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FRW Cosmology with Chiral Tensor Particles

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Abstract: We discuss an extended model of FRW cosmology with additional chiral tensor particles. We discuss the influence of these particles on the expansion rate of the Universe, their direct interactions with the constituents of the early Universe plasma, we determine their cosmological place and derive updated cosmological constraints on their interaction strength.

Keywords: chiral tensor particles; beyond standard model; Big Bang nucleosynthesis; right handed neutrino

1. Introduction

We discuss an electroweak model with a new type of boson particles, chiral tensor particles (*CTP*), and *CTP* effects in the primeval plasma of the early Universe.

CTP are chiral particles with spin-1 and carry only chiral interactions with the known fermions [1].

The cosmological influence of the *CTP*, specifically the *CTP dynamical effect* and *CTP direct and indirect interactions*, discussed in previous publications [2–5] are reviewed. It was found that *CTP* have *dynamical effect* due to their contribution to the matter tensor in the Einstein-Hilbert equation, leading to a change in the dynamical evolution of the Universe. *CTP* also have *direct interactions* with particles present at the early stages of the Universe.

Non-direct effects of the *CTP* particles on the early evolution of the Universe were considered as well [2,6–8]. Cosmological constraint on the *CTP* coupling constant, based on possible interactions of *CTP* with right-handed neutrinos and their influence on the Big Bang Nucleosynthesis (BBN) were obtained. *CTP* interaction strength was constrained to be centi-weak or weaker.

In this publication we consider *CTP* indirect effects during the BBN , and use them to obtain updated cosmological constraints on *CTP* interaction strength. The constraints are based on the most recent precise data on the light element abundances of D and ^4He. As will be shown in this work, we obtain by order of magnitude stronger constraints.

Next section presents a short review on the extended electroweak model with additional chiral tensor particles. In Section 3 the influence of the *CTP* in the early Universe is discussed, in Section 4 we derive updated constraints on *right handed neutrino freezing temperature* and on *CTP coupling strength*, obtained on the basis of the indirect *CTP* effect on BBN.

2. Extended Electroweak Model with Additional Chiral Tensor Particles

An electroweak model with additional chiral tensor particles was proposed on the basis of theoretical considerations, namely the completeness of the representation of the Lorentz group, in the pioneer publication by M. Chizhov [1]. These chiral tensor particles resemble the Higgs doublet and transform under the fundamental representation of $SU(2)_L$ group of the Standard Model. However, contrary to the scalar Higgs field *CTP* are spin-1 chiral particles and are carriers of new interaction and have chiral interactions with the known fermions, through tensor Pauli anomalous coupling. More detail about the extended model with *CTP* can be found in the review [9].

CTP are represented by an *antisymmetric* tensor fields of a rank two. Therefore, *CTP* are introduced as doublets $(T^+_{\mu\nu} T^0_{\mu\nu})$. An additional doublet $(U^0_{\mu\nu} U^-_{\mu\nu})$ with an opposite chiral- and hypercharge and

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also the extended Higgs sector $(H_1^+ H_1^0)$, $(H_2^0 H_2^-)$ with second doublet are introduced to avoid chiral anomalies, connected with *CTP*. As in the Standard Model, a Higgs-like mechanism is used to provide mass to the massless tensor particles, which have just longitudinal degrees of freedom. However, contrary to the Standard Model, the role of the Higgs field is played by gauge vector particles: four $SU(2)_L$ singlets $P_\mu^i (i = 1, ..., 4)$ or by a triplet, denoted by C_μ, and singlet, P_μ^5 (depending on the chiralities of the *CTP*). These vector fields have triple interactions with *CTP* and the Higgs fields, which enable *CTP* to acquire transverse physical degrees of freedom. To avoid flavor violation of neutral currents due to the doubling of doublets it is assumed that the doublets H_1 and $T_{\mu\nu}$ interact only with down-type fermions, while the doublets H_2 and $U_{\mu\nu}$ — with up-type ones.

