos (se, s , and s) are introduced to accommodate all available neutrino data. The atmospheric neutrino anomaly is explained by – s oscillation with maximal mixing; the solar neutrino problem is resolved through e- se oscillation of the small-angle Mikheyev-Smirnov-Wolfenstein type; and the LSND data arise from e- oscillations. Consequently, neutrinos can constitute the hot component of dark matter. The big bang nucleosynthesis constraint is satisfied by taking the tau neutrino to be 10 MeV heavy. The decay is discussed in a model of gauge-mediated supersymmetry breaking. The decay mode → ˜G with ˜G being the gravitino is proposed. The has a rather long lifetime of 1013 sec, and its implication for gamma-ray bursts is discussed.

I. Introduction

Various experiments have provided growing evidence that neutrinos are massive. The recent Super-Kamiokande data on atmospheric neutrinos have demonstrated neutrino oscillations [?], implying that the muon-type neutrino has maximal mixing with another neutrino x (x e), with mass-squared difference Δm2 10−3 eV2. The solar neutrino deficit can be explained by either the Mikheyev-Smirnov-Wolfenstein (MSW) solution [?] or vacuum oscillation [?]. The MSW solution allows two parameter sets: Δm2 10−5 eV2 with sin22 ey 10−2-10−3, and Δm2 10−7 eV2 with sin22 ey 1. The vacuum oscillation solution gives Δm2 10−10 eV2 with sin22 ey 0.8. When the direct observation of ¯e → ¯ oscillations at the Liquid Scintillation Neutrino Detector (LSND) experiment [?] is considered, the relevant parameters are Δm2 1 eV2 and sin2(2 e) 0.8-1.0.

In addition, astrophysics and cosmology provide constraints on neutrino masses. Various measurements support the existence of dark matter, with one scenario suggesting that not all cosmological dark matter is cold—some hot component exists [?]. The canonical candidate for hot dark matter (HDM) is a neutrino with mass at the electron-volt scale [?]. If massive neutrinos are stable, their masses must be less than a few tens of eV to avoid over-closure of the Universe [?].

Non-vanishing neutrino mass might be the first discovery of physics beyond the Standard Model (SM). The neutrino mass pattern provides valuable information for exploring flavor physics in the SM. Several theoretical mechanisms have been suggested to accommodate massive neutrinos. The most popular is the seesaw mechanism, which naturally explains the smallness of neutrino mass by introducing heavy right-handed neutrinos [?]. Another example is the supersymmetric extension of the SM with R-parity violation, where trilinear lepton-number-violating interactions induce small neutrino masses at loop level [?]. However, large neutrino mixing is not expected from our experience with other SM fermions.

Phenomenological analyses suggest the existence of light sterile neutrinos. At least one light sterile neutrino is necessary to explain all three different scales of Δm2 [?]. It is more natural to have three light sterile neutrinos si (i = e, ,). Then the first two generations can fully explain all neutrino data. In this framework, the neutrino mixing pattern is uniquely fixed: the atmospheric and solar neutrino anomalies arise from - s and e- se oscillations, respectively. The large mixing between and s can be understood naturally, and the LSND evidence is attributed to e- mixing. At least one neutrino pair should have mass around a few eV, implying neutrinos can be the hot component of dark matter. This scenario was studied previously [?, ?], but we reconsider it in a different theoretical background.

In this scheme, the third-generation neutrinos have a separate story. The requirements for the first two generations leave a wider room for . The can be either ordinary with mass smaller than 10 eV, or exotic—for instance, with m 10 MeV [?]. Tau-neutrino physics is influenced by the astrophysical constraint from big bang nucleosynthesis (BBN): the number of light neutrino species in thermal equilibrium during the BBN era is limited to N 4.2 [?]. This must be seriously examined in scenarios with more than four light neutrinos. Note that the small mixing angle for e- se oscillations causes only active neutrinos to contribute at the BBN era [?], as the oscillation time is too long for se to reach thermal equilibrium. Analyses of solar neutrino data have shown that the only viable pattern is the small-angle MSW type [?]. Therefore, the first two generations contribute a factor of three to N . As for and s , at least one must decouple at BBN. If is light (m 10 eV), the sterile tau neutrinos must decouple from the primordial plasma, equivalent to introducing just two sterile neutrinos [?]. Alternatively, we may consider m 10 MeV so that decouples [?]. We are interested in this latter situation, which has alternative theoretical motivation [?] and makes the two-generation oscillation scenario more economical.

