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SEVERAL COSMOLOGICAL NUCLEOSYNTHESIS CONSTRAINTS ON NEUTRINO AND NEW PHYSICS

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Abstract. We provide short review of the contemporary Big Bang Nucleosynthesis (BBN) and the new more precise measurements of the primordially produced abundances of the light elements D and He-4. We present several cosmological constraints, based on contemporary BBN, on the physical characteristics of neutrino and on beyond Standard Model sterile neutrino.

1. INTRODUCTION

Our motivation to study neutrino is supported by the following main arguments: ***First,*** neutrino is elusive (as it has only weak interactions) but important particle. It is a constituent of the Standard Model (SM) of particle physics. ***Second,*** physical characteristics of neutrino are not yet fully studied. ***Third,*** neutrino has astrophysical importance: sources of neutrino are the Sun and other stars, SN, AGN, early Universe. In particular, neutrino plays important role in early Universe processes. Hence, cosmology constrains neutrino characteristics, its mass, number density, the number of different light neutrino types, oscillation parameters, etc. and, thus, presents complimentary knowledge about neutrino.

Moreover, in recent years combined neutrino oscillations data including reactor experiments +LSND +MiniBooNe +Gallium experiment hint to the possible presence of 1 light right handed neutrino, called further sterile neutrino ν_s, participating in neutrino oscillations with flavor neutrinos with squared mass difference of the order of $\sim eV^2$. Sterile neutrino, as well as neutrino oscillations phenomenon, present physics beyond SM. It is predicted by Grand Unified Theories models. It is used in theoretical models to explain small non-zero neutrino masses. It is also among the preferred particles candidates for Dark

Matter (DM). It has applications in models of large scale structure formation, models of natural baryogenesis through leptogenesis, etc.

In the following sections we will discuss how sterile neutrino is constrained by cosmology, in particular by Big Bang Nucleosynthesis (BBN). It has strong dynamical effect during the early Universe - it increases the expansion rate in case sterile neutrino is brought into equilibrium and, hence, influences light elements production. In case of oscillations with flavor neutrinos it effects nucleons kinetics during pre-BBN epoch and, hence, its mixing parameters are constrained by BBN. We will discuss contemporary cosmological constraints on the number of light neutrino families and the degree of population of the sterile neutrino, We will present recent update to the BBN constraints on neutrino oscillation parameters, and on the temperature of decoupling of light sterile neutrinos.

2. BBN - THE DEEPEST RELIABLE EARLY UNIVERSE PROBE OF NEW PHYSICS

Big Bang Nucleosynthesis is theoretically well established and experimentally and observationally confirmed model explaining the production of the light elements in the early Universe during its hot stage, when the Universe cooled from T~ 1 MeV until 0.1 MeV. Precise data on nuclear processes rates exists from experiments carried out at low energies (10 KeV – MeV). Analyses of nuclear rates for BBN are used like NACRE-I (Angulo et al. 1999) and NACRE-II (Xu et al. 2013). More than 400 nuclear reactions are considered and precise BBN codes are used, namely PArthENoPE, AlterBBN, PRIMAT, etc. (Pisanti et al, 2008, Consiglio et al., 2017, Arbey, 2012, Pitrou et al., 2018, Miele et al. 2011). Observational data on deuterium D, helium He-3, He-4 and lithium Li-7 exists and during the last years the determination of primordially produced D and He has reached high precision.

