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Updated BBN constraints on neutrino oscillation parameters, lepton asymmetry and the solution of dark radiation problem

Daniela Kirilova, Mariana Panayotova, Emanuil Chizhov

Institute of Astronomy and NAO
Bulgarian Academy of Sciences, Sofia, Bulgaria

Outline

- Neutrino influence on early Universe processes at pre-BBN and BBN epoch
  - neutrino oscillation effects
- BBN - the reliable early Universe probe
- BBN with neutrino oscillations
- BBN with neutrino oscillations and lepton asymmetry
  - lepton asymmetry - neutrino oscillations interplay
  - dark radiation problem
  - lepton asymmetry from EMPRESS experiment

Kirilova, Panayotova, Chizhov, Symmetry 2024 16, 1.

Kirilova, Panayotova, Journal of Physics 2024

Kirilova,Panayotova, Chizhov, PoS 2023

Oscillating Neutrino at RD stage presents BSM

- Universe is filled with oscillating neutrinos

three neutrino flavours exist ν_e, ν_μ, ν_τ

$\delta m^2 \neq 0$ at least 2 neutrino with $m_\nu \neq 0$

- The lepton asymmetry maybe non zero
- Non equilibrium energy distribution of neutrinos.

$$n_\nu^{cnb} \neq n_\nu^{eq} = \exp(-E/T)/(1+\exp(-E/T))$$

➢ Neutrino contributes to the energy density of the Universe and thus influences the expansion rate of the Universe, BBN effect, etc

Neutrino Oscillations Effects

- Dynamical effect: Excite additional light particles into equilibrium δN_s

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

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

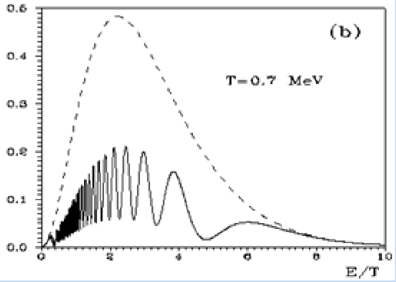
Dolgov 81. Kirilova 88, Barbieri, Dolgov 90, Kainulainen 91, Enqvist et al.,92

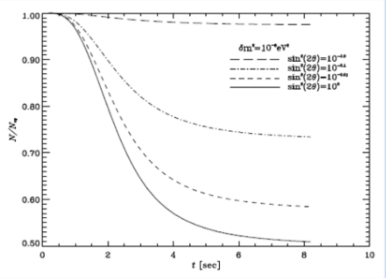
✓ Distorting the neutrino energy distribution from the equilibrium FD form

$$n_\nu^{cnb} \neq n_\nu^{eq} = \exp(-E/T)/(1+\exp(-E/T))$$

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

DK 88, D.K&Chizhov,96,PLB 97





He-4 depends on the ν_e characteristics: ν_e decrease → n/p freezes earlier → ^{4}He is overproduced

✓ Change neutrino-antineutrino asymmetry of the medium (suppress / enhance)

D.K&Chizhov,96; Foot&Volkas 95,96; Shi 96

Active-sterile oscillations may have considerable cosmological influence!

BBN is sensitive to additional species and to distortions in neutrino distribution
BBN constrains oscillation parameters.

DK&Chizhov 98,2000, Dolgov&Villante 03, DK04,07 DK 04, 2012, DK&Panayotova 06

Evolution of neutrino in presence of late $\nu_e \leftrightarrow \nu_s$

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

$$\delta m^2 \sin^4 2\theta \le 10^{-7}$$

DK 1988, Chizhov, DK, 1997

- The evolution of the oscillating ν and ν_s, accounting simultaneously for Universe expansion, neutrino oscillations and neutrino forward scattering is described by:

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

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

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

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

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

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

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

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

In case of late oscillations distortion of neutrino momentum distribution by oscillations is possible.

Precise description of neutrino momenta distribution is needed: 1000 bins used to describe it in non-resonant case, and up to 10 000 in the resonant case.

Standard BBN

The chemical composition of the baryonic component of Universe now is mainly 24.5% He^4 and H.

This content is synthesized during the hot early stage of the Universe evolution when its temperature T (1–0.1 MeV) and density were suitable for nuclear reactions to proceed, i.e. during primordial nucleosynthesis BBN.

Besides He-4 several light elements with negligible quantities were synthesized: D, He^3, Li^7 , and even less abundant C, N and O.

