ISNP “Particle and Nuclear Astrophysics”

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On lepton asymmetry and BBN

Daniela Kirilova

Institute of Astronomy
Bulgarian Academy of Sciences, Sofia, Bulgaria

Why explore LA ?

- ✓ Cosmology can be used to probe neutrino properties.
- ✓ Knowledge about LA helps to determine the cosmological parameters

  Neutrinos are abundant, significant cosmological effect is expected.
- ✓ There exist cosmological evidence about the presence of additional relativistic density - additional light particles, LA , etc. ..

  N_{BBN}=3.8+0.8-0.7 N_{CMB}=4.34+0.9-0.9 N_{SDS}=4.8+1.9-1.8
- ✓ Combined neutrino oscillations data (including MiniBoone and LSND) require 1 or 2 additional sterile neutrino. Active-sterile oscillations may generate LA.
- ✓ LA provides relaxation or enhancement of BBN constraints on oscillations.
- ✓ Determining LA at BBN would test the assumption that sphalerons equilibrate L and B asymmetries
- ✓ In case of ξ>2 Plank will be able to detect small neutrino mass ~0.07 eV because LA enhances the effect of the mass
- ✓ LA chaotic behavior may result in formation of leptonic domains
- ✓ Inhomogeneous BBN - Abundances of light elements may be sensitive to LA magnitude and sign.

Outline

Introduction

Neutrino oscillations generated LA

BBN with oscillations generated LA

BBN with initially present LA

BBN constraints in the presence of LA

Lepton Asymmetry

Lepton asymmetry of the Universe

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

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

$$\xi = \mu / T$$

may be up to 8 orders of magnitude larger than the baryon one,

$$\beta = (n_b - n_{\bar{b}}) / n_\gamma \sim 6.10^{-10}$$

measured precisely by different independent means (by BBN and CMB data, etc.)

Though usually assumed $L \sim \beta$, big LA may reside in the neutrino sector .

(universal charge neutrality implies $L_e = \beta$) .

$$L \sim \sum_i L_{\nu_i}$$

CNB has not been detected yet, hence LA may be measured/constrained only indirectly through its effect on other processes, which have left observable relics or traces in the Universe:

Dolgov,2002

light element abundances from Big Bang Nucleosynthesis

Wagoner et al.1967….Terasawa&Sato, 1988 …

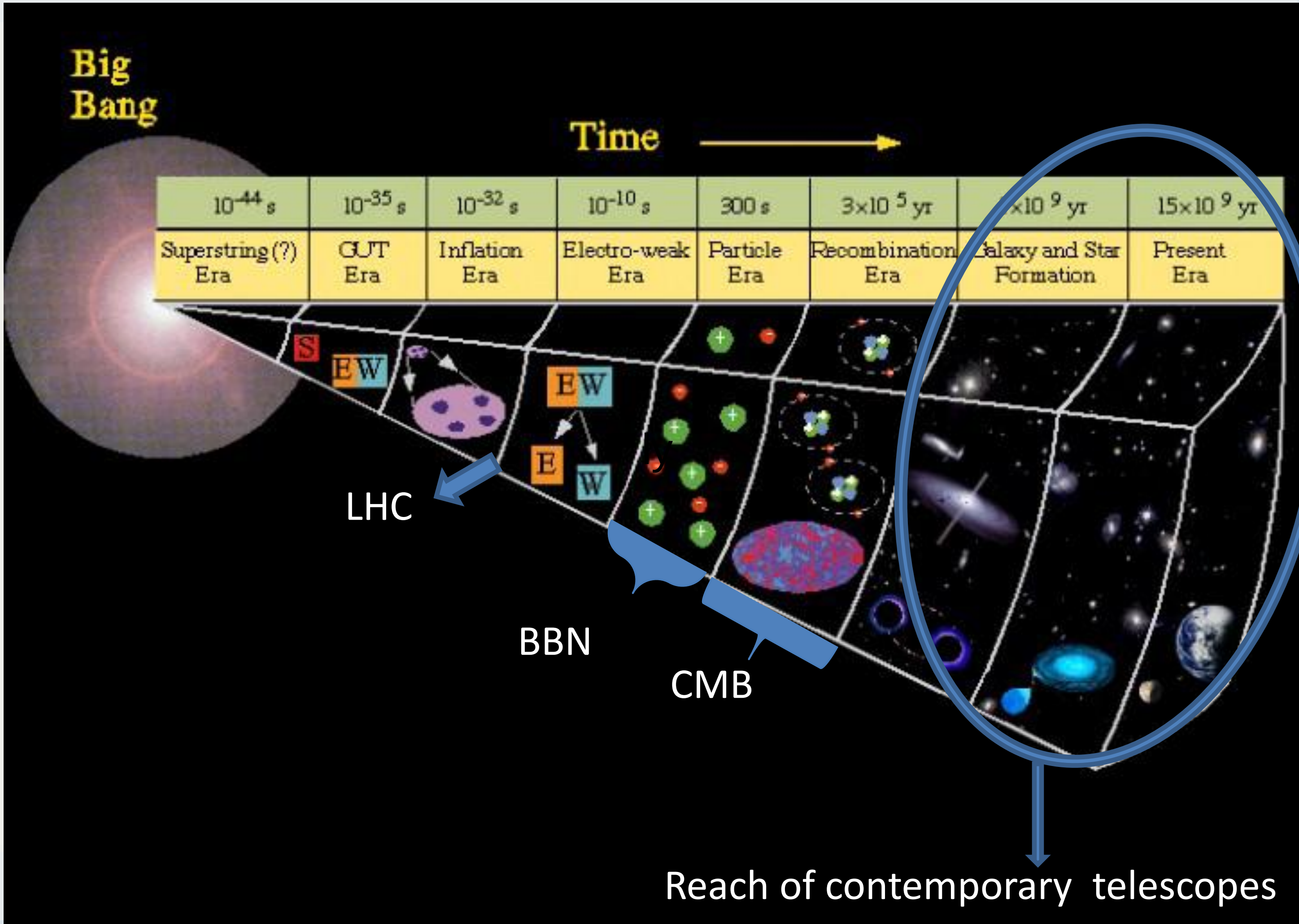
Serpico&Raffelt, 2005; Pastor, Pinto&Raffelt,2009; Simha&Steigman, 2008

Cosmic Microwave Background

Lesgourgues&Pastor,1999; Shiraishi et al., 2009; Popa&Vasile, 2008

LSS, etc.

