Bulg. J. Phys. **38** (2011) 242–251

From Mateev's Baryogenesis Ideas to Contemporary Cosmological Constraints*

D. Kirilova[1]

[1]Institute of Astronomy and NAO, Bulg. Acad. Sci., Sofia 1784, Bulgaria

Received *20 July 2011*

Abstract. Mateev's ideas on baryogenesis and the possibility to constrain new physics on the basis of cosmological observations present the first impulse for the development of the physical cosmology and astroparticle physics in Bulgaria. Contemporary cosmological models of baryogenesis, leptogenesis, primordial nucleosynthesis and cosmological constraints on new physics are discussed.

PACS codes: 98.80.Cq, 98.80.Ft, 26.35.+c, 14.60.St

1 Introduction – Mateev's Baryogenesis Idea

Cosmology in the 80s was not the precision science it is now. Its observational milestones were almost the same like today's: BBN abundances, Hubble expansion, CMB, LSS, only the CMB anisotropy was not yet measured and SNIa observations at big redshift z were not yet available, so we did not know about the accelerated expansion of the universe during the last 5 billions years. However, the accuracy of the cosmological measurements was poor compared to todays 5% precision. For example the expansion rate H was known to be between 40 and 100 (km/s)/Mpc, the baryon number was found to be

$$\beta = (n_b - n_{\bar{b}})/n_\gamma \sim 10^{-10} - 10^{-8},$$

where n_b, $n_{\bar{b}}$ and n_γ are the number densities of baryons, antibaryons and of photons, correspondingly.

Saharov's baryogenesis conditions: B violation, CP violation and the necessity of nonequilibrium, were known. However, it was already realized that CP violation in the minimal SU(5) was not enough to generate the observed baryon asymmetry.

*This work is dedicated to my teacher Professor Matey Mateev.

Mateev's baryogenesis idea was to use the CP violation of the extended quantum field KM model (Kadyshevski and Mateev) [1] and define the fundamental length in this model to get the appropriate baryon asymmetry value. As Mateev's student I had to do the calculations of the baryon asymmetry generated in this model and provide the constraints on the fundamental length of KM model for my M.S. thesis. The results of our work appeared also in the paper "Baryon-Antibaryon Asymmetry of the Universe and the Fundamental Length" [2]. This was the first work on physical cosmology and astroparticle physics in Bulgaria. *Matey Mateev was an open-minded scientist* , who at the time when cosmology was not really accepted as a serious science in Bulgaria, and also in most of the Eastern European countries, dared to work on cosmological topic. Besides, *Matey Mateev was a scientist with a wide scientific interests and knowledge*: QFT being his background he worked on topics of cosmology, astroparticle physics and in the 90s on astrophysics also.

Cosmology now is a precision science, both primordial abundances and CMB characteristics have been measured to a high precision, and the contemporary telescopes have reached the observable horizons of the universe, looking at the epochs 13 billion years back in time (apart from us).

2 Universe Baryon Asymmetry and Baryogenesis

Contemporary baryon density β is measured by different independent means, the most precise among them being BBN and CMB.

2.1 Cosmological baryometers of different epochs

BBN baryometer: BBN is the most early and precision probe for physical conditions in the Universe, and in particular of its baryon density [12]. Four light elements: D, ^{3}He, ^{4}He, ^{7}Li were produced during the early hot stage of the Universe evolution. In the standard BBN their primordial abundances are functions of only one parameter – the baryon-to-photon ratio $\eta = n_b/n_\gamma$. Thus, measuring and comparing their primordial yields with the BBN predicted ones, it is possible to determine η.