Y_p~0,247, D/H ~ 3×10^{-5} , He^3/H ~ 3×10^{-5} , Li/H ~10^{-10}

Heavier than Li-7 nuclei were not produced during BBN in considerable quantities mainly because of the fast decrease of the baryon density and T due to Universe expansion.

Heavier elements were produced much later in star cores, during SN bursts and in CR.

Standard BBN

The primordially produced abundances depend on:

- ✓ baryon-to-photon ratio, $\eta_{CMB} = (6.104 \pm 0.055)\ 10^{-10}$
- ✓ relativistic energy density (effective number of neutrino)

(nonst interactions, extra rel degrees of freedom, exotic physics)

$$\rho_\nu + \rho_X(?) \equiv N_\nu \ \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

- ✓ n lifetime: 879.6±0.8s *(Particle Data Group 2024)*

$$H_0, \Omega_B, \Omega_\nu, N_{eff}, L, etc$$

Over 400 reactions are considered.
More and more precise BBN codes are used.

Modern analyses of nuclear rates for BBN have been provided: NACRE compilation of *Angulo et al. 1999*; NACRE-II, *Xu et al. 2013*.

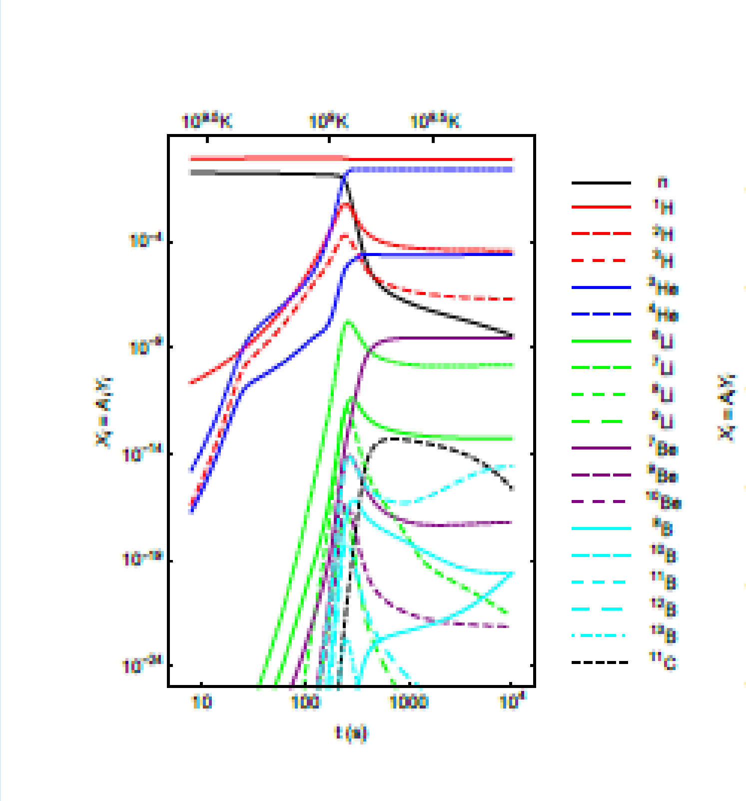


FIG. 25 *Left* : Evolution of light elements abundances. *Right* : Ev

Evolution of light element abundances.
Pitrou, Coc et al. 2018

PArthENoPE, AlterBBN, PRIMAT $Y_P(N_\nu,\eta)$, $X_D(N_\nu,\eta)$

$Y_T = 0,24709 \pm 0,00017$

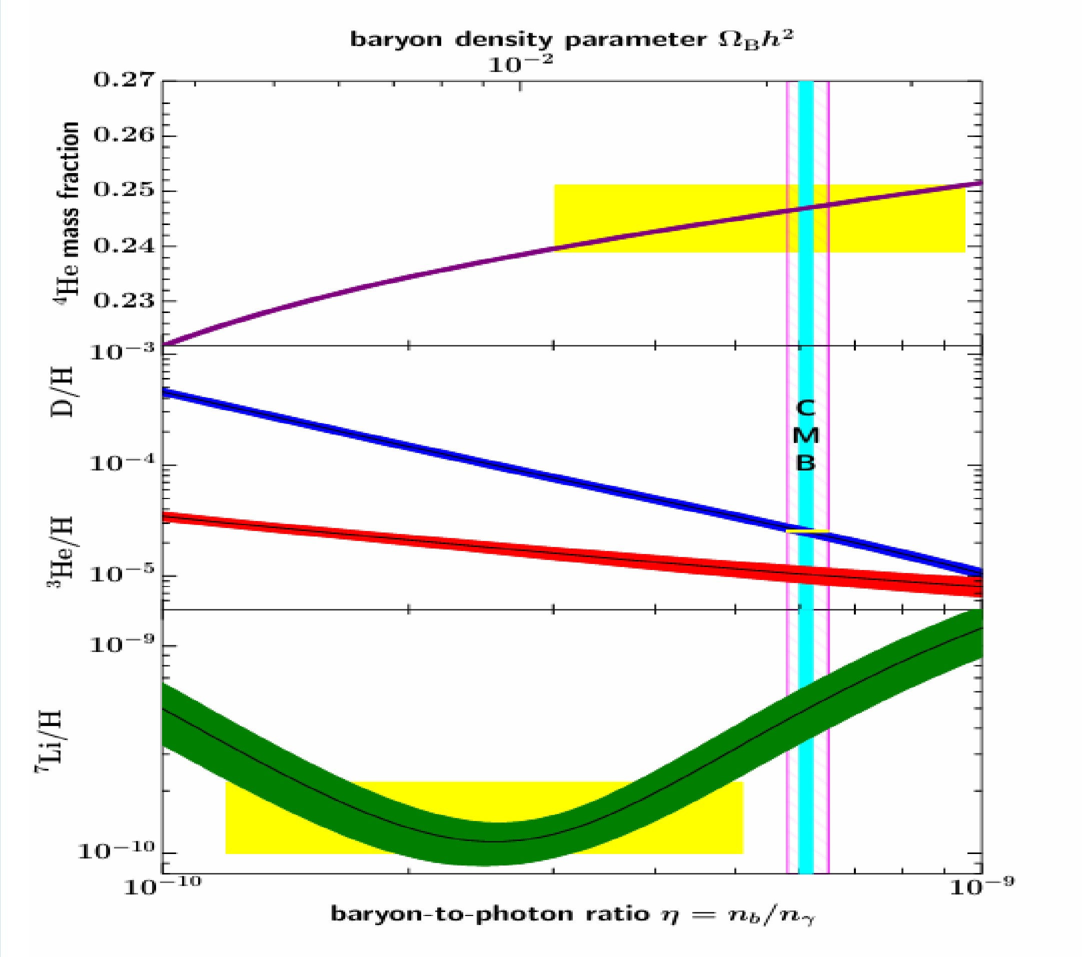
$D/H = (2.459 \pm 0,036)\ 10^{-5}$

$Y_p = 0.245 \pm 0,003$