The introduction of additional particles, namely two additional tensor doublets, the triplet and singlets gauge vector particles and the extra Higgs doublet increases the total effective number of the degrees of freedom by

$$g_{CTP} = g_T + g_U + g_C + g_P + g_H = 4 + 4 + 6 + 10 + 4 = 28. \quad (1)$$

Due to *CTP* unique properties it is possible to disentangle them from other hypothetical particles at hadron colliders [10–12]. The possibility of production of new chiral tensor particles at the hadron colliders the Tevatron and LHC was first considered [13]. Their coupling constants to ordinary fermions can be fixed using the hypothesis about a dynamical generation of kinetic terms for the bosons and assuming an universality of interactions of these particles. Quantitative estimations of the production cross-sections of the chiral particles were made. It is noteworthy that, due to their non-gauge interactions with fermions, their decays to light fermions do not lead to Jacobian peak in the transverse momentum and mass distribution.

Moreover, the lightest chiral particles show leptophobic character, which makes their detection at hadron colliders challenging.

Search for *CTP* has been conducted by the international collaboration ATLAS at CERN. There exists experimental constraints on *CTP* masses [14,15]. Namely: experimental constraints on the masses of the tensor particles interacting with down type fermions at 95% CL are: $M_{T^0} > 2.85$ TeV and $M_T^+ > 3.21$ TeV . The masses of tensor particles interacting with up-type fermions are not yet experimentally constrained.

3. Chiral Tensor Particles in the Early Universe

An extended cosmological model with *CTP* was studied in a cycle of publications, where cosmological influence of *CTP* has been considered [3,4,6,8,16–18].

3.1. CTP Dynamical Effect

CTP contribute to the matter tensor in the right-hand side of the Einstein–Hilbert equation. In the extended cosmological model with *CTP* the total effective number of the degrees of freedom is increased $g_* = g_{SM} + g_{CTP}$, hence the energy density and the expansion rate of the Universe is increased compared to the Standard Cosmological Model: $H = \sqrt{8\pi^3 G_N g_*/90}\, T^2$. It has been shown that *CTP* presence slightly change the Universe expansion rate at a very early stage of the Universe's evolution, while *CTP* are abundantly present (the period is defined below, in the next subsection) .

3.2. CTP Direct Interactions

CTP characteristic direct interactions with the particles present at the high energy stage of the Universe have been calculated [5]. Using experimental constraints on *CTP* [14,15]

The processes involving *CTP* in the early Universe, namely their interactions with the constituents of the early Universe plasma, their creation (Figure 1a), annihilation (Figure 1a with reversed time), scattering (Figure 1b) and decay (Figure 1c) were considered [5].

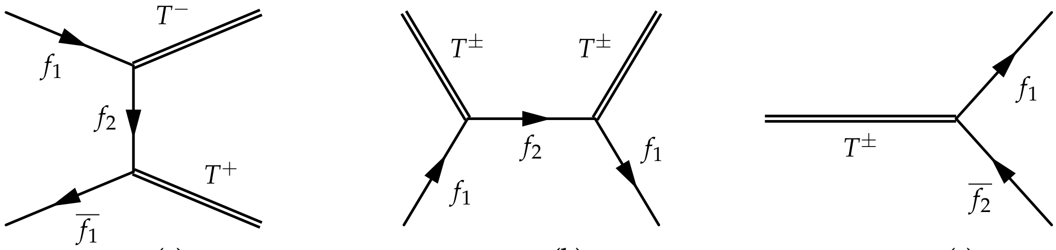

Figure 1. (**a**) Chiral tensor particles creation from fermion-antifermion collisions (**b**) Fermions scattering on *CTP* particles (**c**) Decay of *CTP* $T^\pm$.

Process efficiency vs expansion were analyzed. At early epoch while *CTP* particles were relativistic their cross-sections decrease with energy increase, $\sigma \sim E^{-2}$, and therefore *CTP* particles have been frozen. With the cooling of the Universe due to expansion, the mean energy of particles E decreases and *CTP* interactions unfroze. The characteristic temperatures and the corresponding cosmic times have been calculated for the *CTP* direct interactions.

$$\Gamma_{int} = \sigma(T) \times n(T) \geq H(T) = \frac{1}{2t}, \text{where } n(T) = \frac{3}{4}\frac{\zeta(3)}{\pi} T^3 \tag{2}$$

It has been found that *CTP* creation becomes effective when T falls below $\approx 1.83 \times 10^{17}$ GeV, corresponding to cosmic time $t_c \approx 6 \times 10^{-42}$ s.