D is the most sensitive to η among the BBN produced elements and is considered the best baryometer. The empirical dependence is $D/H_{|p} \sim \eta^{-1/6}$. Besides, D has a straight forward post-BBN evolution: due to nucleosynthesis in stars and chemical evolution in galaxies, D is only destroyed. The primordially produced D, measured in highredshift, low-metallicity quasar absorption line systems [4], is $D/H = (2.87 \pm 0.2) \times 10^{-5}$, which corresponds to a baryon density at BBN

$$\eta = (5.7 \pm 0.3) \times 10^{-10},$$

or in terms of the baryon fraction of the total density: $\Omega_b h^2 = 0.021 \pm 0.001$, where $\Omega_b h^2 = 3.65 \times 10^7 \eta$, $\Omega_b = \rho_b/\rho_c$, $\rho_c = 3H^2/8\pi G_N$ and $H = 100h$ (km/s)/Mpc. D measurements provide a key baryometer at the time of BBN with a precision of 5%. It is interesting to note for the sake of the following discussion of baryogenesis scenarios, that the existing dispersion between D measurements leaves some room for non-standard BBN and non-homogeneous baryogenesis.

CMB baryometer: CMB anisotropy measurements determine β with comparable accuracy

$$\eta = (6.11 \pm 0.19) \times 10^{-10},$$

corresponding to $\Omega_b h^2 = 0.0223 \pm 0.0007$. WMAP7 data provided even better accuracy: $\Omega_b h^2 = 0.0226 \pm 0.0005$, where the recent value of h is ~ 0.7.

The good correspondence between the two values means that η has not been changing in the period between the first minutes after the Big Bang, and CMB formation 380 000 years later. Actually, according to the known baryogenesis models the baryon excess has been produced before BBN.

Baryons consist less than 5% of the universe density today, $\Omega_b \sim 0.046$ (to within 0.1% accuracy). They are an order of magnitude bigger than the luminous matter, $\Omega_l \sim 0.005$, *i.e.*, most of them are dark (most probably hidden in MACHOS). Baryons are considerably less than the gravitating matter $\Omega_m \sim 0.3$, hence it should be nonbaryonic dark matter.

In conclusion, the measured value of the local baryon asymmetry now is:

$$\beta \sim \eta \sim 6 \times 10^{-10}$$

This seemingly small number, actually looks too big within the framework of the standard cosmological model (SCM).

2.2 Where is the antimatter?

SCM predicts equal quantities of matter and antimatter at the early stage of Universe and $\eta \sim 10^{-18}$ today. Thus, the measured baryon density is 8 orders of magnitude bigger than the expected one.

Why the baryon-photon ratio is so big? Is the baryon asymmetry global? Observations show that the local Universe is asymmetric. We do not know the mechanism of its generation or the mechanism of the separation of matter from antimatter regions.

To explain the observed β different kinds of baryogenesis mechanisms, following the Saharov's one, were invented [5]. Another solution of the problem might be a mechanism separating matter from antimatter, implying the presence of antimatter regions beyond our local vicinity. Several dedicated missions searched for it: BESS, MASS, CAPRICE, AMS, PAMELA. *Cosmic ray data* from these missions show no evidence for primary antimatter ($\overline{p}$, anti nuclei) within 1 Mpc. The detected quantity of $\overline{p}$ is explained as secondaries.

Another probe of antimatter is provided by the *gamma ray data*.It excludes significant amounts of antimatter up to galaxy cluster scales $10 - 20$ Mpc. At distances bigger than 20 Mpc, a presence of antimatter is not excluded. [1]

I have continued my work on the theme of baryogenesis, started with prof. Mateev, during my Ph.D. studies in Moscow with prof. A. Dolgov and in the following years with my collaborators in Bulgaria. We proposed a baryogenesis scenario [6] according to which the baryon excess in the Universe is a result of the decay of a scalar condensate $\langle\phi\rangle$, carrying a baryon charge, generated at the inflationary stage. At large values of $\langle\phi\rangle$ there are B-violating self-interaction terms in its potential $U(\phi)$. CP violation is a stochastic one. We have provided both analytical and numerical analysis of the scalar field evolution after the inflationary stage till the field's decay and determined the values of model's parameters for which the observed baryon asymmetry can be generated. It was shown that *particle creation by a time variable scalar field play an essential role for baryogenesis and reheating* [7]. Inhomogeneous baryogenesis models based on this scenario [8, 9] allow *a natural production of large antimatter domains in the Universe, compatible with LSS*: antigalaxies, clusters of antigalaxies, *etc*.