$D/H = (2.527 \pm 0.03)\ 10^{-5}$

Peimbert,2016;Aver et al. 2015 Cooke et al. 2017

Concordance between theory and observations



Predicted light elements abundances by BBN – 95% CL. Observational data (in yellow compared to throretical predictions for He-4 , D , He-3 и Li-7. Vertical band gives the baryon density from CMB (Planck) and CMB+BBN D и He-4. (*Fields, 2020*)

Remarkable concordance b/n theoretically predicted and derived from observations abundances of light elements produced primordially!

BBN predictions are in agreement with observations for $\Omega_B \sim 0.05$.

Best Speedometer at RD stage, probes neutrino oscillations, exact baryometer and leptometer

BBN is the most early and precision cosmology probe for physical conditions in the early Universe, and for constraining new physics, relevant at BBN energies.

He-4 – preferred for BBN constraints on new physics

- The post BBN evolution of ^{4}He is simple: only produced in the stellar and galactic chemical evolution.
- It is the most abundantly produced (after H)
- most precisely calculated (0.1% uncertainty)

$$Y_p=0{,}2482\pm 0{,}0007$$

- very sensitive to nucleons kinetics before BBN

sensitive to neutrino characteristics (n, N, sp, L.)

- precisely measured element – best determined in metal poor galaxies

The accuracy of the determination is limited by systematic errors.