CTP annihilations proceed till $t_a \approx 2.42/\sqrt{g_*}T_a^2[MeV]\ s$ where $T_a = 2M_T$. Then for $M_T = 3\ TeV$ we calculated the annihilation time $t_a = 5 \times 10^{-14}\ s$. However if we take the estimation about the masses following from BBN cosmological constraint discussed in Section 4, namely $M_T \sim 8\ TeV$ the corresponding annihilation epoch will end earlier, $t_a = 7 \times 10^{-15}\ s$.

With the decrease of the Universe temperature during its expansion, the *CTP* become non-relativistic. Then the inverse decay processes can be neglected. *CTP* decay width is estimated to be:

$$\Gamma \approx g_T^2 M_T / 4\pi. \tag{3}$$

The cosmic time corresponding to the decay at $T_d \approx M_T$, assuming $M_T = 3\ TeV$ $t_d = 2 \times 10^{-13}\ s$. Assuming $M_T \leq 8\ TeV$ the corresponding decay time will be $t_d = 2.8 \times 10^{-14}\ s$.

The provided analysis of the cosmological place of the *CTP* shows, that the decay time is later than the annihilation time, so *CTP* mainly disappear from the cosmic plasma due to annihilations and the rest decay rapidly soon after that at t_d. The period of efficiency of *CTP* direct interactions, defined in case $M_T = 3\ TeV$, is: $6 \times 10^{-42}\ s < t < 5 \times 10^{-14}\ s$ corresponding to T interval $1.8 \times 10^{17} - 6.0 \times 10^3\ GeV$. Otherwise, in case $M_T \sim 8\ TeV$ the period of efficiency is slightly shortened $6 \times 10^{-42}\ s < t < 7 \times 10^{-15}\ s$. Thus, the analysis showed that *CTP* direct interaction were effective for a very short period at a very early stage of Universe evolution and during this period *CTP* have been abundant. So they could not directly effect BBN or Cosmic Microwave Background, which proceed at much later epochs.Therefore, the cosmological observational data from BBN and CMB do not constrain *CTP* on the basis of their direct interactions.

However, it is still possible to obtain cosmological bounds on the *CTP* interaction strength G_T [2] on the basis of BBN considerations in case right handed neutrinos nu_R interact with the chiral tensor particles. Then ν_R can be produced during BBN epoch through *CTP* exchange and they may effect the primordial production of elements and hence, BBN constraints may be derived. We discuss these BBN constraints on *CTP* and the temperature of freezing of r.-h. neutrino below.

4. BBN Constraints on the Freezing Temperature of Right Handed Neutrino and on Its Interactions with *CTP*

Big Bang Nucleosynthesis is among the most reliable tests of Beyond Standard Model (BSM) physics, thanks to the remarkable agreement between the theoretically predicted and derived from

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observations abundances of light elements produced during BBN. Cosmological constraint on the *CTP* coupling constant G_T based on possible interactions of *CTP* with right-handed neutrinos and their influence on the Big Bang Nucleosynthesis were first discussed in [2]. In case right-handed neutrinos interact with *CTP* they may be produced via *CTP* exchange during BBN epoch. The term of the effective Lagrangian corresponding to the right handed neutrino coupling to the Standard Model fermions reads:

$$L = \frac{4}{\sqrt{2}} G_T \bar{e}_L \sigma_{\alpha\beta} \nu_R \,.\, \bar{u}_L \sigma_{\alpha\beta} d_R + h.c., \tag{4}$$

where G_T measures the effective *CTP* interaction strength, $\sigma_{\alpha\beta} = \frac{i}{2}(\gamma_\alpha\gamma_\beta - \gamma_\beta\gamma_\alpha)$.