Baryogenesis obviously requires new physics - physics beyond the standard electroweak model, like big CP violation, B violation, *etc*. Another domain of physics, which observational data convincingly point to new physics during the last 40 years, is the neutrino physics and astrophysics. Prof. Mateev not only followed the progress in that area with great interest, but also worked on topics connected with neutrino in stars [10]. Therefore, in the following I will discuss topics on neutrino in cosmology.

3 Neutrino in Cosmology

3.1 Neutrino oscillations

Solar neutrino problem, atmospheric neutrino anomaly and the positive results of terrestrial neutrino experiments were resolved by the phenomenon of neutrino oscillations. Recent analyses [11] of global neutrino data within 3-flavor framework, including SKI+SKII+SKIII, MINOS and Kamland data, provide precision information about neutrino mass differences and mixing

$$\delta m_{12}^2 \sim (7.6 \pm 0.2) \times 10^{-5}\mathrm{eV}^2, \quad \sin^2\theta_{12} < 0.3,$$

$$\delta m_{31}^2 \sim (2.4 \pm 0.1) \times 10^{-3}\mathrm{eV}^2, \quad 0.007 < \sin^2\theta_{13} < 0.03,$$

$$\sin^2\theta_{23} \sim 0.5 \pm 0.06.$$

However, the recent analysis of neutrino oscillations data from LSND, MiniBooNE, Gallium experiments and global short-baseline neutrino oscillation data

[1] Small quantities of antimatter are possible even in our Galaxy: antistars, an anti globular cluster.

suggests the existence of 1 or 2 light sterile neutrinos, participating in oscillations with the flavor ones with sub-eV mass [5, 13], namely $\delta m^2_{41} \sim 0.5$ eV^2 and $\delta m^2_{51} \sim 0.9$ eV^2.

It is known that neutrino active-sterile oscillations may effect considerably early Universe processes. Does cosmology allow 2 light sterile neutrinos?

Interestingly, recent cosmological data favor additional relativistic density, which can be represented by the discussed light sterile neutrinos. Namely, recent primordial ^{4}He measurements point to a higher central value than previously accepted, which corresponds to an effective number of neutrino flavors $N_{eff} = (3.68 - 3.80)^{+0.80}_{-0.70}$ [1]. The CMB WMAP7 favors $N_{eff} = 4.34^{+0.86}_{-0.88}$ at 68% CL [2], *i.e.*, relativistic density also bigger than in the standard cosmological model $N_{eff} = 3.046$. However, as will be discussed further on, although BBN favors some non-zero ν_s, BBN He and D data likely exclude $3+2$ models.

3.2 BBN and active-sterile neutrino oscillations

Active-sterile oscillations exert considerable cosmological influence. They influence *Universe dynamics* exciting additional light particles species into equilibrium [17], denoted $\delta N_s = N_\nu - 3$, since the expansion rate $H(t) \sim (g_{eff} G T^4)^{1/2}$ depends on the number of relativistic species in equilibrium: $g_{eff} = 10.75 + \frac{7}{4}\delta N_s$. Fast active-sterile neutrino oscillations effective before flavor neutrino decoupling - effect CMB and BBN through increasing the energy density $\rho \sim g_{eff} T^4$ and H, leading to overproduction of primordially produced ^{4}He, because its mass fraction Y_p depends on the effective number of light stable particles at BBN epoch $Y_p \sim 0.013\delta N_s$ and, therefore, Y_p is known as the best speedometer.