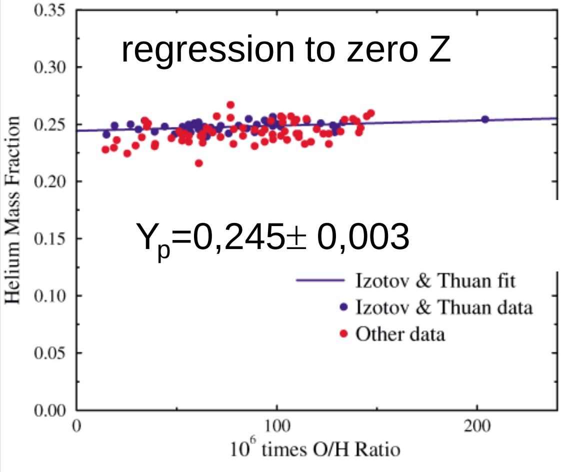
During the last decade the precision of helium measurements increased.

Many systematic effects were corrected in recent observations in order to derive from the observed intensities of He spectral lines its primordial value.

Main problem: Primordial abundances are not observed directly (chemical evolution after BBN).

The primordial abundance of ^{4}He is obtained from observations of He and H emission lines from metal poor HII regions, like compact blue dwarf galaxies.

Linear fit of all the data obtained from spectra of HII regions is made and then extrapolated to zero metallicity. The linear correlation between ^{4}He, produced in stars and metals Z (C, N and O) is used to derive the primordial mass fraction helium.



Recently primordial He-4 was determined with better than 3% accuracy.

- Inclusion of He 10830 infrared emission line in the analysis which shows a strong dependence on the electron density and is thus useful to break the degeneracy with the temperature, allowing for a more robust helium abundance determination;
- the underlying 4He stellar absorption, and/or the newly derived values of the HeI-recombination and H-excitation-collisional coefficients were considered
- New observations of HeI λ10830 emission line in the brightest HII region in the extremely metal poor galaxy Leo P were made.

These observations combined with previous ones allowed to derive an improved helium abundance:

$$Y_p = 0.2453 \pm 0.0034.$$

Aver E. et.al., JCAP 2015,2021; Hsyu et.al., ApJ 2020, Valerdi et.al., ApJ 2019

This allows to update and strengthen the Big Bang Nucleosynthesis constraints on neutrino physics beyond Standard Model.

- EMPRESS survey of 10 extremely metal poor systems $<0.1Z_{\mathrm{Sun}}$

and 51 galaxies $(0.1-0.4Z_\odot)$ *Matsumoto et al, EMPRESS VIII, 2203.09617v.3, accepted Ap.J.*

2σ deviation from SM, lower primordial He-4 value than the predicted

$$Y_p = 0.237^{+0.0034}_{-0.0033}$$

Here we present previous BBN constraints on beyond SM physics, based on primordial helium-4 values with 3-7% uncertainty and our recently updated BBN constraints corresponding to the latest data on primordially produced ^{4}He, which correspond to Y_p/Y_p=1-2% uncertainty.

We consider several models representing beyond SM physics and present updated constraints on new physics:

- ➢ In the model of BBN with neutrino oscillations stringent BBN constraints on neutrino oscillations parameters were obtained corresponding to the present accuracy of He-4 determination
- ➢ In the model of BBN with neutrino oscillations and lepton asymmetry we present BBN constraints on lepton asymmetry and change in BBN constraints on oscillations
- ✓ We discuss lepton asymmetry as a solution of DR problem
- ✓ lepton asymmetry from EMPRESS experiment

BBN with ν oscillations

Production of He-4 in BBN with $\nu_e \leftrightarrow \nu_s$

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

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

Evolution of nucleons in the presence of $\nu_e \leftrightarrow \nu_s$

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

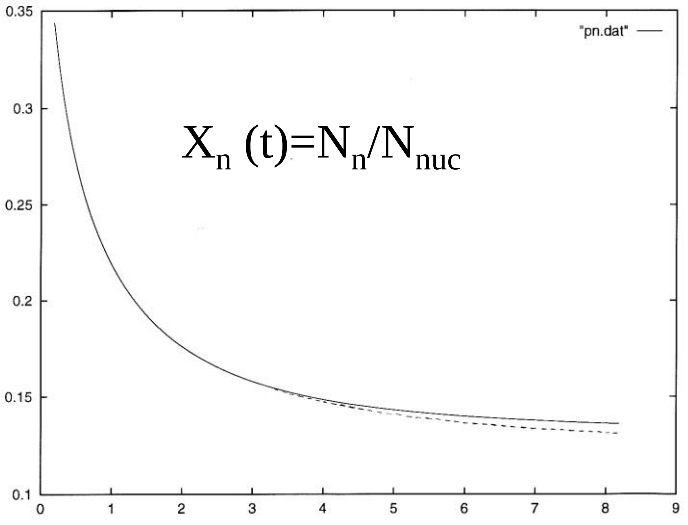
$$- \int d\Omega(e^+, p, \tilde{\nu}) \left| A(e^+ n \to p \tilde{\nu}) \right|^2 (n_{e^+} n_n - n_p \bar{\rho}_{LL})$$