All 3 parameters, on which primordially produced elements depend have been measured with good precision. Namely, the *baryon-to-photon ratio* η has been measured independently by CMB with high precision: $\eta_{CMB} = (6.104 \pm 0.055)\ 10^{-10}$. It is in good agreement with the value obtained in BBN analysis of all the light elements, and in particular its value derived on the basis of D primordial abundance, as D is the best baryometer among the elements produced primordially. Namely, the concordance η range is $\eta_{BBN} = (6.143 \pm 0.190)\ 10^{-10}$.at 1 sigma error (Fields et al., 2020). *The number of the effective degrees of freedom of light particles* N_{eff} during the BBN epoch is also known with much higher precision than before $\Delta N_{eff} < 0.3$, where N_{eff} is usually defined by the energy density of light neutrino:

$$\rho_\nu = 7/8(T/T_\nu)^4 N_{eff}\rho_\gamma(T)$$

Thus, ΔN_{eff} may indicate nonstandard interactions, extra relativistic degrees of freedom, exotic physics, i.e. physics beyond SM. *The neutron lifetime* has been also measured with higher accuracy τ = 879.4±0.6 s (see Serebrov et al., 2017, PDG 2022).

There exist remarkable concordance between theoretically predicted and derived from observations abundances of light elements primordially produced. In particular an excellent agreement exists between the predicted for $\eta = 6.10^{-10}$ and derived from observations data abundances of D and He-4. Namely: the theoretically predicted by BBN mass fraction of primordial He-4 is (Pitrou et al., 2018)

$$Y_T = 0.24709 \pm 0.00017,$$

the predicted D to hydrogen ratio is

$$D/H_T = (2.459 \pm 0.036)\ 10^{-5}$$

while their values obtained from observations read correspondingly (Aver et al., 2015, Cooke et al., 2017, Fields et al., 2022 PDG):

$$Y_p = 0.245 \pm 0.003,\ D/H = (2.536 \pm 0.026)\ 10^{-5}$$

Hence, the contemporary BBN is often used as the most deep reliable precision probe for physical conditions in early Universe and as a unique test for new physics.

During the last decade the precision of D and He-4 observational data improved considerably, due to new observations of QAS for D (Cooke et al., 2018, Balashev et al., 2016) and due to the inclusion of He10830 infrared emission line for He-4 that helped for precise primordial abundance determinations.

Primordial He-4 was determined with better than 3% accuracy, mainly due to the inclusion of He 10830 infrared emission line measured in the extremely metal poor galaxy Leo P (Aver et al., 2020):

$$Y_p = 0.2453 \pm 0.0034.$$

This better accuracy of He-4 determinations allows to update and strengthen the Big Bang Nucleosynthesis constraints on physics beyond Standard Model. In the following section we present updates of BBN constraints on several beyond Standard Model neutrino physics based on this uncertainty of Y_p.

3. NEUTRINO COSMOLOGICAL EFFECTS AND BBN CONSTRAINTS ON NEUTRINO CHARACTERISTICS

Here we present updated BBN constraints on beyond SM neutrino physics, corresponding to ^{4}He Y_p/Y_p = 1-3% uncertainty. We consider several beyond SM physics models and present updated constraints on new physics. Namely: first we discuss the recent cosmological constraints on the number of the effective degrees of freedom of light particles during the BBN epoch; Then we discuss the model of BBN with neutrino oscillations and present the updated stringent BBN constraints on neutrino oscillations parameters recently derived (Kirilova&Panayotova, 2022). Next we discuss BBN constraints on lepton asymmetry in BBN model with neutrino oscillations and lepton asymmetry (Kirilova, 2012, 2013, 2019). Finally we present updated BBN based constraints on the freezing temperature of light sterile neutrinos (Kirilova, E.Chizhov, 2019, Kirilova, E. Chizhov, V.Chizov, 2020).

3.1. Cosmological constraints on the number of light neutrino types

Additional light particles into equilibrium increase universe expansion rate thus influencing BBN, hence BBN constrains the effective number of relativistic species N_{eff} .