Besides, active-sterile oscillations have a strong effect on *BBN kinetics*: Namely they may distort the neutrino energy spectrum from its equilibrium Fermi-Dirac form [18]. In case of electron-sterile oscillations this leads to changes in the nucleons kinetics in the pre-BBN epoch, since the weak rates depend on the ν_e characteristics, $\Gamma \sim G_F^2 E_{\nu_e}^2 N_{\nu_e}$, where N_{ν_e} is the number density of neutrino. Due to ν_e decrease caused by oscillations, the n/p freezes earlier leading to overproduction of primordially produced ^{4}He.

For active-sterile oscillations proceeding after decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ eV^2 spectrum distortion effect is the major one, because for these oscillations the sterile state is filled for the sake of ν_e, which is no longer refilled due to interactions with the plasma [19, 20]. *The energy spectrum distortion caused by oscillations and the kinetic effect of oscillations depend on the level of initial population of ν_s* - they decrease with δN_s [21]. The total effect is a result of an interplay between the dynamical effect (increasing with δN_s) and the kinetic effect. Depending which effect dominates, it may result in overproduction or underproduction of ^{4}He compared with $\delta N_s = 0$ case.

The maximal overproduction of ^{4}He in BBN due to oscillations caused spectrum distortion is 32% in the resonant case and 13% in the non-resonant, *i.e.*, much stronger than the dynamical effect [22].

Another well-known effect of active-sterile oscillations is their ability to *change neutrino-antineutrino asymmetry of the medium* (suppress [23] or enhance [24] it).

3.3 BBN constraints on active-sterile oscillations parameters

Since BBN is a sensitive probe both to additional species and to distortions in the energy distribution of neutrinos, caused by neutrino active-sterile oscillations, it puts stringent limits on oscillation parameters δm^2 and $\sin^2 2\theta$.

Primordially produced ^{4}He is the preferred element for obtaining limits on non-standard physics: it is calculated with precision better than 0.1%: $Y_p = 0.2482 \pm 0.0007$, and most precisely measured among BBN produced elements [12]. For recent BBN constraints see [25–28]. BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$, effective after neutrino decoupling, allows to constrain neutrino oscillation parameters for ^{4}He uncertainty up to 32% (13%) in resonant (non-resonant) case, correspondingly [2].

Additional sterile neutrino population changes the BBN constraints non-trivially [27,28]: It may either strengthen (in case dynamical effect dominates) or relax (in case the kinetic effect dominates) BBN constraints. The recent observations point to a larger central value and bigger uncertainty of Y_p determination: $Y_p = 0.256 \pm 0.0108$ [1]. The value of Y_p corresponds to nearly 5% overproduction of Y_p than previously accepted. It may be interpreted as overproduction due to the late oscillations, discussed above. Then the oscillations parameters correspond to the 5% Y_p overproduction contour

$$\delta m^2 (\sin^2 2\theta)^7 \sim 3 \times 10^{-9}\,\mathrm{eV}^2, \mathrm{at}\ \delta N_s = 0,$$

while BBN constrained area is situated above the contour corresponding to 5% overproduction and $\delta N = 0.7$, presented in Figure 2. of Ref. [27].

However, $3+2$ oscillations models predict sterile neutrinos, with higher mass differences and mixing fixed by the neutrino oscillations data. Then 2 light ν_s would have been brought into equilibrium during BBN epoch. The dynamical effect of these active-sterile oscillations is the dominant one. The standard BBN hardly allows them, since primordial ^{4}He point to an effective number of neutrino flavors $N_{eff} = (3.68 - 3.80)^{+0.80}_{-0.70}$ [1]. However, BBN constraints depend nontrivially on lepton asymmetry: It can suppress oscillations, and relax BBN constraint on $3+2$ oscillations models. I will discuss the lepton asymmetry cosmological effects below.

[2] In contrast to the case of fast oscillations, for which the dynamical effect dominates, and thus the maximal possible overproduction is 5% (caused by one additional species brought into equilibrium).