In following papers BBN constraints have been derived corresponding to different BBN bounds on δN_{eff} [6,8]. In the last decade primordial ^{4}He was known with 3-5% precision and the BBN constraints on BSM physics used this precision. Here we present the obtained constraints on T_f and G_T corresponding to the recently obtained stringent BBN constraint on the additional relativistic degrees of freedom $\delta N_{eff} < 0.2$ and for different assumptions about the number of light right handed neutrinos.

Besides, during the last decade the primordial abundances of the light elements D and He-4 were determined with higher and higher accuracy [19–21]. The higher precision of He-4 determination is mainly due to the inclusion of HeI λ 10830He infrared emission line measured in the extremely metal poor galaxy Leo P. These observations together with previous ones lead to the primordial helium abundance Y_p [21–23]:

$$Y_p = 0.2453 \pm 0.0034. \tag{5}$$

The higher precision of helium measurements allows to update and strengthen the cosmological BBN constraints on BSM physics. In this section we revise the cosmological constraints and present their more stringent values corresponding to around 1% uncertainty of He-4.

We discuss first the new cosmological constraints on the number of the effective degrees of freedom of relativistic particles during the BBN epoch and apply it to update the BBN constraints on the freezing temperature of the light r.-h. neutrinos. Then we derive updated BBN constraints on the interaction strength of BSM interactions of right handed neutrino with *CTP*.

4.1. Recent Constraints on Light Neutrino Types

BBN constrains the effective number of relativistic species N_{eff} or light neutrino types because additional light particles into equilibrium increase the expansion rate of the Universe $H \sim (G_N\rho)^{1/2}$, where $\rho = \rho_\gamma + \rho_\nu$ is the relativistic density. The effective number of relativistic species N_{eff} is defined by $\rho_\nu = 7/8T/T_\nu)^4 N_{eff}\rho_\gamma(T)$. Non-zero $\delta N_{eff} = N_{eff} - 3.045$ indicates any extra relativistic component. BBN, and in particular He-4, is a sensitive probe to additional species. He-4 is the best speedometer among the light elements produced during BBN. It is a strong function of the effective number of light stable particles at BBN epoch. BBN and the recent precise determination of primordially produced helium-4 provide the following stringent constraints on the number of light neutrino types during BBN epoch: $N_{eff} < 3.18$ at 95% C.L. [24].

Thus, although this BBN constraint is consistent with the standard model value $Neff = 3.045$, the deviations from it may indicate extra relativistic component like right handed neutrinos. In what follows we use $\delta N_{eff} < 0.2$ for obtaining BBN constraints on right handed neutrino decoupling and on new *CTP* physics.

4.2. BBN Constraint on Right Handed Neutrino Decoupling

In the expanding Universe particles are kept in thermal equilibrium while their interaction rates $\Gamma(T)$ are higher than the expansion rate H(T). Freeze-out occurs when they become comparable

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$\Gamma(T_f) \sim H(T_f)$. We updated the cosmological constraint on the freezing temperature of r.-h. neutrino T_f using recent BBN constraint $\delta N_{eff} = g_R (T_R/T_L)^4 < 0.2$, and using the entropy conservation

$$gT^3 = const \quad (6)$$

valid in case of adiabatic expansion of the Universe. Here T_R and T_L denote the temperatures of the right handed neutrino and left handed neutrino, correspondingly.

In refs. [6,7] we have updated the analysis of previous studies. Namely, for the relation between the effective degrees of freedom in the early Universe and the freezing temperature we used the data provided in ref. [25].

Assuming the existence of 3 light right-handed neutrinos types ν_R , from the BBN constraint it follows:

$$\delta N_{eff} = 3(T_R/T_L)^4 < 0.2 \quad (7)$$

This leads to a constraint on the freezing temperature of the right-handed neutrinos T_f using the BBN constraint on δN_{eff} and entropy conservation relation $gT^3 = const$, namely

$$T_R/T_L = (\frac{43}{4}/g_*(T_f))^{1/3} < 0.508. \quad (8)$$

The derived constraint on the decoupling temperature is $T_f > 1600$ MeV.