BBN and recently determined primordial He-4 and D (Pitrou et al., 2018, Cooke et al., 2017) lead to the following constraint:

$$N_{eff} = 2.88 \pm 0.154 \ (95\%).$$

A maximum likelihood analysis on η and N_{eff} based on He-4 and D abundances finds (Fields et al. 2020):

$$N_{eff} = 2.843 \pm 0.27 \ (95\%) \text{ and } \eta = 6.09 \pm 0.055 \ (95\%).$$

Recent cosmological constraint on N_{eff} , based on BBN+CMB (Yeh et al., 2022) is even more restrictive:

$$N_{eff} = 2.898 \pm 0.141 \qquad N_{eff} < 3.18 \text{ at } 95\% \text{ CL}$$

Combined constraints based on updated Planck CMB data (Pitrou, 2018) give:

$$N_{eff} = 3.01 \pm 0.15 \text{ at } 95\% \text{ CL.}$$

BBN and CMB neutrino numbers are *consistent* with the standard cosmological model value $N_{eff} = 3.045$ within uncertainties. Still, non-zero $\Delta N_{eff} = N_{eff} - 3.045$ may indicate extra relativistic component, like light right handed neutrino usually called sterile neutrino.

In subsection 3.4 we will use $\delta N_{eff} < 0.2$ for obtaining BBN constraints on sterile neutrino decoupling and on new beyond SM interactions. This constraint corresponds to 1% He-4 uncertainty discussed in the following subsection 3.2, where we obtain BBN limits on the electron-sterile neutrino oscillations.

3.2. BBN constraints on neutrino oscillations

In BBN with $\nu_e \leftrightarrow \nu_s$ proceeding ***before active neutrino decoupling*** oscillations can exite into equilibrium the sterile neutrino state (Dolgov, 1988, Barbieri, Dolgov, 1990,1991) and lead to higher expansion rate. While in case neutrino oscillations proceed ***after the electron neutrino decoupling*** neutrino energy distribution and the density of electron neutrino may considerably differ from the equilibrium ones in standard BBN. This leads to different nucleon kinetics and modifies BBN element production (Kirilova, 1988, Kirilova, Chizhov, 1996, 1997). Nucleons evolution in the pre-BBN period in the presence of late $\nu_e \leftrightarrow \nu_s$ effective after neutrino freezing, was numerically analyzed for different sets of oscillation parameters, accounting for the distortion in electron neutrino energy distribution due to neutrino oscillations in a cycle of papers. The primordially produced He-4 was calculated and compared with its observational uncertainty to provide BBN constraints on neutrino oscillation parameters – squared mass differences δm^2 and mixing $\sin^2 2\theta$.

In the 90ies ^{4}He was known with ~3-7% accuracy and we have obtained BBN constraints on δm^2 and $\sin^2 2\theta$ corresponding to 3-7% overproduction of ^{4}He (Kirilova, Chizhov, 1998, 2000). These constraints were more precise, namely orders of magnitude more stringent than previous ones, due to the precise account for energy spectrum distortion caused by late neutrino oscillations. They excluded LOW active-sterile solution to the solar neutrino problem in addition to the already excluded LMA active-sterile solution to the solar neutrino problem in previous publications (Kainulainen, 1990, Barbieri, Dolgov, 1991, Enquist et al., 1992)

Recently we have provided numerical analysis of more than 100 BBN models with electron-sterile neutrino oscillations with different sets of oscillation parameters (Kirilova, Panayotova, 2022). We have used updated data on baryon density and the neutron life time. We have followed numerically the evolution of the neutron-to-proton ratio in these beyond SM models from the epoch of neutrino freezing until the formation of elements. We have calculated the production of He-4 and obtained different isohelium contours, on the basis of which we have obtained updated BBN constraints on neutrino $\nu_e \leftrightarrow \nu_s$ oscillations parameters, based on 1% ^{4}He uncertainty.

In Fig.1 combined iso-helium contours for 1, 3 and 5% ^{4}He overproduction, accounting for all oscillations effects on BBN, for initial population $\delta N_s = 0$, for non-resonant $\delta m^2 < 0$ and resonant $\delta m^2 > 0$ cases, are given. The lowest contour presents the updated more stringent BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillations parameters.