4 BBN and Lepton Asymmetry

Lepton asymmetry of the Universe $L = (n_l - n_{\bar{l}})/n_\gamma$ may be orders of magnitude bigger than the baryon one and hide in the neutrino sector. As far as Cosmic neutrino background has not been detected yet, L is constrained only indirectly through its effect on processes, which have left observable traces in the Universe, like BBN, CMB, LSS, *etc*.

4.1 Lepton asymmetry effects

There are several effects of L known: A. The *dynamical effect* – L increases the radiation energy density

$$\Delta N_{eff} = \frac{15}{7}\,[(\xi/\pi)^4 + 2(\xi/\pi)^2].$$

where L in equilibrium is expressed through $\xi = \mu/T$: $L = 1/12\zeta(3)\sum_i T_{\nu_i}^3/T_\gamma^3(\xi_{\nu_i}^3 + \pi^2\xi_{\nu_i})$. This causes faster expansion $H = (8/3\pi G\rho)^{1/2}$, matter/radiation equality epoch delay, thus influences BBN, CMB, LSS, *etc*. For example the change in Y_p due to that effect is $\delta Y_p \sim 0.013\delta N_{eff}$.

B. The *direct kinetic effect* of L – Big enough asymmetry in the electron neutrino sector L_e, $|L_{\nu_e}| > 0.01$, effects neutron-proton kinetics in pre-BBN epoch. This effect on BBN is sign dependent on L (ξ) and is estimated by $\delta Y_p \sim -0.3\xi_{\nu_e}$

C. The *indirect kinetic effect* – There exists asymmetry-oscillations interplay: Oscillations in a medium are capable to suppress pre-existing asymmetryand in case of MSW resonant neutrino oscillations they may generate asymmetry. On the other hand, pre-existing asymmetry is capable to suppress [23, 29] or enhance neutrino oscillations [20, 29] because L change the medium induced neutrino potential energy and thus the evolution of oscillating neutrino. Thus small asymmetries $10^{-8} \leq L \leq 0.01$ indirectly influence nucleons kinetics and BBN [20, 29].

4.2 Lepton asymmetry constraints

BBN provides the most stringent constraints on L, CMB and LSS put much looser bounds. Depending on the different combinations of observational data sets used and the assumed uncertainties, cosmology provides an upper limit in the range $|L_{\nu_{\mu,\tau}}| < 10^{-2} - 10$ and $|L| < 0.01 - 0.2$. The most conservative BBN constraints due to the dynamical A. and direct kinetic effect B. of L read: $|\xi_{\nu_{\mu,\tau}}| < 1.5$, $|\xi_{\nu_e}| < 0.1$. In case neutrino degeneracies in different neutrino sectors equilibrate before BBN due to neutrino oscillations with big e θ_{13}, the constraint for all neutrino sectors is: $|\xi_\nu| < 0.1$ [30]

These values are many orders of magnitude larger than the baryon asymmetry value. The possibility of degenerate BBN to feel much smaller L will be discussed in the last subsection.

4.3 Leptogenesis by neutrino oscillations

L generation possibility in MSW resonant active-sterile neutrino oscillations in the early Universe was first found possible for $\delta m^2 > 10^{-5}$ eV^2 in collisions dominated oscillations by Foot and Volkas [31] and for small mass differences $\delta m^2 < 10^{-7}$ eV^2 in the collisionless case by Kirilova and Chizhov [24].

Recent analysis of asymmetry generation in the latter case [32] showed that generation of L up to 5 orders of magnitude larger than its initial value, taken of the order of β, is possible, *i.e.*, $L \sim 10^{-5}$. The region of parameter space for which large generation of L is possible was found, which to a good approximation is: $\delta m^2 \sin^4 2\theta \leq 10^{-9.5}$ eV^2.