Information form different epochs



Lepton Asymmetry

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Cosmic Microwave Background

Lesgourgues&Pastor,1999; Shiraishi et al., 2009; Popa&Vasile, 2008

LSS, etc. *Larsen&Madsen, 1995*

information from LA effect on QCD transition *talk of M. Stuke* ; *Schwarz&Stuke,09*

Lepton Asymmetry Effects

- Non-zero LA increases the radiation energy density

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

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

leading to faster expansion $H=(8/3\pi G\rho)^{1/2}$, delaying matter/radiation equality epoch …

⟹ influence BBN, CMB, evolution of perturbations i.e. LSS

- $|L_{\nu e}|> 0.01$ effect neutron-proton kinetics in pre-BBN epoch

$$\nu_e + n \leftrightarrow p + e^-$$
$$e^+ + n \leftrightarrow p + \tilde{\nu}_e$$
$$n \to p + e^- + \tilde{\nu}$$

⟹ influence BBN, outcome is L sign dependent

Simha&Steigman, 2008:

$$Y_p \sim (0.2482 \pm 0.0006) + 0.0016\eta_{10} + 0.013\Delta N_{eff} - 0.3\xi_{\nu_e}$$

- $L \geq 10^{-7}$ effects neutrino evolution, its number density, spectrum distribution, oscillations pattern and hence n/p kinetics and BBN

DK&Chizhov, 1996, PLB 97, NPB98,2000,2001 , DK2010

- LA changes the decoupling T of neutrino

Lepton Asymmetry Constraints

- At present BBN provides the most stringent constraint on L $|\xi_{\nu_{\mu,\tau}}| < 1.5$ $|\xi_{\nu}| < 0.1$
  in case of combined variation of chemical potenials

Hansen et al.,2002 $-0.01 < \xi_{\nu_e} < 0.2$ $|\xi_{\nu_{\mu,\tau}}| < 2.6$

In case of neutrino oscillations degeneracies equilibrate due to oscillations before BBN

Dolgov et al., NPB, 2002 $|\xi_{\nu}| < 0.1$

Serpico&Raffelt,2005 $-0.04 < \xi_{\nu} < 0.07$

Serpico, Pinto&Raffelt θ_{13} role $\xi_{\nu_e} \neq \xi_{\nu_\mu} = \xi_{\nu_\tau}$: $\xi_{\nu} < 2.3$ $L < 5$

Simha&Steigman, JCAP, 2008 $\xi_{\nu_e} = \xi_{\nu_\mu} \neq \xi_{\nu_\tau}$: $\xi_{\nu\tau} < 4$ $L < 7.6$

$\xi_{\nu_e} = \xi_{\nu_\mu} = \xi_{\nu_\tau}$: $|\xi_{\nu}| < 0.1$ $L \sim 0.07 \mp 0.05$

Practically standard H, δN~0.03 in the last case (undetectable). However, large and opposite ξ in two flavours are allowed $\delta N_{eff} L(\xi)$ ~1 detectable by BBN,CMB *Pastor,Pinto&Raffelt, 2009*

- CMB and LSS provide much looser bounds

$\delta N_{eff} L(\xi)$ modifies the power spectra of radiation and matter *Lesgourgues&Pastor, 99*

CMB (WMAP5+all) and LSS: $\xi_{\nu} < 0.7$ $L < 0.6\_(2\sigma)$

Popa&Vasile, 2008 forcast for Planck: $\xi_{\nu} < 0.3$

Sihiraishi et al.,09 WMAP5+Y(BBN) $-0.04 < \xi_{\nu} < 0.02$ $-0.03 < \xi_{\nu_e} < 0.13$ $|\xi_{\nu_{\mu,\tau}}| < 1.67$

Christel Smith talk $-0.1 < \xi_{\nu} < 0$

Asymmetry - Oscillations Interplay
Lepton Asymmetry Generation

- Oscillations in a medium are capable to suppress pre-existing asymmetry
  Barbieri&Dolgov ,90.91; Enqvist et al.,1992
- Asymmetry is capable to suppress oscillations
  Foot&Volkas, 95; DK&Chizhov , NPB 98
- LA can enhance neutrino oscillations
  DK&Chizhov , NPB 98
- LA may be generated by MSW resonant neutrino oscillations in the early Universe in active sterile oscillations

- There are different mechanisms producing large LA.

LA generation possibility in MSW resonant neutrino oscillations in the early Universe in active sterile oscillations was first found

$\delta m^2 > 10^{-5} eV^2$ in collisions dominated oscillations *Foot&Volkas 96*

$\delta m^2 < 10^{-7} eV^2$ in the collisionless case *DK&Chizhov , 96*.

$$\theta_m(\delta m^2, \theta, L, T, ..)$$

L-T=M

-L-T=M

We studied the interplay between small LA and neutrino oscillations in the early Universe and their effect on BBN in more detail for the specific case:

- Neutrino electron-sterile oscillations

$$\nu_1 = \nu_e \cos\theta + \nu_s \sin\theta$$
$$\nu_2 = - \nu_e \sin\theta + \nu_s \cos\theta$$

effective after active neutrino decoupling $\delta m^2 \sin^4 2\theta \le 10^{-7}$ eV^2 were discussed.

- Two different cases of LA were studied:

initially present and dynamically generated by oscillations.

LA effect in density and direct effect in n-p kinetics – negligible

Even for fast oscillation case <p> approximation – not suitable, LA growth overestimated. Approximate solutions of L(t) were developed.

Foot&Volkas 97, Bell,Volkas&Wang,99

In case of late oscillations – strong distortion of neutrino spectrum due to oscillations. Neutrino momentum distribution should be taken into account.

DK&Chizhov , NPB 96, 98, 2001 *DK2010*

Neutrino oscillations during BBN

❖ **Active-sterile oscillations** may have considerable cosmological influence!