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

$$2\ MeV \ge T \ge 0.3\ MeV$$

$$Y_p = 2(X_n)_f e^{-\frac{t}{\tau_n}}$$

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



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

Numerical analysis:

- Evolution of oscillating neutrino
- Evolution of nucleons and n/p freezing
- He-4 production

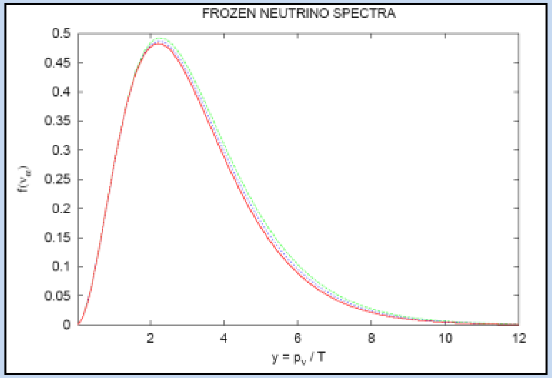
Dynamical and kinetic effect of $\nu_e \leftrightarrow \nu_s$ on BBN were explored.

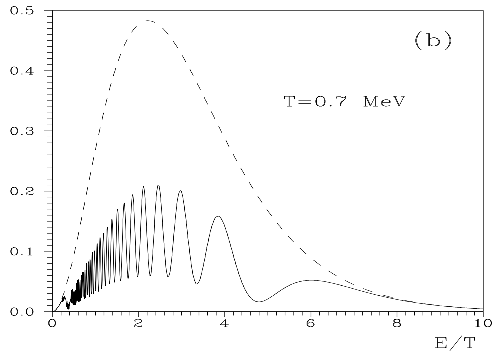
- Nucleons evolution in the pre-BBN period in the presence of $\nu_e \leftrightarrow \nu_s$ was numerically analyzed and He-4 was calculated for thousands sets of oscillation parameters.

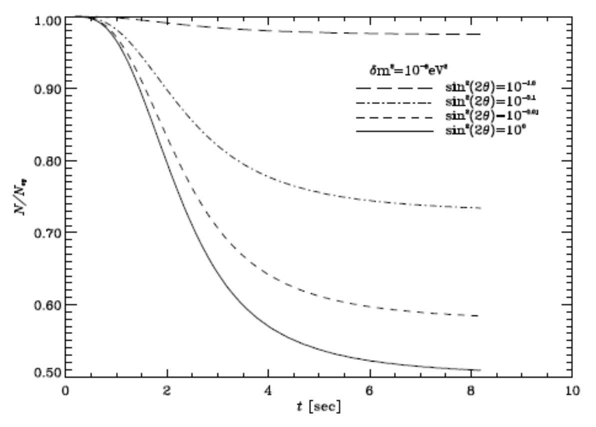
DK, Chizhov M, NPB ,1998,DK, Panayotova JCAP 2006, DK, JCAP 2012

- Active-sterile oscillations proceeding after decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$

  major effect - distortion of neutrino energy spectrum and depletion of electron neutrino.







$$n_\nu^{eq} \neq \exp(-E/T)/(1+\exp(-E/T))$$

$N_e < N_{eq}$

2 neutrino mixing: Sterile state is filled for the sake of ν_e

4 neutrino mixing: ν_e is partially re-filled for the sake of muon and tau neutrino