4.4 Small lepton asymmetry and BBN

The dynamical and direct kinetic effects of $L \ll 0.01$ are negligible. However, small L, either relic or oscillations generated influences indirectly BBN with $\nu_e \leftrightarrow \nu_s$, effective after neutrino decoupling [20, 29].

Oscillations generated asymmetry: In BBN with resonant $\nu_e \leftrightarrow \nu_s$ L generation leads to changes in the energy spectrum distribution and the number densities of ν_e from their SCM values, modifies BBN element production. In particular, the production of ^{4}He decreases at small mixing. Hence, the neutrino-antineutrino asymmetry growth caused by resonant oscillations relaxes the BBN constraints at small mixings.

Small relic asymmetry: BBN with late oscillations presents the most sensitive leptometer, because Y_p in this model feels L as small as 10^{-8} [32]. This is due to the fact that small L, $10^{-8} < L \ll 0.01$, influence indirectly BBN *via* oscillations. It was found that $L > 10^{-7}$ may considerably influence BBN: $L \sim 10^{-7}$ enhances oscillations, $L > 0.1(\delta m^2/\text{eV}^2)^{2/3}$ suppresses oscillations, while $L > (\delta m^2/\text{eV}^2)^{2/3}$ inhibits oscillations. Small asymmetries may relax or strengthen BBN constraints while big enough asymmetry, $L > (\delta m^2)^{2/3}$, eliminates BBN constraints on oscillations. *Vice versa*, the relations can be observed as constraints on L, provided the values of oscillation parameters are known: the observation of oscillation with $\delta m^2 \sim 7.6 \times 10^{-5}$ eV^2 (solar neutrino anomaly) means that $L < 1.8 \times 10^{-3}$.

Hence it seems that degenerate BBN with big L may principally allow $3 + 2$ oscillations models. [3]

[3] However, the exact L value should be obtained studying the concrete degenerate BBN with 3+2 neutrino oscillations.

In conclusion, the cosmological indications of additional relativistic density by BBN, CMB and LSS data, might be due to big lepton asymmetry or/and light oscillating sterile neutrino.

5 Conclusions

The problem of the baryon asymmetry of the Universe, is still fascinating. Though baryon density is measured with a high accuracy today, the exact baryogenesis mechanism is not known yet. The possibility for astronomically large antimatter objects is experimentally and theoretically studied.

Besides being very accurate baryometer, BBN depends strongly on the expansion rate and on the lepton asymmetry of the Universe - it is the best speedometer and leptometer. It is the most sensitive cosmological probe of new physics, like additional number of light particle species, the distortions in the energy distribution of neutrinos, lepton asymmetry, neutrino mass differences and mixing, *etc*.

Effective lepton asymmetry generation mechanism in active-sterile Mikheyev-Smirnov-Wolfenstein oscillations exists, able to produce L much bigger than the baryon asymmetry. Small lepton asymmetry $L \ll 0.01$, either relic or generated by active-sterile neutrino oscillations, may have considerable cosmological influence. Thus its value is constrained by cosmology, the most fine leptometer being BBN. Lepton asymmetry is able to enhance, suppress or inhibit oscillations. Hence, it can provide relaxation or enhancement of BBN constraints on oscillations. Large enough L alleviates BBN constraints on oscillation parameters. Therefore, there exists perhaps a possibility for $2+3$ oscillations models to be cosmologically allowed in case of big L.

The cosmological indications of additional relativistic density by BBN, CMB and LSS data, might point to active-sterile neutrino oscillations, lepton asymmetry or/and additional sterile neutrino states.

References

[1] V. Kadyshevski, M. Mateev (1981) *Phys. Lett. B* **106** 139

[2] D. Kirilova, M. Mateev (1988) in *Theoretical physics and high energy physics*, Sofia: Bulg. Acad. Sci., 55.