✓ Dynamical effect: Excite additional light particles into equilibrium δN_s

$\rho \sim g_{eff} T^4$ $\quad H \sim \sqrt{g_{eff} G} T^2$ $\quad g_{eff} = 10.75 + \frac{7}{4}\delta N_s$ $\quad \delta N_s = N_\nu - 3$

Fast $\nu_a \leftrightarrow \nu_s$ effective before ν_a decoupling - effect CMB through increasing ρ and BBN by increasing H

He-4 mass fraction is a strong function of the effective number of light stable particles at BBN epoch $\delta Y_d \sim 0.013\, \delta N_s$ (the best speedometer).

✓ Distort the neutrino energy spectrum from the equilibrium FD form
change neutrino-antineutrino asymmetry of the medium (suppress / enhance)

$$\Gamma \sim G_F^2 E_\nu^2 N_\nu$$

Effect both expansion rate and the weak interactions rates, may distort ν_e energy spectrum, causing ν_e depletion, neutrino-antineutrino asymmetry generation and influences the neutrino involved processes in Universe, like BBN Kinetics, CMB, etc.

Active-sterile oscillations may play crucial role for neutrino involved processes in the Universe during BBN, CMB, LSS, CNB

He-4 depends also on the ν_e characteristics ν_e decrease $\rightarrow$ n/p freezes earlier $\rightarrow$ ^{4}He is overproduced

Dolgov 81. DK 88, Barbieri, Dolgov 90, Kainulainen 91, Enqvist et al.,92, Foot&Volkas 95,96; DK&Chizhov 96,97,2000; Dolgov&Villante 03; DK04,07

Evolution of neutrino in presence of $\nu_e \leftrightarrow \nu_s$ oscillations and LA

- We followed the evolution of the oscillating ν and ν_s, accounting simultaneously for Universe expansion, neutrino oscillations and neutrino forward scattering. In case of oscillations after neutrino decoupling the last term is negligible.

$$\frac{\partial\rho(t)}{\partial t} = Hp_\nu \frac{\partial\rho(t)}{\partial p_\nu} + i\left[\boldsymbol{H}_0, \rho(t)\right] + i\sqrt{2}G_F\left(L - \frac{Q}{M_W^2}\right)N_\gamma\left[\alpha, \rho(t)\right] + O\left(G_F^2\right)$$

$$\frac{\partial\bar{\rho}(t)}{\partial t} = Hp_\nu \frac{\partial\bar{\rho}(t)}{\partial p_\nu} + i\left[\boldsymbol{H}_0, \bar{\rho}(t)\right] + i\sqrt{2}G_F\left(-L - \frac{Q}{M_W^2}\right)N_\gamma\left[\alpha, \bar{\rho}(t)\right] + O\left(G_F^2\right)$$

$$\alpha = U_{ie}^* U_{je}, \quad \nu_i = U_{il}\nu_l \quad l = e, s$$

$\boldsymbol{H_0}$ *is free neutrino Hamiltonian*

$$Q \sim E_\nu T \qquad L \sim 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} \qquad L_{\nu_e} \sim \int d^3p\left(\rho_{LL} - \bar{\rho}_{LL}\right)/N_\gamma$$

$$g_{eff} = 10.75 + \frac{7}{4}\delta N_s \qquad \delta N_s = N_\nu - 3$$

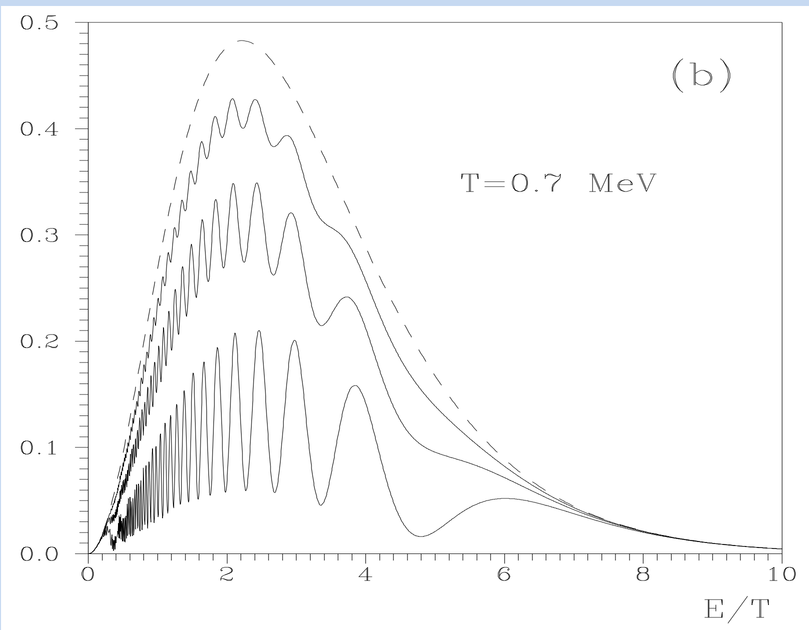
$$\rho_{LL}^{in} = n_\nu^{eq} = \exp\left(-(E_\nu + \mu_\nu)/T\right)\Big/\left(1 + \exp\left(-(E_\nu + \mu_\nu)/T\right)\right) \qquad \rho^{in} = n_\nu^{eq}\begin{pmatrix} 1 & 0 \\ 0 & \delta N_s \end{pmatrix}$$