Constructing a spectrum of very light sterile neutrinos is theoretically challenging. Several ideas have been suggested, related to extra symmetry [?], mirror world [?], axino [?], modulino [?], gravitino [?], string theory [?], gauge-mediated supersymmetry breaking (GMSB) [?], U(2) symmetry [?], seesaw mechanism [?], compositeness [?], top-flavor model [?], and extra dimensions [?].

This paper is organized as follows. In the next section, we present a mass matrix consistent with all available neutrino data and discuss the naturalness of our assumptions. In Section III, we study tau neutrino decay in a supersymmetric model and propose the decay mode → ˜G . Further discussions, including implications for gamma-ray bursts (GRB), are made in Section IV. The summary is given in the final section.

II. Neutrino Mass Matrix

We assume three light sterile neutrinos, one associated with each fermion generation. As will be seen, the atmospheric and LSND data are naturally accommodated, and the tau neutrino can be as heavy as 10 MeV without contradicting experiments. The full 6 × 6 neutrino mass matrix consists of three parts: the 3 × 3 active Majorana neutrino mass matrix Mactive, the 3 × 3 Dirac mass matrix MDirac representing mixing between active and sterile neutrinos, and the 3 × 3 Majorana mass matrix of sterile neutrinos Msterile:

$$\begin{pmatrix} M_{\text{active}} & M_{\text{Dirac}} \\ M_{\text{Dirac}}^T & M_{\text{sterile}} \end{pmatrix}$$

For Mactive, we assume that except for the component, it originates from the ordinary seesaw mechanism [?], while the component is about (1-10) MeV. The ordinary seesaw mechanism suppresses neutrino masses to v2/MGUT, where v is the electroweak scale and MGUT is the grand unification scale, giving v2/MGUT 10−3 eV. This is natural because there is evidence that new physics beyond the SM is GUT-scale physics [?]. The introduction of sterile neutrinos does not affect gauge coupling unification. Furthermore, as seen below, this 10−3 eV mass fits the atmospheric neutrino data. Thus, the neutrino mass itself provides indirect evidence for GUT. Note that even without heavy right-handed neutrinos, the seesaw mechanism still works in GUT scenarios from general effective field theory arguments. The MeV tau-neutrino has been discussed in Ref. [?]; we introduce it here to avoid the BBN constraint and make the two-generation oscillation scenario more economical.

For MDirac, we adopt proportionality to up-type quark masses. This similarity is understandable from a GUT perspective if sterile neutrinos are regarded as right-handed neutrinos. Remarkably, this simple proportionality is compatible with all current neutrino data. In this quark mass matrix, the up quark is taken to be 10−4mc. The up quark mass has not been determined experimentally; even a massless up quark is allowed [?, ?].

For Msterile, we simply assume it is approximately vanishing. This assumption highlights the lightness of sterile neutrinos, though it could be relaxed to the extent that Msterile plays no other role in understanding neutrino experiments.

Since the main understanding of neutrinos does not involve intergenerational flavor mixing, we further assume without loss of generality that all these mass matrices are diagonal. We remark that other zero entries of the Majorana mass matrices should be regarded as 10−5 eV in general, which is inevitable from quantum gravity considerations [?]. However, such a scale is not essential for understanding neutrinos in this framework.

Therefore, the neutrino mass matrix takes the following form:

$$\begin{pmatrix} \frac{v^2}{M_{\text{GUT}}} & 0 & 0 & \lambda m_u & 0 & 0 \\ 0 & \frac{v^2}{M_{\text{GUT}}} & 0 & 0 & \lambda m_c & 0 \\ 0 & 0 & 10\,\text{MeV} & 0 & 0 & \lambda m_t \\ \lambda m_u & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda m_c & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda m_t & 0 & 0 & 0 \end{pmatrix}$$

where is a constant.