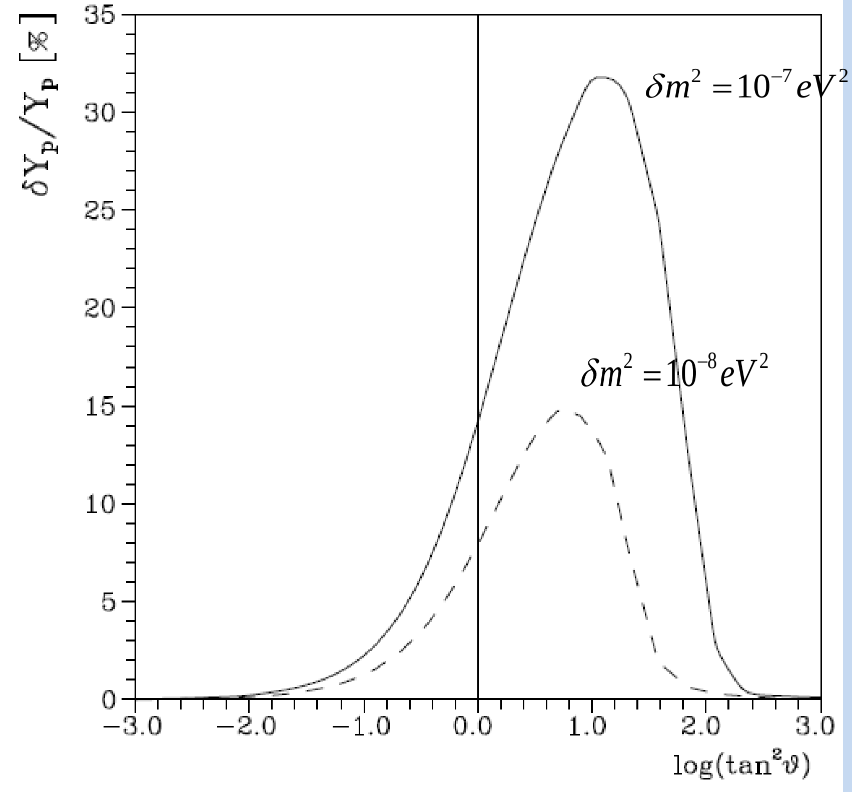
$\delta N_{k,4} < \delta N_{k,2}$ Flavor mixing decreases the depletion and spectrum distortion

Precise description of neutrino momenta distribution is needed: 1000 bins used to describe it in non-resonant case, and up to 10 000 in the resonant case.

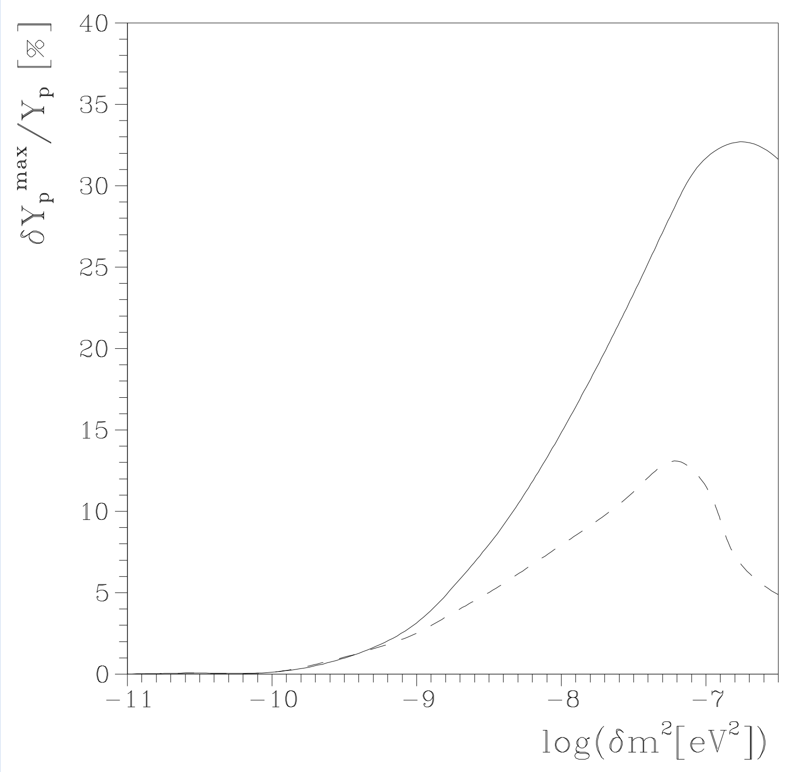
Energy spectrum distortion caused by oscillations depends on the level of initial population of $\nu_{s.}$