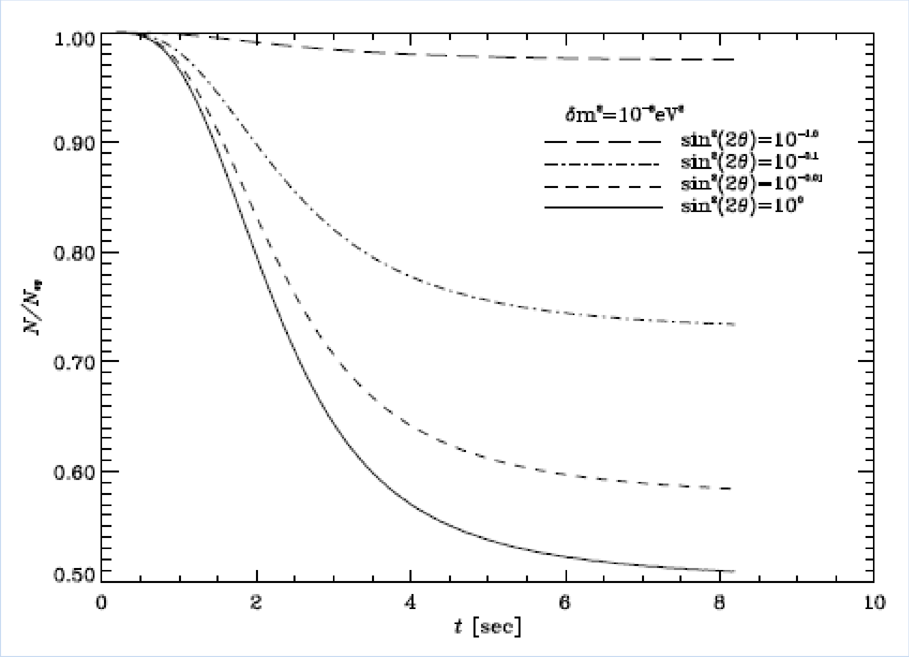
Non-zero LA term leads to coupled integro-differential equations and hard numerical task .
LA term leads to different evolution of neutrino and antineutrino.

Small L<<0.01, that do not effect directly BBN kinetics, influence *indirectly* BBN via oscillations by:

- ✓ changing neutrino number densities
- ✓ changing neutrino distribution and spectrum distortion
- ✓ changing neutrino oscillations pattern (suppressing or enhancing them)

- Active-sterile oscillations proceeding after decoupling may strongly distort neutrino energy spectrum.





DK,IJMPD,2004, 2007

Precise description of neutrino momenta distribution is needed, which further complicates the numerical task. Therefore, this parameter space was not explored in other studies.

In the analysis 1000 bins are used to describe it in non-resonant case, and up to 5000 in the resonant case.

Oscillations generated lepton asymmetry

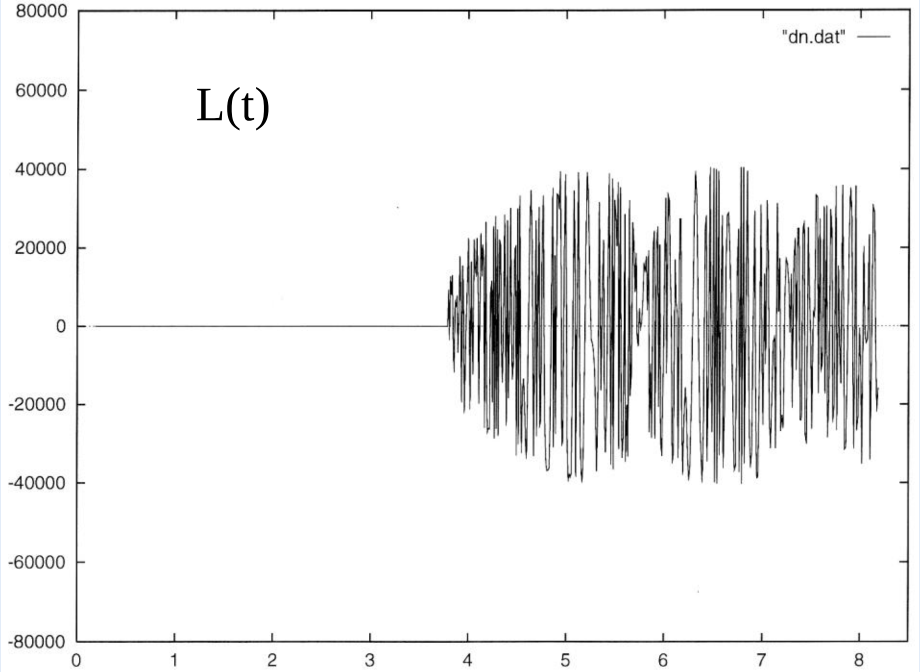
In the region $\delta m^2 \sin^4 2\theta < 10^{-7} eV^2$ evolution of LA is dominated by oscillations and typically LA has rapid oscillatory behavior. The region of parameter space for which large generation of LA is possible: $|\delta m^2| \sin^4 2\theta \le 10^{-9.5} eV^2$

Generation of LA up to 5 times larger than β is found possible, i.e. $L \sim 10^{-5}$

The analytical approximation is in agreement with bounds existing in literature .

Distribution of the neutrino momenta was found to play extremely important role for the correct determination of LA evolution.

L



In some cases increasing the resolution of momentum space leads to changes of oscillatory character and diminishes LA. Further analysis is required to decide if the oscillatory behavior and LA strong growth is induced by numerical error. This observation is in accordance with the studies of other authors in other parameter regions. Bari&Foot ,2000

Usually generated lepton number oscillates and changes sign, as illustrated in the figure. It presents the evolution of LA for $\delta m^2 \sim 10^{-8.5} eV^2$ and $\sin^2 2\theta = 10^{-0.5}$

Dynamical asymmetry and BBN

❖ In BBN with $\nu_e \leftrightarrow \nu_s$ and LA neutrino spectrum distortion and the density of electron neutrino may considerably differ from the standard BBN one, leading to different nucleon kinetics, and modified BBN element production.

Simultaneous calculation of evolution of nucleons in the presence of $\nu_e \leftrightarrow \nu_s$

$$\frac{\partial n_p}{\partial t} = Hp_n \frac{\partial n_n}{\partial p_n} + \int d\Omega(e^-, p, \nu) \left| A(e^- p \to \nu n) \right|^2 (n_{e^-} n_p - n_n \rho_{LL})$$

$$- \int d\Omega(e^+, p, \tilde{\nu}) \left| A(e^+ n \to p \tilde{\nu}) \right|^2 (n_{e^+} n_n - n_p \bar{\rho}_{LL})$$

$$\delta m^2 \leq 10^{-7}\, eV^2 \qquad all\ mixing\ angles\ \theta \quad 0 \leq \delta N_s \leq 1$$