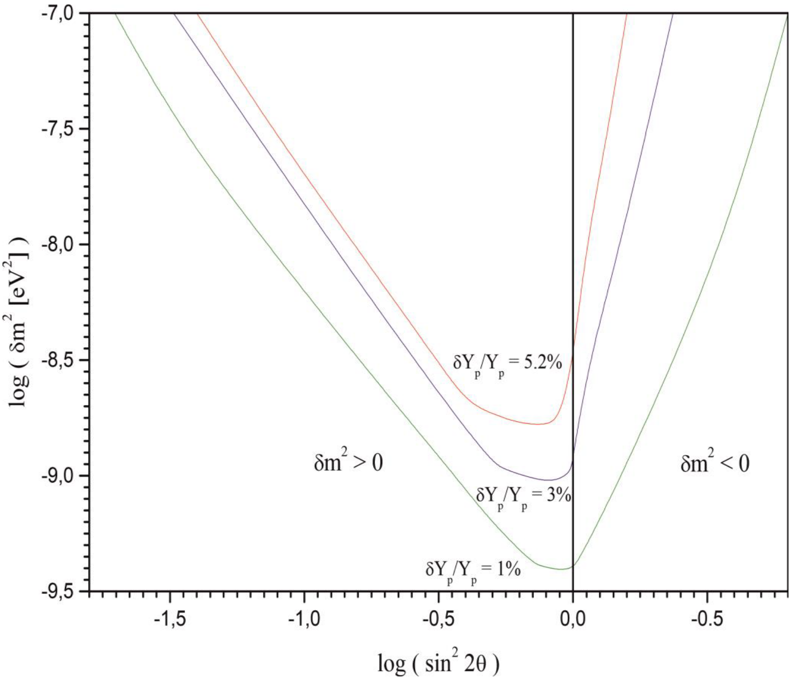

Figure 1: BBN constraints on $\nu_e \leftrightarrow \nu_s$ neutrino oscillation parameters, corresponding to different He-4 uncertainty.

3.3. BBN with lepton asymmetry and neutrino oscillations

Lepton asymmetry L is usually defined as the difference between the number of leptons and antileptons over the number of photons:

$$L = (n_l - n_{\bar{l}}) / n_\gamma$$

In case of equilibrium it can be also expressed through the chemical potentials ξ, as

$$L = \sum_i \frac{1}{12\zeta(3)} \frac{T_{\nu_i}^{\ 3}}{T_\gamma^{\ 3}} (\xi_{\nu_i}^3 + \pi^2 \xi_{\nu_i})$$

Degenerate BBN has been studied in numerous papers since first analysis of (Wagoner et al., 1967). It is known that L has **dynamical effect**, it increases the radiation energy density, leading to faster expansion, delaying matter/radiation equality epoch and, thus, influencing BBN, CMB, and the evolution of Large Scale Structure. This effect can be described in terms of change of N_{eff}:

$$\Delta N_{eff} = 15/7((\xi/\pi)^4 + 2(\xi/\pi)^2)$$

L present in the electron neutrino sector $|L_{\nu e}| > 0.01$ exerts a ***direct kinetic effect*** – it influences the neutron-proton kinetics during pre-BBN epoch, influencing BBN.

This effect is L sign dependent. Due to neutrino flavor oscillations degeneracies in different neutrino sectors equalize (Dolgov et al., 2002, Mangano et al., 2011). BBN conservative constraint for all neutrino sectors reads is

$$|\xi| < 0.1, \text{ i.e. } |L| < 0.07.$$

In case of BBN with late electron-sterile neutrino oscillations there exists ***indirect kinetic effect*** of L: L in the range $10^{-8} < L << 0.01$, that is too small to effect directly BBN kinetics, influences BBN via oscillations. It effects neutrino evolution, its number density, spectrum distribution, oscillations pattern and hence n/p kinetics and BBN (Kirilova, Chizhov, 1998, Kirilova, 2012, 2019). Depending on its value it can suppress neutrino oscillations (Foot&Volkas, 1995, Kirilova, Chizhov, 1998) or lead to their resonant enhancement (Kirilova, Chizhov, 1998, Kirilova, 2012). We have numerically studied that interplay and determined the parameter range for which L is able to enhance, suppress or inhibit oscillations (Kirilova, 2012, 2019). Recently we have updated our results (Kirilova, 2019). We have found that $L \sim 10^{-7}$ enhances oscillations, strengthens the BBN bounds on them while larger L suppresses oscillations. Thus L, depending on its value, can relax or strengthen BBN constraints on neutrino oscillations. Full suppression of oscillations with squared mass difference δm^2 is possible for