Numerical analysis begins here. As mentioned, v2/MGUT is taken to be 10−3 eV. We take mc 1 eV. It is easy to see that and s have almost maximal mixing with Δm2 10−3 eV2, explaining the atmospheric neutrino data. The mixing between e and se is very small: sin22 (10−4/3 × 10−3)2 10−5 with Δm2 10−5 eV2. This is the small-angle MSW solution for the solar neutrino data. The Dirac mass of the tau neutrino is 100 eV, leading to no observable consequences for sterile tau neutrinos because the Majorana mass of is about 10 MeV, making the - s mixing O(10−5). As discussed, this small mixing precludes sterile tau neutrinos from contributing during the BBN era. The LSND data for e- oscillations is accounted for by Δm2 1 eV2. Intergenerational mixings are determined by the neutrino mass matrix and the charged lepton mass matrix, which is too complicated to fix in this framework. Since the Dirac mass of the electron neutrino is negligible, the e- mixing depends only on Mactive and the charged lepton mass matrix. When Mactive is diagonal in a certain weak basis, we expect the charged lepton mass matrix to fix the e- mixing as me/m 10−3, consistent with data. The and s have masses around 1 eV, allowing them to be HDM. The cannot be stable due to cosmological considerations.

III. The Decay of

In the previous section, we discussed the phenomenology of three light sterile neutrinos, necessarily assuming a heavy Majorana tau neutrino. To study the 10 MeV tau neutrino and its decay, a specific theoretical model is required. First, may decay via ordinary weak interactions into e+e− e through W-boson exchange. Its lifetime is:

$$\tau_{\nu_\tau} \simeq \frac{192\pi^3}{G_F^2 |V_{e\tau}|^2 m_{\nu_\tau}^5} \simeq 10^2 \left(\frac{10\,\mathrm{MeV}}{m_{\nu_\tau}}\right)^5 \left(\frac{10^{-4}}{|V_{e\tau}|}\right)^2 \mathrm{s}.$$

Since the neutrino mass matrix leads to very small mixing, only the charged lepton mass matrix determines Ve . It is generally expected that |Ve | me/m 10−4, giving 103 sec. However, this decay mode is disfavored by observations of Supernova 1987A [**?**]. Even if marginally viable with smaller Ve , alternative decay channels merit consideration.

There is an alternative decay channel independent of e- mixing: → ˜G . In Ref. [**?**], a supersymmetric model for charged lepton masses is suggested where, due to family symmetries, the lepton acquires mass from the non-vanishing vacuum expectation value (VEV) of a Higgs field, while the muon gets mass only from the sneutrino VEV that violates family symmetries. Lepton number violation is allowed, and the sneutrino VEV generating a 10 MeV tau-neutrino mass is as large as (5-10) GeV, resulting in mixing between ordinary neutralinos and [**?**]. This model adopts the GMSB framework [**?**]. The is in fact the lightest neutralino (except for the gravitino), and the is the lightest chargino. Therefore, can decay to ˜G , where the gravitino has mass of a few eV. From the neutralino mass matrix in Ref. [?], mixes with Bino at the level of m H/M˜ 10−3, where m H is the mixing mass between the neutrino and neutralinos.

In ordinary GMSB models [?], the next-to-lightest neutralino (photino ˜) decays to ˜G and . The relevant matrix element can be written using current algebra as:

$$\langle \tilde{G}\gamma|\nu_\tau\rangle = \frac{1}{F}\langle 0|\partial_\mu \tilde{j}^\mu|\tilde{G}\gamma\rangle,$$

where the supersymmetry current is ˜j = F ˜G + ˜ F + ···with √F being the supersymmetry breaking scale (100 TeV). From this, the matrix element is easily evaluated. Considering the suppression factor (m H/M˜)2, the → ˜G decay rate is:

$$\Gamma(\nu_\tau \to \tilde{G}\gamma) = \left(\frac{m_{\tau H}}{M_{\tilde{\gamma}}}\right)^2 \frac{\cos^2\theta_W m_{\nu_\tau}^5}{16\pi F^2}.$$

This corresponds to a lifetime of 1013 sec if we switch off Ve . Though very long compared to the BBN epoch, this is still short compared to the age of the Universe.