$$2\ MeV \geq T \geq 0.3\ MeV$$

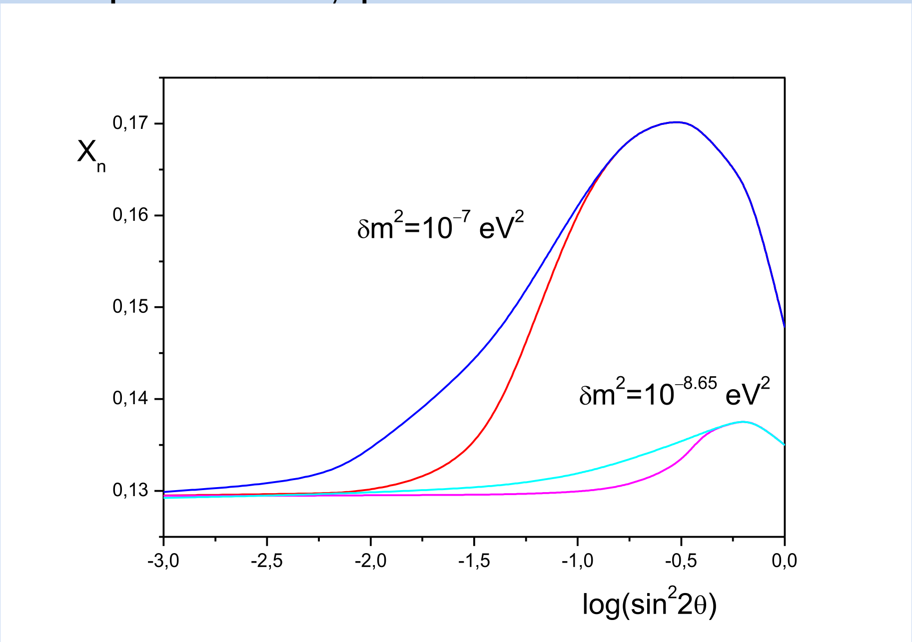
Oscillations dynamical and kinetic effect on BBN were found possible.

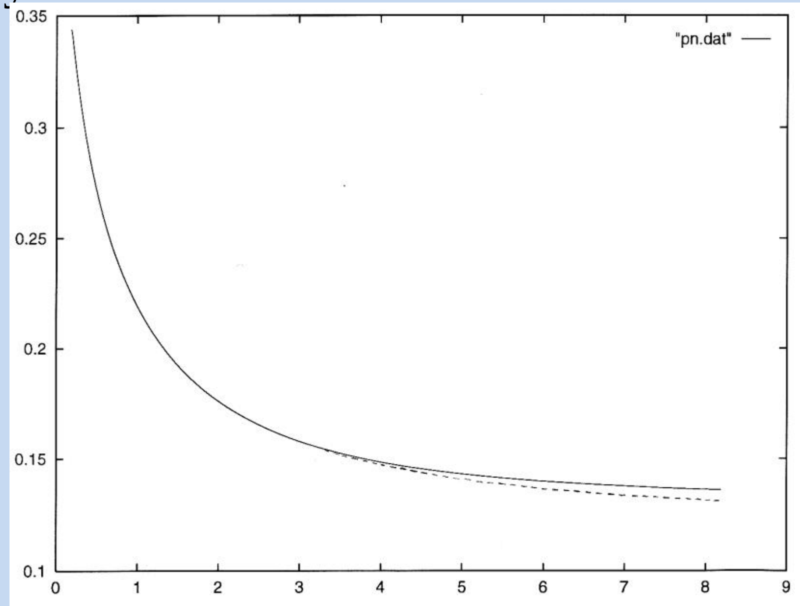
$\delta Y \sim 0.013\ \delta N$

$\delta N = \delta N_{k,0} - \delta N_{k,0}\, \delta N_s + \delta N_s$

Dynamical asymmetry and BBN

- Nucleons evolution in the pre-BBN period in the presence of $\nu_e \leftrightarrow \nu_s$ was numerically analyzed for different sets of oscillation parameters and the primordially produced He-4 was numerically calculated.





The figure (l.h.s.) shows neutron-to-nucleons freezing ratio dependence for two different mass differences on the mixing in case of the account of asymmetry growth (red curves) and in case without asymmetry growth account. *DK, 2010*

The figure shows neutron-to-nucleons freezing ratio evolution in the case of asymmetry growth (solid line) and in case asymmetry growth neglected (dotted line).

- The neutron-to-nucleons freezing ratio X_n (and correspondingly the primordially produced He-4) decreases at small mixing parameters values due to asymmetry growth.

BBN constraints on neutrino oscillation parameters

He-4 is the preferred element:

- ✓ abundantly produced (25% by mass),
- ✓ precisely measured (<3 % uncertainty)

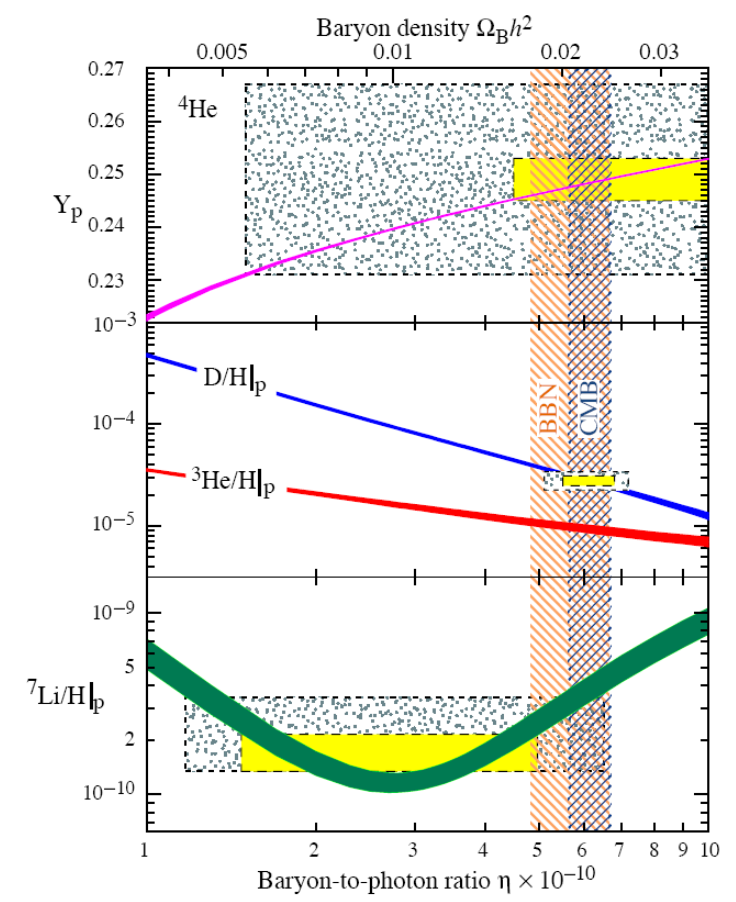
Y_p=0,2565 ± 0.001(stat)± 0,005(syst)

Izotov&Thuan, 2010 93 Sp of 86 low Z HII

- ✓ precisely calculated (0.1% uncertainty)

Y_p=0,2482± 0,0007

- ✓ has a simple post-BBN chemical evolution
- ✓ best speedometer and leptometer
- ✓ sensitive to neutrino characteristics (n, N, sp,LA…)



BBN constraints corresponding to $\delta Y_p/Y_p$=3% in case proper account for spectrum distortion and asymmetry growth due to oscillations were obtained.