$$L > (0.01\delta m^2)^{3/5}$$

These results can be applied to solve the so called dark radiation problem. Namely, several small base line experiments: reactor experiments, LSND, MiniBooNe, Gallium expt, SAGE and recently Ice Cube hint to a presence of sterile neutrino participating into oscillations with flavor neutrinos with large mixing and mixing squared mass difference in the range $\Delta m^2_{41} = 10^{-2}$ to several eV^2 (Kopp et al., 2011, Dentler et al., 2018, Aartsen et al., 2020). However, oscillations with ν_s with eV^2 mass and large mixing lead to thermalization of ν_s at BBN epoch, i.e. to one full additional light neutrino species into equilibrium. Fully hermalized light inert state is not allowed by BBN ($\delta N_{eff} \sim 0.2$).

Different solutions to the DR problem have been discussed. We have proposed the following solution (Kirilova, 2012, 2013): Large enough L present during BBN, capable to suppress neutrino oscillations, will prevent the thermalization of ν_s, and thus avoid BBN cosmological constraints. See also the analyses by (Mirizzi et al., 2012, Hannestad et al., 2012).

Therefore, from our analysis (Kirilova, 2019) we can conclude that: In case sterile neutrino of mass difference 0.1 eV^2 exists, (as indicated by some reactor experiments) to prevent neutrino oscillations with the active neutrinos it is required that $|L| > 0.016$. In case of mass difference of 1 eV^2 bigger L is needed $|L| > 0.063$, for mass difference of 1.3 eV^2 correspondingly, L should be $|L| > 0.074$. Thus, the detection of sterile neutrino oscillations and their squared mass difference might be used to put lower bound on L present during the BBN epoch.

Recent EMPRESS survey of extremely metal poor systems *(Matsumoto et al. 2022)* obtained 3σ lower primordial He-4 value than the predicted:

$$Y_p = 0.2379^{+0.0031}_{-0.003}$$

This result can be interpreted as a hint for L in the electron neutrino sector:

$$\xi_{\nu e} = 0.039 \pm 0.014 \text{ at } 3\sigma.$$

On the basis of our analysis it is possible to estimate that L corresponding to this $\xi_{\nu e}$, L~0.027±0.01, is capable to suppress neutrino oscillations with

$$\delta m^2 \leq 0.3 eV^2$$

For bigger mass differences, predicted by some neutrino oscillations experiments, L~ 0.03 is able only to suppress partially oscillations. To estimate the exact degree of thermalization of the sterile state in this case more sophisticated numerical analysis is necessary.

It is intriguing that the Hubble tension can be resolved for similar value of ξ~0.04 and $0.3<\delta N_{eff}<0.6$ (Selo, Toda, 2021).

Hence, the preference of the solution of dark radiation puzzle by non-zero L increases.

3.4. BBN constraint on sterile neutrino decoupling

Using BBN constraint, (Pitrou et al. 2018) $\delta N_{eff} < 0.3$ at BBN epoch and recent constraint $\delta N_{eff} < 0.2$ and entropy conservation, we have calculated lower limits of the decoupling temperature T_d of sterile neutrinos (Kirilova, E. Chizhov, 2019). See also (Kirilova, E. Chizhov, V. Chizhov, 2020). We have updated the analysis using the study of the effective degrees of freedom in the early universe provided in ref. (Husdal, 2016).