The constraint in case of 2 light r.-h. neutrino is correspondingly $T_f > 200$ MeV. In case of only 1 light r.-h. neutrino $T_f > 170$ MeV. These values are slightly lower than the determined in previous publications.

4.3. BBN Constraint on CTP Interactions

The freezing temperature of a given species depends on its interaction coupling strength:

$$\Gamma_R/\Gamma_L = (T_f/2)^3 (G_{new}/G_F)^2 \sim 1 \quad (9)$$

Comparing this freezing temperature with the electron neutrino decoupling temperature 2 MeV, one can get an insight of the coupling constant of new interactions of the right handed neutrinos [26]. For example constraints can be obtained on right handed neutrino coupling to Z' gauge bosons in models of superstrings, extended technicolor, etc.

In particular, in the case when right handed neutrinos interact with the chiral tensor particles, they may be produced through chiral tensor particles exchange during BBN (see Figure 2) and the corresponding Lagrangian of equation (4). Then, it is possible to obtain BBN constraint on *CTP* interaction strength.

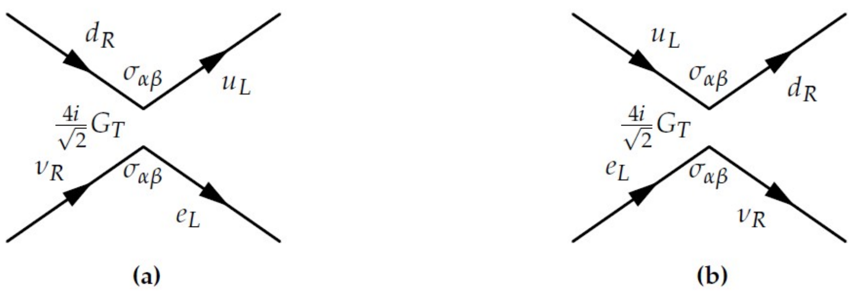

Figure 2. Feynman diagrams corresponding to Lagrangian (4).

Namely, the constraints on T_f can be interpreted as constraints on *CTP* interactions with right-handed neutrinos because

$$(G_F/G_T)^2 \sim (T_f/2\,\text{MeV})^3, \quad (10)$$

where 2 MeV is the freezing temperature of the electron neutrino, G_F is the weak interaction strength and G_T is the interaction strength of *CTP* interactions right handed neutrino may participate in. Then the following constraints follow: in case of 3 light right handed neutrinos

$$G_T/G_F < 4.5 \times 10^{-5}. \tag{11}$$

This BBN constraint points to the possibility of a smaller than milli-weak tensor interactions.

For 2 light right handed neutrinos similar analysis leads to the constraint: $G_T/G_F < 4.2 \times 10^{-4}$, for 1 light right handed neutrinos, correspondingly, the constraint reads: $G_T/G_F < 1.2 \times 10^{-3}$.

These constraints on G_T are much stronger than estimated in previous works. Such interactions should be at least thousands times weaker than the weak interactions, i.e. milli-weak interactions or weaker. Alternatives are that *CTP* have no interactions with fermions, or no light right handed neutrinos exist.

Here it is interesting to note that such a possibility about a lepto-phobic character of *CTP* interactions has been proposed [27] similar to the Higgs properties. Hence, *CTP* detection at hadron colliders may be even more challenging.

The analysis provides also a hint to the *CTP* masses. Namely, since $G_F \sim (g/M_W)^2$ and $G_T \sim (t/M_T)^2$ assuming $G_T \sim 10^{-4} G_F$ and $t \sim g$, it follows: $M_T \sim 100 M_W$. This prediction points to particle masses $M_T \sim 8$ TeV, i.e. considerably higher than the available experimental constraints.