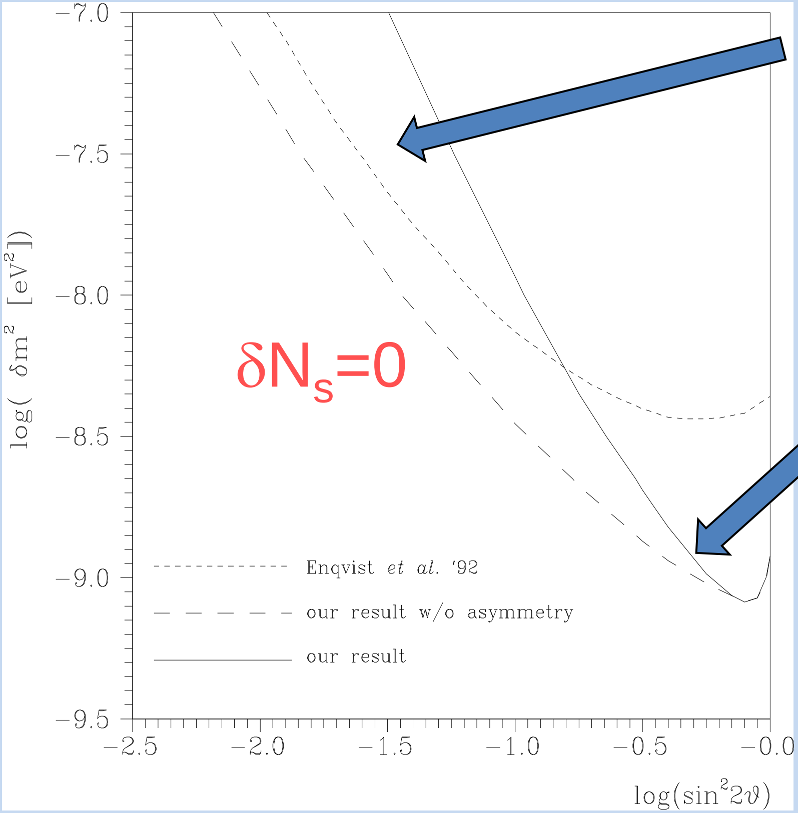
$$\delta m^2 \left(\sin^2 2\theta\right)^4 \le 1.5\times10^{-9} eV^2 \quad \delta m^2 > 0$$

$$\delta m^2 < 8.2\times10^{-10} eV^2 \quad \text{large } \theta,\ \delta m^2 < 0$$

DK, Chizhov NPB2000,2001; DK&Panayotova JCAP 2006;DK IJMPD 07

Effects of neutrino-antineutrino asymmetry and distortion of spectrum

❖LA changes energy spectrum distribution and the number densities of ν_e from standard BBN case. This influences the kinetics of nucleons during BBN and changes the produced light element abundances.

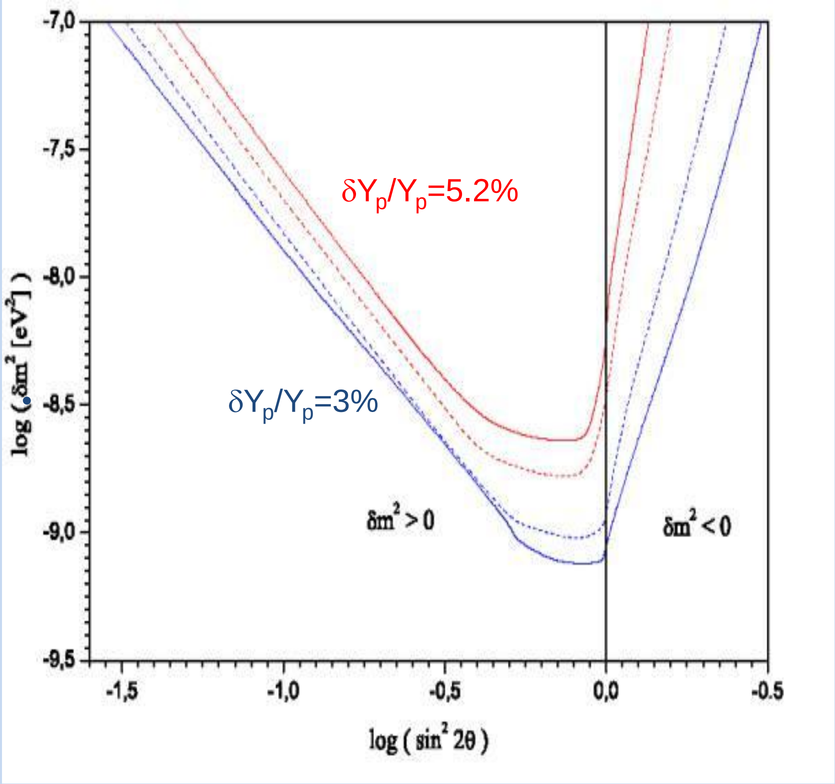


- ❖ The account of the neutrino-antineutrino asymmetry growth caused by resonant oscillations leads to relaxation of the BBN constraints for small mixings.

- ❖ The spectrum distortion leads to a decrease of the weak rates, to an increase of the n/p freezing T and He overproduction. Correspondingly the account of spectrum distortion leads to strengthening of BBN constraints at large mixings.