For the case of 3 light sterile neutrino types and $\delta N_{eff} < 0.3$ we have determined $T_d > 200$ MeV. In case of 2 light sterile neutrino $T_d > 180$ MeV, for 1 light sterile neutrino $T_d > 140$ MeV.

Using the more stringent BBN constraint, $\delta N_{eff} < 0.2$, analogously we have obtained for 3, 2 and 1 light sterile neutrino, correspondingly: $T_d > 1600$ MeV, $T_d > 200$ MeV, $T_d > 170$ MeV. These are slightly lower values than previously estimated.

Comparing this decoupling temperature with the electron neutrino decoupling temperature 2 MeV, one can get an insight of the coupling constant of the eventual interactions of the sterile neutrinos. For example constraints can be obtained on sterile neutrino coupling to Z' gauge bosons in models of superstrings, extended technicolor, etc.

For example, in case sterile neutrinos interact with the chiral tensor particles (CTP), proposed in a model of beyond SM physics (M. Chizhov, 1993), they may be produced through chiral tensor particles exchange during BBN. Then, using the calculated T_d, BBN constraints on the new chiral tensor interactions can be obtained. Our analysis (Kirilova, Chizhov, 2019, Kirilova, Chizhov, Chizhov, 2020) shows that CTP interactions either are milliweak or weaker, or CTP do not interact with sterile neutrinos.

4. CONCLUSIONS

We use recent precise determinations of the primordial abundances of D and He-4 with 1% precision and the stringent cosmological constraints on the number of the effective degrees of freedom of light particles during the BBN epoch $\Delta N_{eff} \leq 0.2$ to obtain BBN constraints on several characteristics of neutrino.

We analyze the model of BBN with $\nu_e \leftrightarrow \nu_s$ neutrino oscillations and derive stringent updated BBN constraints on neutrino oscillations parameters corresponding to the present accuracy of determination of the primordially produced He-4.

The role of lepton asymmetry L was studied. Large L may provide relaxation of BBN constraints on oscillations, by suppressing oscillations. New stringent cosmological constraints on L were derived in the model of degenerate BBN with neutrino oscillations.

A solution to the dark radiation problem is discussed: in model of BBN with neutrino oscillations and large enough L, L is capable to suppress oscillations, and thus to hinder thermalization of the sterile neutrino due to oscillations and avoid BBN constraints on neutrino oscillations with big mass differences and mixings. The values of L necessary for solving the dark radiation problem for different mass differences are estimated.

Cosmological constraints on the decoupling T of sterile neutrino were obtained

In case of any new interactions with right-handed neutrinos stringent BBN constraints may be obtained on their interaction strength.

Neutrino cosmological influence may be considerable. Hence, studying its cosmological effects provides important complimentary and unique physical knowledge. This is precious knowledge having in mind that due to its extremely week interactions sterile neutrino is difficult to be studied experimentally.