The BBN constraint on light neutrino species counts e, , and se, . A lifetime of 103 sec occurs at the finishing stage of BBN, so such tau neutrinos may be considered unstable during BBN. With e as the decay product, this might help understand Deuterium production and structure formation in cosmology [?]. However, it is more appropriate to consider with lifetime 1013 sec as stable during BBN [?]. In this case, decouples during BBN and must be Majorana, as we have assumed [?, ?].

IV. Discussions

Several aspects of our neutrino scenario require discussion. The essential new ingredients are the 10 MeV Majorana tau neutrinos and three light sterile neutrinos. While we have discussed a theoretical model for the 10 MeV and its decay, the lightness of sterile neutrinos lacks theoretical discussion. To our knowledge, for more than one light sterile neutrino, two attractive frameworks exist: the compositeness idea [?] and the mirror world [?]. Both warrant further study; we introduce them phenomenologically here.

While R-parity-violating supersymmetry generates the MeV mass for , one might expect trilinear R-parity-violating interactions to contribute to other entries of Mactive. However, this contribution is rather small, arising at one-loop level involving the A-term of the relevant trilinear R-parity-violating interaction.

In GMSB, A-terms are very small, making the contribution generally smaller than 10−3 eV.

Experimentally, our scenario can be tested in the near future. First, the current laboratory mass limit for is 18.2 MeV [?], which can be improved to a few MeV—posing a serious challenge to this scenario. Second, future neutrino experiments will determine whether the atmospheric neutrino deficit is due to – or - s oscillation. Although present data favor – [?], - s cannot be ruled out by global fits [?]. Recent Super-Kamiokande results claim → oscillation is favored at 99% C.L. [?], though more data and analyses are needed before concluding [?]. Long-baseline experiments [?] will check the oscillation channel. Meanwhile, the solar neutrino oscillation channel may be identified by new SNO observations [?] combined with previous experiments. Third, the short-baseline experiment BooNE will confirm whether the LSND anomaly is real. Though KARMEN [?] has excluded much of LSND' s favored parameter region, full confirmation awaits future experiments. Some LSND solution space is preserved by combined statistical analysis of LSND evidence and KARMEN exclusion [?].

Cosmological and astrophysical aspects deserve further study. Implications for BBN and HDM were discussed previously. For the decay mode → ˜G , it might partially explain GRBs [?]. In stellar collapse, huge numbers of tau neutrinos are emitted. The decay product has energy of a few MeV or 100 keV—the typical GRB energy scale. If lifetime is 1013 sec (and Ve negligible), 10 MeV from Supernova 1987A did not have time to decay before reaching Earth [?]. However, when supernovae occur at cosmological distances (1027 cm), the GRB will be detected. The (1-10) MeV may help our understanding of cold dark matter (CDM) [?]. As for sterile neutrinos, assuming s has Majorana mass of thousands of electron volts makes it a candidate for warm dark matter (WDM) [?].

On the other hand, if purely decays to ˜G with lifetime 1013 sec, excessive cosmic background radiation and matter density are produced [?]. To reduce background radiation, one might prolong lifetime from 1013 sec to 1021 sec by adjusting the supersymmetry breaking scale (and other parameters) up to 104 TeV (in which case the gravitino mass rises from a few eV to 100 keV). To avoid the matter density problem, non-standard cosmology may be needed. For example, a recent study [?] showed that if the maximum temperature of the radiation era is as low as 0.7 MeV, even a stable 10 MeV tau neutrino is consistent with cosmology.

Within GMSB, sterile neutrino superpartners can be very light because they lack gauge interactions. However, their mixings with ordinary sneutrinos (typically 100 GeV-1 TeV heavy) are very small, so their lightness does not influence BBN physics. Meanwhile, these light scalar particles could also be CDM candidates [?].

Compared to previous MeV tau neutrino studies, our scenario' s distinguishing feature is that the (1-10) MeV tau neutrino is a Majorana particle whose decay products do not contain a Majoron. Unlike pseudo-Dirac neutrino scenarios [?], our explanation of the solar neutrino deficit uses the small-angle MSW solution. Previous motivation was mainly to reduce the number of neutrino species during BBN below 3; our present motivation is to keep that number exactly at 3.