BBN constraints on neutrino oscillation parameters

Constraint contours, corresponding to 3 and 5% Helium-4 overproduction.



DK,Panayotova, 2006 ; DK, 2007

The dotted blue (red) contour presents $\delta Y_p/Y_p=3\%$ ($\delta Y_p/Y_p=5.2\%$) for $\delta N_s=0$, the solid blue (red) contour presents $\delta Y_p/Y_p=3\%$ ($\delta Y_p/Y_p=5\%$) for $\delta N_s=0,5$.

- ✓ An order of magnitude better in mass differences than the existing cosmological constraints due to the exact account of spectrum distribution distortion
- ✓ More precisely constraining the mixing angle thanks to the correct account of asymmetry growth and spectrum distortion
- ✓ Excluded 2 of the possible solutions of the solar neutrino problem – LMA (large mixing angle solution) and LOW (low mixing angle solution) (1996, 1999)
- ✓ Excludes electron-sterile solution to LSND

Additional ν_s population and additional LA may strengthen or relax BBN constraints on oscillations.

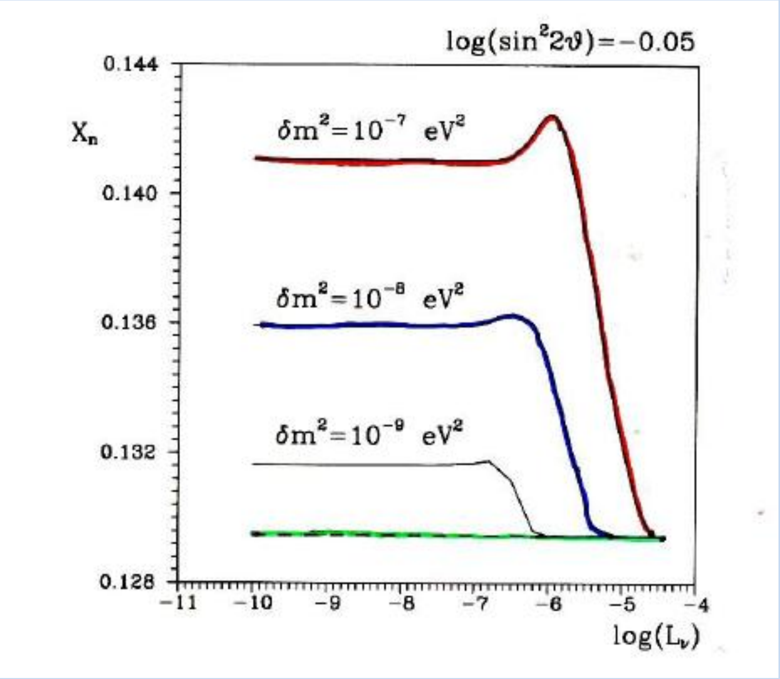
Initial asymmetry, oscillations and BBN

The numerical analysis of BBN for the entire range of mixing parameters of the model and with initial small LA has proved that $L > 10^{-7}$ may considerably influence BBN:

smaller asymmetries may be safely neglected (which reduces enormously the computational time),

$L \sim 10^{-7}$ enhances oscillations, while $L > 0.1(\delta m^2)^{2/3}$ suppresses oscillations, and asymmetries as big as $L > (\delta m^2)^{2/3}$ inhibit oscillations.

$Y_p\left(\delta m^2, \theta, L\right)$



Small $10^{-7} < L << 0.01$, not effecting directly BBN kinetics, influence *indirectly* BBN via oscillations.

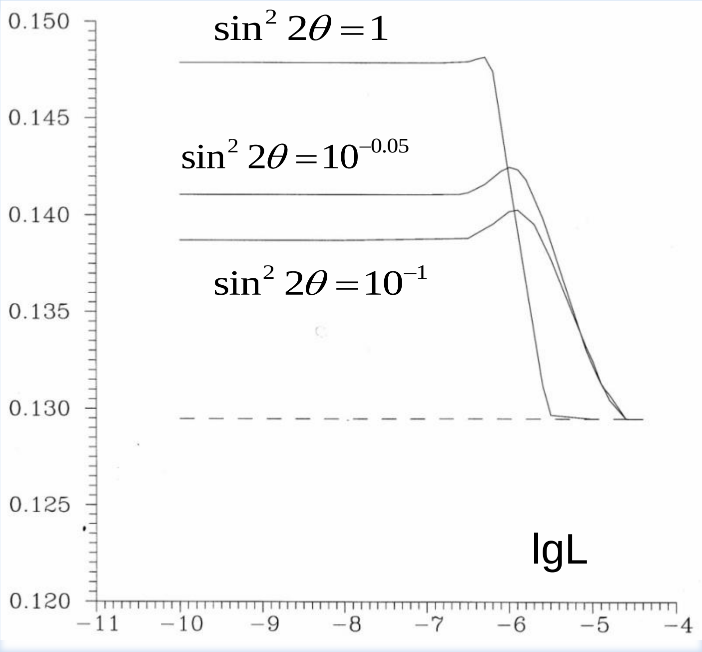
He-4 production dependence on oscillation parameters and on LA shows that,
in case of neutrino oscillations:

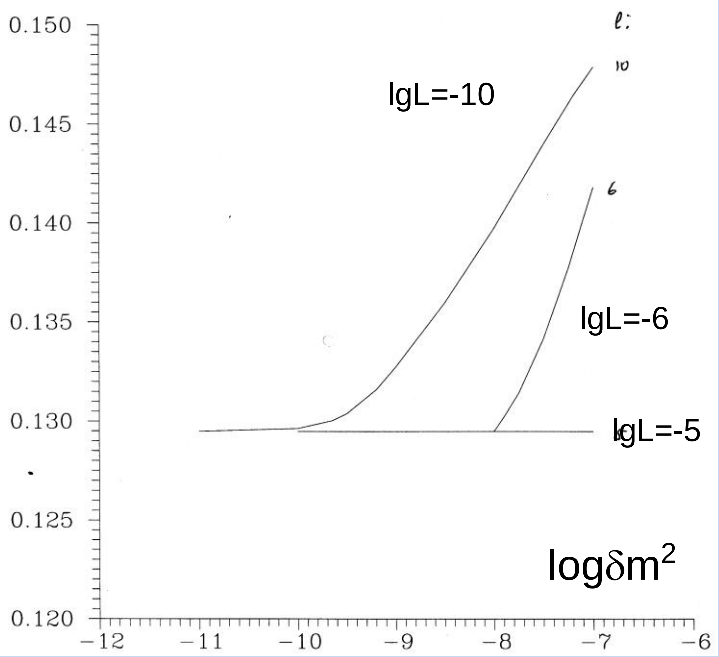
- BBN can feel extremely small L: down to 10^{-7}
- Large enough L change primordial production of He by enhancing or suppressing oscillations.