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References

Aartsen M. et al.: 2020, *Phys. Rev. Lett*., 125(14),141801.
André de Gouvêa et al.: 2022, arXiv 2204.09130.
Angulo C. et al.: 1999, *Nucl. Phys. A*, 656, 3.
Arbey A.: 2012, *Comput. Phys. Commun*., 183, 1822.
Aver E., Olive K., Skillman E.: 2015, *JCAP*, 7, 011.
Aver E. et. al.: 2021, *JCAP,* 3, 027 .
Balashev et al.: 2016, *MNRAS*, 458(2), 2188.
Barbieri R., Dolgov A.: 1990, *Phys. Lett. B,* 237, 440.
Barbieri R., Dolgov A.:1991, *Nucl. Phys. B*, 349, 743.
Sz. Borsanyi et al.: 2017, *Nature*, arXiv:1606.07494v2
M. Chizhov: 1993, *Mod. Phys. Lett. A*, 8, 2753.
Consiglio et al.: 2017, arXiv 1712.04378.
Cooke R., Pettini M., Steidel C.: 2017, *Astrophysical Jour*nal, 855(2), 102.
Dentler et al.: 2018, Updated Global Analysis of Neutrino Oscillations with eV-Scale Sterile Neutrinos, *JHEP*, 08, 010.
Dolgov A.: 1981, *Sov. J. Nucl. Phys*., 33, 700.
Dolgov A.: 2002, *Phys. Rept*., 370, 333.
Dolgov A. et al., 2002, *Nucl. Phys B*, 632, 363.
Enqvist K., Kainulainen K., Thompson M.: 1992, *Nucl. Phys.B,* 373, 498.
Fields et al.: 2022, *Big Bang Nucleosynthesis*, Particle Data Group
Fields et al.: 2020, *JCAP*, 2020, 3, 010
Fields et al.: 2020, *JCAP*, 2020, 11, E02.
Foot R., R. Volkas: 1995, *Phys.Rev.Lett*., 75, 4350.
S. Hannestad, I. Tamborra, T.Tram: 2012, *JCAP*, 1207, 025.
Hsyu T. et.al., arXiv:2005.12290 accepted *ApJ* 2020
Husdal L.: 2016, *Galaxies*, 4, 78
Kainulainen K.: 1990, *Phys.Lett.B*, 244, 191-195
Kirilova D., Panayotova M.: 2022, to be published.
Kirilova D., E. Chizhov, V. Chizhov: 2020, *Journal of Physics: Conference Series*, 1668(1), 012022
Kirilova D.: 2019, PoS CORFU2018, v. 48
Kirilova D.: 2013, *Hyperfine Interact*., 215,111.
Kirilova D.: 2012, *JCAP*, 06, 007.
Kirilova D.: 2007, *IJMPD*, 16(7), 1
Kirilova D.: 2004, *Int. J. Mod. Phys. D,* 13, 831.
Kirilova D.: 1988, *JINR,* preprint E2-88-301.
Kirilova D., E. Chizhov, 2019, *IJ Mod. Phys. A*, 34, N11, 1950065
Kirilova D., V. Chizhov: 2017, *IJ Modern Physics Letters A*, 32, 1750187.
Kirilova, D., Chizhov, M.: 1996, *Neutrino*, 96, 478.
Kirilova, D., Chizhov, M.:1997, *Phys. Lett. B*, 393, 375.
Kirilova D., M. Chizhov: 1998a, *Phys.Rev.D*, 58, 073004,
Kirilova D., M. Chizhov: 1998b, *Nucl. Phys. B*, 534, 447.
Kirilova D., M. Chizhov: 2000a, *MNRAS*, 314, p.256.
Kirilova D., M. Chizhov: 2000b, *Nucl.Phys.B*, 591,457.
Kopp J., Maltoni M., Schwetz T.: 2011, *Phys.Rev.Lett*., 107, 091801.
Mangano G.,Serpico P.: 2011, *PLB*, 701, 296.
Mangano G., G. Miele, S. Pastor, O.Pisanti, S. Sarikas: 2011, *JCAP*, 11, 035.

Matsumoto A. et al., EMPRESS VIII: 2022, arXiv 2203.09617
A. Mirizzi et al.: 2012, *PRD*, 86, 053009.
Pisanti O. et al.: 2008, *Comput. Phys. Commun.*, 178, 956.
Pitrou C., Coc A., Uzan J.-P., Vangioni E.: 2018, *Physics Reports*, 04, 005.
Serebrov A. et al.: 2017, arXiv 1712.05663, *Phys.Rev.C*, 97, 055503.
Valerdi M. et.al.: 2019 *Astrophys. J.*, 876(2), 98.
Wagoner R., Fowler W., Hoyle F.: 1967, *Astrophys. J.Supp.*, 148, 3.
Xu Y. et al.: 2013, *Nucl. Phys. A*, 918, 61.
Yeh Tsung-Han, J. Shelton, K. Olive, B. Fields: 2022, *JCAP*, 10, 046.