V. Summary

Before summarizing the main points, we list the dark matter candidates in this model. Besides and s as HDM, there are many CDM and WDM candidates: (1-10) MeV ' s, keV-massive s ' s, light sterile sneutrinos ˜ si, and gravitinos. However, these are just possibilities. The lifetime is not yet fixed, ranging from 103–1013 sec (or longer), and the heaviness of si is merely assumed, requiring theoretical study of the lightness mechanism for sterile neutrinos. Note that by taking the supersymmetry breaking scale as √F 100 TeV, the gravitino is not dark matter in simple GMSB models. However, raising √F, the keV ˜G can be WDM (regardless of R-parity violation). Additionally, in GMSB scenarios, the lightest stable baryons with mass 100 TeV in the hidden sector are also CDM candidates [?]. Among these five possibilities, the long-lived decaying —specific to this model—is reasonably favored as the CDM. For stable , the matter density was discussed in Ref. [?]; the same discussion applies to very long-lived . The requirement Ω h2 < 1 implies m > 3 MeV for reheating temperature 0.7 MeV.

In summary, we have introduced three light sterile neutrinos se, s , s to accommodate all available neutrino data. The atmospheric neutrino anomaly is explained by - s oscillation with maximal mixing, and the solar neutrino problem by e- se oscillation of small-angle MSW type. The LSND data of e- oscillations with Δm2 1 eV2 can be accommodated, providing a canonical HDM candidate. The BBN constraint is satisfied by taking the tau neutrino to be 10 MeV heavy. We have discussed decay in a GMSB model and proposed the decay mode → ˜G , pointing out its implication for GRBs. Although current data do not favor this oscillation scenario, it will be conclusively tested by atmospheric, long-baseline, and solar neutrino experiments in the near future.

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References

[1] Y. Fukuda et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. 81 (1998) 1562.

[2] S. P. Mikheyev and A. Yu Smirnov, Sov. J. Nucl. Phys. 42 (1985) 913; L. Wolfenstein, Phys. Rev. D 17 (1978) 2369.

[3] For an example, see V. Barger, R. J. N. Phillips and K. Whisnant, Phys. Rev. Lett. 69 (1992) 3135.

[4] For a recent review, see M. C. Gonzales-Garcia and C. Peña-Garay, hep-ph/0009041.

[5] C. Athanassopoulos et al. (LSND Collaboration), Phys. Rev. Lett. 75 (1995) 2650.

[6] J. R. Primack, J. Holtzman, A. Klypin, and D. O. Caldwell, Phy. Rev. Lett. 74 (1995) 2160; For a review, see J. R. Primack and M. A. K. Gross, astro-ph/0007165.

[7] For a review, see E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley, Reading, 1990).

[8] M. Gell-Mann, P. Ramond and R. Slansky, in Sanibel talk, CALT-68-709 (Feb. 1979), and in *Supergravity* (North Holland, Amsterdam, 1979); T. Yanagida, in Proc. of the Workshop on Unified Theory and Baryon Number of the Universe (KEK, Tsukuba, 1979); R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980) 912.

[9] C. Aulakh and R. Mohapatra, Phys. Lett. B 119 (1982) 136; S. Dimpoulos and L. Hall, Phys. Lett B 207 (1988) 210; C. Liu, Mod. Phys. Lett. A 12 (1997) 329; M. Drees, S. Pakvasa, X. Tata and T. Veldhuis, Phys. Rev. D 57 (1998) R5335; E. J. Chun, S. K. Kang, C. W. Kim and U. W. Lee, Nucl. Phys. B544 (1999) 89; G. Bhattacharyya, H. V. Klapdor-Kleingrothaus and H. Päs, Phys. Lett. B 463 (1999) 77; M. Bisset et al., Phys. Rev. D 62 (2000) 035001; A. Abada and G. Bhattacharyya, Phys. Rev. D 63 (2001).