5. Conclusions

We provided a short review of the cosmological influence of new chiral tensor particles on the early Universe. *CTP* particles characteristic processes: creation, annihilation, scattering and decay have been calculated. It was shown that their direct interactions, assuming $M_T \sim 8$ TeV, are effective for a short period $6 \times 10^{-42}\,s < t < 7 \times 10^{-15}\,s$ during the Universe evolution, which corresponds to the energy window $1.8 \times 10^{17} GeV < T < 1.6 \times 10^4$ GeV. Thus, *CTP* have been in equilibrium, i.e. abundantly present at a very early stage of Universe evolution, so that they could not directly effect BBN, CMB or other processes at much later epoch, which have left observable relics in today's Universe. Hence, *CTP* cannot be constrained on the bases of their direct interactions and their influence on these relics.

CTP also lead to an increase of the effective degrees of freedom and hence slightly speed up the expansion of the Universe and change its temperature-time dependence while CTP are in thermodynamical equilibrium in the early Universe plasma. However this effect again has negligible influence on the later epochs of BBN and CMB.

It was shown that, assuming that *CTP* interact with right handed neutrino, it will be possible to constrain *CTP* interactions from cosmology. Here, we provide an update of the BBN constraints on the freezing temperature of the light right handed neutrinos and the *CTP* interaction strength in case these neutrinos are produced via *CTP* exchange. This BBN constraint corresponds to the recent more precise measurements of the primordial abundances of the light elements and the corresponding cosmological constraint on the effective number of relativistic during BBN species. It was found that *CTP* interactions should be at least thousands times weaker than the weak interactions, i.e. *CTP* interactions are milli-weak or weaker depending on the number of light right-handed neutrino species. These results are important for studies of new physics in general.

The eventual future detection of the chiral tensor particles at LHC will provide a TeV window on the Universe, revealing the realm of milli weak interactions.

Besides, *CTP* may be present at energies typical for inflation, Universe reheating and leptogenesis and baryogenesis, therefore it is interesting to explore further the role of *CTP* in the very early Universe. Moreover, the extended model with *CTP* proposes new source for CP-violation and may present a natural mechanism for leptogenesis and baryogenesis scenarios.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CTP	Chiral Tensor Particles
BBN	Big Bang Nucleosynthesis
BSM	Beyond Standard Model

References

1. Chizhov, M.V. New Tensor Particles from $\pi \to e\nu\gamma$ and $K \to \pi e\nu$ Decays. *Modern Physics Letters A* **1993**, *8*, 2753–2762.
2. Kirilova, D.; Chizhov, M. A possible TeV window on the Universe. *Proceedings of XXIth Rencontres de Blois" Windows on the Universe* **2009**, pp. 21–26.
3. Chizhov, M.V.; Kirilova, D.P. Speeding the Friedmann expansion by chiral tensor particles. *Int. J. Mod. Phys. A* **2009**, *24*, 1643–1647. doi:10.1142/S0217751X09045157.
4. Kirilova, D.P.; Chizhov, V.M. Chiral tensor particles in the early Universe — Present status. *Mod. Phys. Lett. A* **2017**, *32*, 1750187, [arXiv:hep-ph/1711.07895]. doi:10.1142/S0217732317501875.
5. Kirilova, D.P.; Chizhov, V.M. Chiral tensor particles in the early Universe — Present status. *Mod. Phys. Lett. A* **2017**, *32*, 1750187, [arXiv:hep-ph/1711.07895]. doi:10.1142/S0217732317501875.
6. Kirilova, D.P.; Chizhov, E.M. Cosmological Constraints on Chiral Tensor Particles. *Int. J. Mod. Phys. A* **2019**, *34*, 1950065, [arXiv:physics.gen-ph/1905.06806]. doi:10.1142/S0217751X19500659.
7. Kirilova, D.; Chizhov, E.; Chizhov, V. Several BBN Constraints on Beyond Standard Model Physics. *Journal of Physics: Conference Series* **2020**, *1668*, 012022. doi:10.1088/1742-6596/1668/1/012022.
8. Kirilova, D.; Panayotova, M.; Chizhov, E. Updated BBN cosmological constraints on Beyond Standard Model physics. *PoS* **2023**, *BPU11*, 034. doi:10.22323/1.427.0034.
9. Chizhov, M.V. Theory and phenomenology of spin-1 chiral particles. *Physics of Particles and Nuclei* **2011**, *42*, 93–183.
10. Chizhov, M.V.; Bednyakov, V.A.; Budagov, I.A. Proposal for chiral bosons search at LHC via their unique new signature. *Physics of Atomic Nuclei* **2008**, *71*, 2096–2100.
11. Chizhov, M.V. Disentangling between Z′ and Z* with first LHC data, 2008, [arXiv:hep-ph/0807.5087].
12. Chizhov, M.V. Theory and phenomenology of spin-1 chiral particles. *Physics of Particles and Nuclei Letters* **2009**, *6*, 361–364.
13. Chizhov, M.V. Production of new chiral bosons at Tevatron and LHC, 2006, [arXiv:hep-ph/hep-ph/0609141].
14. Aad, G.; others. *Phys. Rev.D* **2014**, *90*, 205.
15. Aad, G.; others. Search for new particles in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector. *JHEP* **2014**, *09*, 037, [arXiv:hep-ex/1407.7494]. doi:10.1007/JHEP09(2014)037.
16. Kirilova, D.P.; Chizhov, M.V.; Velchev, T.V. First cosmology study of CTP. *Comptes Rendus de l'Académie bulgare des Sciences* **1995**, *48*.
17. Kirilova, D.P.; Chizhov, M.V. Is there cosmological evidence for additional particles? *Astronomical & Astrophysical Transactions* **1998**, *15*, 205–210, [https://doi.org/10.1080/10556799808201770]. doi:10.1080/10556799808201770.