[3] F. Iocco et al. (2009) *Phys. Rep.* **472** 1; G. Miele, these proceedings

[4] M. Pettini et al. (2008) *MNRAS* **391** 1499

[5] A. Dolgov (2009) *AIP Conf. Proc.* **1116** 155; A. Dolgov (1992) *Phys. Rep.* **222** 309

[6] A. Dolgov, D. Kirilova (1991) *J. M. Phys. Soc.* **1** 217

[7] A. Dolgov, D.Kirilova (1990) *Yad. Fiz.* **51** 273; D. Kirilova, M. Panayotova (2007) *Bulg. J. Phys.* **34** 330

[8] D. Kirilova (1998) *Astronom. Astrophys. Transections* **15** 211; D. Kirilova (2003) *Nucl. Phys. Proc. Suppl.* **122** 404.

[9] M. Chizhov, A. Dolgov (1992) *Nucl. Phys. B* **372** 521; D. Kirilova, M. Chizhov (2000) *MNRAS* **314** 256; D. Kirilova, M. Chizhov (1996) *Astr. Astrop. Tr.* **10** 69

[10] M. Mateev (1996) *Astron.Astrophys.* **313** 679.

[11] T. Schwetz, M. Tortola, J. Valle (2011) arXiv:1103.0734; G. Mention et al. (2011) *Phys. Rev. D* **83** 073006

[12] Giusarma et al. (2011) arXiv: 1102.4774

[13] J. Kopp, M. Maltoni, T. Schwetz (2011) *arXiv:1103.4570v2*

[14] J. Hamann et al. (2010) *Phys. Rev. Lett.* **105** 181301

[15] Yu. I. Izotov, T. X. Thuan (2010) *ApJ* **710** L67; E. Aver, K. A. Olive, E. D. Skillman (2010) *JCAP* **05** 003; E. Aver, K. A. Olive, E. D. Skillman (2010) *arXiv:1012.2385v1*

[16] E. Komatsu et al. (2011) *ApJ S* **192** 18

[17] A. D. Dolgov (1981) *Sov. J. Nucl. Phys.* **33** 700

[18] D. Kirilova (1988) *JINR* **E2-88** 301

[19] D. Kirilova, M. Chizhov (1998) *Phys. Rev. D* **58** 073004

[20] D. Kirilova, M. Chizhov (2000)*Nucl. Phys. B* **591** 457

[21] D. Kirilova (2004) *Int. J. Mod. Phys. D* **13** 831

[22] D. Kirilova (2003) *Astropart. Phys.* **19** 409

[23] R. Foot, R. R. Volkas (1995) *Phys. Rev. Lett.* **75** 4350; R. Foot, M. Thomson, R. Volkas (1996) *Phys. Rev. D* **53** R5349; X. Shi (1996) *Phys. Rev. D* **54** 2753

[24] M. Chizhov, D. Kirilova (1997) *Phys. Lett. B* **393** 375; D. Kirilova, M. Chizhov (1996) *Neutrino96* 478

[25] D. Kirilova, M. Chizhov (2000) *Nucl. Phys.B* **591** 457

[26] A. Dolgov, F. Villante (2004) *Nucl. Phys. B* **679** 261

[27] D. Kirilova, M. Panayotova (2006) *JCAP* **12** 014; M. Panayotova (2011), these proceedings

[28] D. Kirilova (2007) *Int. J. Mod. Phys. D* **16** 1

[29] D. Kirilova, M. Chizhov (1998) *Nucl. Phys. B* **534** 447; D. Kirilova, M. Chizhov (2001) *in Verbier 2000, Cosmology and particle physics* 433

[30] A. Dolgov et al. (2002) *Nucl. Phys. B* **632** 363

[31] R. Foot, M. Thomson, R. Volkas (1996) *Phys. Rev. D* **53**, R5349.

[32] D. Kirilova (2011) *Prog. Part. Nucl. Phys.* **66** 260; D. Kirilova (2011) *arXiv:1101.4177*