[10] D. O. Caldwell and R. N. Mohapatra, Phys. Rev. D 48 (1993) 3269; J. T. Peltoniemi and J. W. F. Valle, Nucl. Phys. B 406 (1993) 409; J. J. Gomez-Cadenas and M. C. Gonzales-Garcia, Z. Phys. C 71 (1996) 443; N. Okada and O. Yasuda, Int. J. Mod. Phys. A 12 (1997) 3669; S. M. Bilenky, C. Giunti and W. Grimus, Eur. Phys. J. C 1 (1998) 247; Q. Y. Liu and A. Yu Smirnov, Nucl Phys. B 524 (1998) 505; V. Barger, S. Pakvasa, T. J. Weiler and K. Whisnant, Phys. Rev. D 58 (1998) 093016; E. J. Chun, C. W. Kim and U. W. Lee, Phys. Rev. D 58 (1998) 093003; Y. Chikira, N. Haba and Y. Mimura, hep-ph/9808254; Q. Shafi and Z. Tavartkiladze, Phys. Lett. B 448 (1999) 46; V. Barger, Y.-B. Dai, K. Whisnant and B.-L. Young, Phys. Rev. D 59 (1999) 113010; C. Liu and J. Song, Phys. Rev. D 60 (1999) 036002.

[11] N. Okada, Phys. Lett. B 388 (1996) 106; D. Ring, Phys. Rev. D 55 (1997) 5767; X.-M. Zhang, talk at the Annual Meeting of High Energy Physics of China (Chengdu, 1999).

[12] M. Kobayashi, C. S. Lim and M. M. Nojiri, Phys. Rev. Lett. 67 (1991) 1685; C. Giunti, C. W. Kim, and U. W. Lee, Phys. Rev. D 46 (1992) 3034; A. Geiser, Phys. Lett. B 444 (1998) 358; D. Chang and O. C. W. Kong, Phys.

Lett. B 477 (2000) 416.
[13] For a review, see K. A. Olive, astro-ph/9901231, Lectures at the Advanced School on Cosmology and Particle Physics (Peniscola, June 1998).
[14] R. Barbieri and A. Doldov, Nucl. Phys. B 429 (1991) 743.
[15] For recent analyses, see J. N. Bahcall, P. I. Krastev and A. Yu Smirnov, Phys. Rev. D 58 (1998) 096016; M. C. Gonzales-Garcia, P. C. de Holanda, C. Peña-Garay and J. W. F. Valle, Nucl. Phys. B 573 (2000) 3.
[16] W. Królikowski, Acta Phys. Polon. B 30 (1999) 227; D. Suematsu, Int. J. Mod. Phys. A 15 (2000) 3967.
[17] C. Liu and H. S. Song, Nucl. Phys. B 545 (1999) 183.
[18] E. Ma and P. Roy, Phys. Rev. D 52 (1995) R4780.
[19] R. Foot and R. R. Volkas, Phys. Rev. D 52 (1995) 6595; Z. G. Berezhiani and R. N. Mohapatra, Phys. Rev. D 52 (1995) 6607.
[20] E. J. Chun, A. S. Joshipura and A. Yu. Smirnov, Phys. Rev. D 54 (1996) 4654; E. J. Chun, Phys. Lett. B 454 (1999) 304.
[21] K. Benakli and A. Yu Smirnov, Phys. Rev. Lett. 79 (1997) 4314.
[22] T. Lee, hep-ph/9902396.
[23] P. Langacker and J. Wang, Phys. Rev. D 58 (1998) 115010.
[24] G. Dvali and Y. Nir, JHEP 10 (1998) 014.
[25] L. J. Hall and N. Weiner, Phys. Rev. D 60 (1999) 033005.
[26] B. Brahmachari, Phys. Lett. B 461 (1999) 243.
[27] N. Arkani-Hamed and Y. Grossman, Phys. Lett. B 459 (1999) 179.
[28] E. Malkawi, E. I. Lashin and H. Widyan, Phys. Rev. D 62 (2000) 033005.
[29] R. N. Mohapatra and A. Perez-Lorenzana, Nucl. Phys. B 576 (2000) 466; Y. Grossman and M. Neubert, Phys. Lett. B 474 (2000) 361 and references therein.
[30] P. Langacker and M.-X. Luo, Phys. Rev. D 44 (1991) 817; C. Giunti, C. W. Kim and U. W. Lee, Mod. Phys. Lett. A 6 (1991) 1745; U. Amaldi, W. de Boer and H. Furstenau, Phys. Lett. B 260 (1991) 447; J. Ellis, S. Kelly and D. Nanopolous, Phys. Lett. B 260 (1991) 131.
[31] H. Georgi and I. N. McArthur, HUTP-81/A011 (1981); K. Choi, C. W. Kim and W. K. Sze, Phys. Rev. Lett. 61 (1988) 794.
[32] C. Liu, Int. J. Mod. Phys. A 11 (1996) 4307; Liu and Song, in [?]; J. E. Kim, B. Kyae and J. S. Lee, Phys. Lett. B 477 (1999) 110.
[33] E. Kh. Akhmedov, Z. G. Berezhiani, G. Senjanovic and Z.-J. Tao, Phys. Rev. D 47 (1993) 3245; For reviews, see E. Kh. Akhmedov, hep-ph/0001264, Lectures at Trieste Summer School in Particle Physics (June, 1999); E. Witten, hep-ph/0006332.
[34] A. Dar and S. Dado, Phys. Rev. Lett. 59 (1987) 2368; R. N. Mohapatra, S. Nussinov and X. Zhang, Phys. Rev. D 49 (1994) 3434.
[35] D. Du and C. Liu, Mod. Phys. Lett. A 8 (1993) 2271; A 10 (1995) 1837.
[36] For reviews, see G. F. Giudice and R. Rattazzi, Phys. Rep. 322 (1999) 419; S. L. Dubovsky, D. S. Gorbunov and S.V. Troitsky, hep-ph/9905466.
[37] For a review, see G. Gyuk and M. S. Turner, Nucl. Phys. B (Proc. Suppl.) 38 (1995) 13; For recent studies, see A. D. Dolgov, S. H. Hansen, S. Pastor and D. V. Semikoz, Nucl. Phys. B 548 (1999) 385; M. Kawasaki, K. Kohri and K.