18. Daniela, P.K.; Chizhov, E.M. Chiral tensor particles in the early universe BBN constraints. *AIP Conf. Proc.* **2019**, *2075*, 090015. doi:10.1063/1.5091229.
19. Pitrou, C.; Coc, A.; Uzan, J.P.; Vangioni, E. Precision big bang nucleosynthesis with improved Helium-4 predictions. *Physics Reports* **2018**, *754*, 1–66. doi:10.1016/j.physrep.2018.04.005.
20. Cooke, R.J.; Pettini, M.; Steidel, C.C. One Percent Determination of the Primordial Deuterium Abundance*. *The Astrophysical Journal* **2018**, *855*, 102. doi:10.3847/1538-4357/aaab53.
21. Aver, E.; Berg, D.A.; Olive, K.A.; Pogge, R.W.; Salzer, J.J.; Skillman, E.D. Improving helium abundance determinations with Leo P as a case study. *Journal of Cosmology and Astroparticle Physics* **2021**, p. 027. doi:10.1088/1475-7516/2021/03/027.
22. Hsyu, T.; Cooke, R.J.; Prochaska, J.X.; Bolte, M. The PHLEK Survey: A New Determination of the Primordial Helium Abundance. *The Astrophysical Journal* **2020**, *896*, 77. doi:10.3847/1538-4357/ab91af.
23. Valerdi, M.; Peimbert, A.; Peimbert, M.; Sixtos, A. Determination of the Primordial Helium Abundance Based on NGC 346, an H ii Region of the Small Magellanic Cloud. *The Astrophysical Journal* **2019**, *876*, 98. doi:10.3847/1538-4357/ab14e4.
24. Yeh, T.H.; Shelton, J.; Olive, K.A.; Fields, B.D. Probing physics beyond the standard model: limits from BBN and the CMB independently and combined. *Journal of Cosmology and Astroparticle Physics* **2022**, *2022*, 046. doi:10.1088/1475-7516/2022/10/046.
25. Husdal, L. On Effective Degrees of Freedom in the Early Universe. *Galaxies* **2016**, *4*, 78. doi:10.3390/galaxies4040078.
26. Dolgov, A. Neutrinos in cosmology. *Physics Reports* **2002**, *370*, 333–535. doi:10.1016/s0370-1573(02)00139-4.
27. Chizhov, M.V.; Bednyakov, V.A. Signatures of lower scale gauge coupling unification in the Standard Model due to extended Higgs sector. *Physics of Atomic Nuclei* **2016**, *79*, 721–725, [arXiv:hep-ph/1509.07610]. doi:10.1134/S1063778816050069.