BBN with oscillations is the best known leptometer.

- LA bigger than 10^{-5} leads to a total suppression of oscillations effect on BBN and hence, eliminates the BBN bounds on oscillation parameters. In that case, instead, the following approximate bound holds:

$$\delta m^2 < L^{3/2}$$

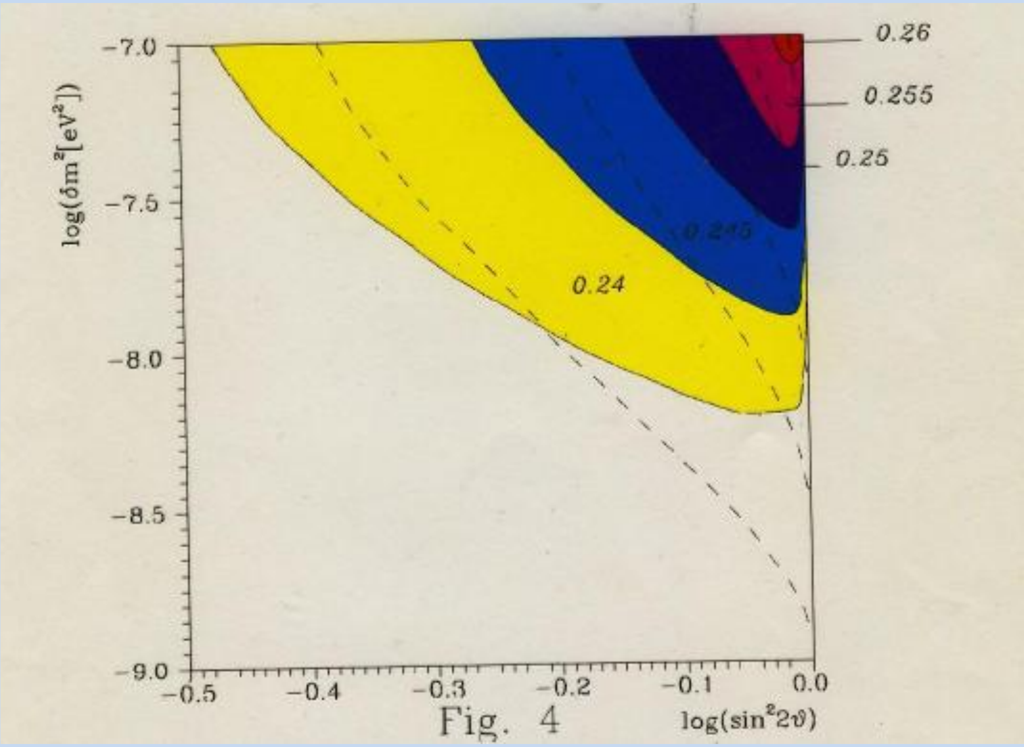




The dependences of helium production on the initial LA for different mixings (to the left) and on mass differences for three different values of LA .

Change of BBN constraints by LA

- ✓ Lepton asymmetry may relax BBN constraints at large mixings and strengthen them at small mixing.



The figure presents the change of the BBN constraints in case of $L=10^{-6}$.
Isohelium contours 0.24 – 0.26 are calculated for the case with lepton asymmetry (in colors), and for the case of lepton asymmetry of the order of the baryon one (dashed lines).

✓Large enougth LA may alleviate BBN oscillations constraints $L > (\delta m^2)^{2/3}$

Summary

- We have found effective lepton asymmetry generation mechanism in active-sterile Mikheyev-Smirnov-Wolfenstein oscillations, effective after neutrino decoupling. Higher resolution for the description of the neutrino momenta distribution is required for the investigation of the asymmetry behavior in this oscillation parameter region.
- The instability region in the oscillation parameter space, where considerable growth of LA takes place, was determined numerically for the case of non-equilibrium neutrino oscillations.
- We provided a detail numerical analysis of the interplay between small lepton asymmetry LA << 0.01, either relic (initially present) or dynamical (generated by MSW active-sterile neutrino oscillations) and neutrino oscillations for the case of active-sterile oscillations occurring after electron neutrino decoupling. The evolution of asymmetry growth in case of small mass differences and relatively big mixing angles was studied in more detail.
- The parameter range for which lepton asymmetry is able to enhance, suppress or inhibit oscillations is determined.
- Cosmological influence of such small lepton asymmetries, which do not have direct effect on nucleons kinetics during BBN, is discussed and shown not to be negligible. Such small asymmetries are invisible by CMB, but may be felt by BBN: lepton asymmetries as small as 10^{-7} may be felt by BBN in case of neutrino oscillations.
- The effect of the dynamically generated and initially present LA on BBN with oscillations was studied.
- Relic LA present during BBN, depending on its value, can strengthen, relax or wave out BBN constraints on oscillations. It relaxes BBN bounds at large mixing and strengthens them at small mixings. Large enough LA alleviates BBN constraints on oscillation parameters.
- Dynamically generated asymmetry relaxes BBN constraints at small mixing angles.

Conclusions

Active-sterile oscillations may considerably distort neutrino spectrum and produce neutrino-antineutrino asymmetry, thus influencing BBN.

BBN is the most sensitive cosmological probe of number of neutrino species, of distortions in the energy distribution of neutrinos, lepton asymmetry, neutrino mass differences and mixings, etc. It provides constraints on many neutrino characteristics.
He-4 primordial production depends strongly on the expansion rate and on the lepton asymmetry of the Universe - it is the best speedometer and leptometer.

BBN constraints on neutrino oscillations parameters depend   nontrivially on the lepton asymmetry in the Universe.

Благодаря за вниманието!

Thanks for the attention!