Sato, Phys. Lett. B 430 (1998) 132.
[38] For a review, see G. G. Raffelt, Nucl. Phys. B (Proc. Suppl.) 70 (1999) 169; For a recent study, see J. B. Rehm, G. G. Raffelt and A. Weiss, Astron. Astrophys. 327 (1997) 443 and references therein.
[39] D. E. Groom et al. (Particle Data Group), Eur. Phys. J. C 15 (2000) 1.
[40] For a recent analysis, see N. Fornengo, M. C. Gonzales-Garcia and J. W. F. Valle, Nucl. Phys. B 580 (2000) 58.
[41] S. Fukuda et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. 85 (2000) 3999.
[42] R. Foot, hep-ph/0007065; M. C. Gonzales-Garcia, talk at ICHEP 2000 (Osaka, August, 2000).
[43] C. Yanagisawa (KEK-SK Collaboration), Proc. Int. Workshop on Phys. beyond the Standard Model: from Theory to Experiment (Valencia, 1997), eds. I. Antoniadis, L. Ibanez and J. W. F. Valle (World Scientific, 1998); D. Michael et al. (MINOS Collaboration), Proc. XVI Int. Workshop on Weak Interactions and Neutrinos (Capri, 1997), eds. G. Fiorilo et al. [Nucl. Phys. B (Proc. Suppl.) 66 (1998) 432]; T.-H. Ho, talk at the ITP Academic Meeting (Beijing, 2000).
[44] SNO Collaboration, Phys. Lett. B 194 (1987) 321; S. M. Bilenky and C. Giunti, Phys. Lett. B 320 (1994) 323.
[45] B. Zeitnits, talk at Neutrino ’ 98 (Takayama, June 1998).
[46] K. Eitel, New Jour. Phys. 2 (2000) 1.
[47] For reviews, see S. Blinnikov, astro-ph/9911138; T. Lu, astro-ph/0002178.
[48] A. H. Jaffe and M. S. Turner, Phys. Rev. D 55 (1997) 7951.
[49] S. Dodelson, G. Gyuk and M. S. Turner, Phys. Rev. Lett. 72 (1994) 3754.
[50] M. Patel and G. M. Fuller, hep-ph/0003034.
[51] G. F. Giudice, E. W. Kolb and A. Riotto, hep-ph/0005123.
[52] I. I. Tkachev, Sov. Astron. Lett. 12 (1986) 315.

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