Maximum He-4 overproduction in BBN with oscillations due to spectrum distortion

Dependence of max overproduction on mixing



Max overproduction on mass difference



DK, Astrop.Phys.,2003

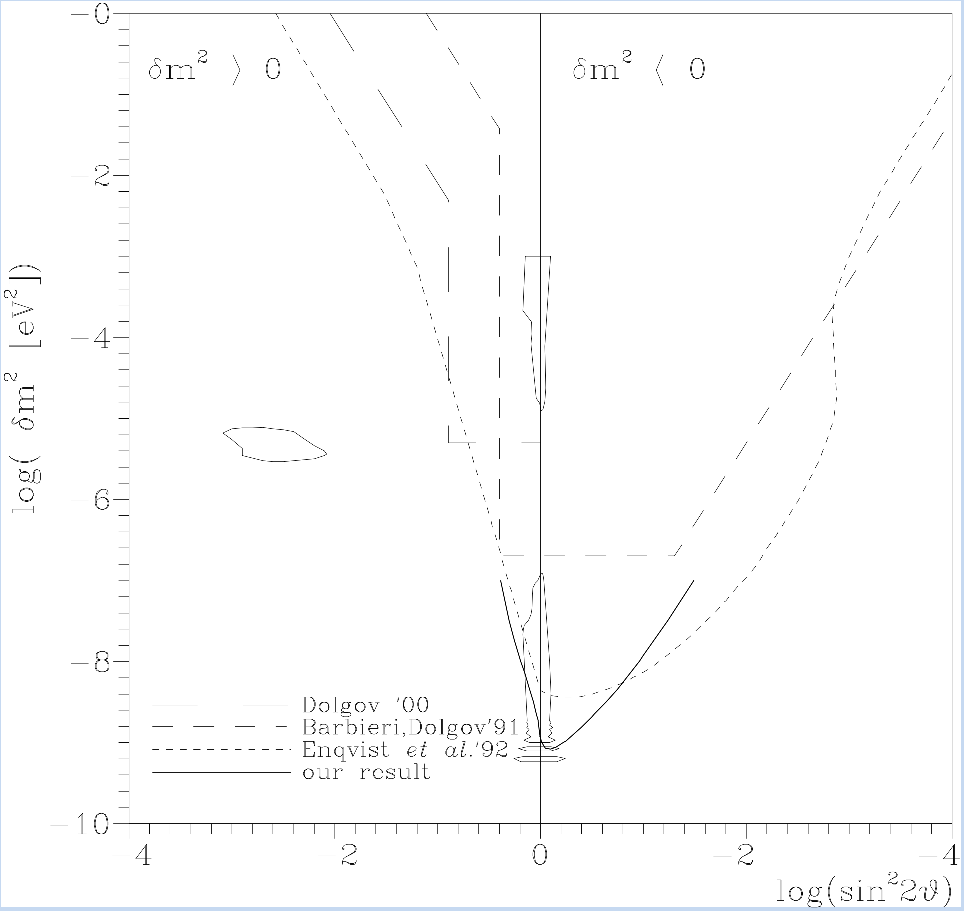
For BBN with $n_e \leftrightarrow n_s$ the maximal overproduction of ^{4}He is 32% in the resonant case and 13% in the non-resonant, i.e. 6 times stronger effect than the dynamical oscillations effect.

BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ allows to constrain ν oscillation parameters for He-4 uncertainty up to 32% (14%) in resonant (non-resonant) case.

Previous BBN constraints on oscillations

BBN with neutrino oscillations between initially empty ν_s and ν_e

In the 90ies ^4He ~ 3-7% accuracy → BBN constraints on δm^2 and $\sin^2 2\theta$ for 3-7% overproduction of ^4He and for $\delta N_s=0$.



BBN constraints on $\nu_e \leftrightarrow \nu_s$:

Barbieri, Dolgov 91 – depletion account
Enqvist et al. 92 – one p approx.
Dolgov 2000 – dashed curve;
Dolgov, Villante, 2003 - spectrum distortion

Fits to BBN constraints

corresponding to $\delta Y_p/Y_p=3\%$:

$\delta m^2 > 10^{-6}$ eV^2

$$\delta m^2_{es} \sin^4 2\theta_{es} \le 3.16\times10^{-5} eV^2 \left(\Delta N_\nu\right)^2$$

$$\delta m^2_{\mu s} \sin^4 2\theta_{\mu s} \le 1.74\times10^{-5} eV^2 \left(\Delta N_\nu\right)^2$$

$$\delta m^2 \sin^4 2\theta \le 10^{-7}$$

DK.,Chizhov 2001 – distortion and asymmetry growth account

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

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

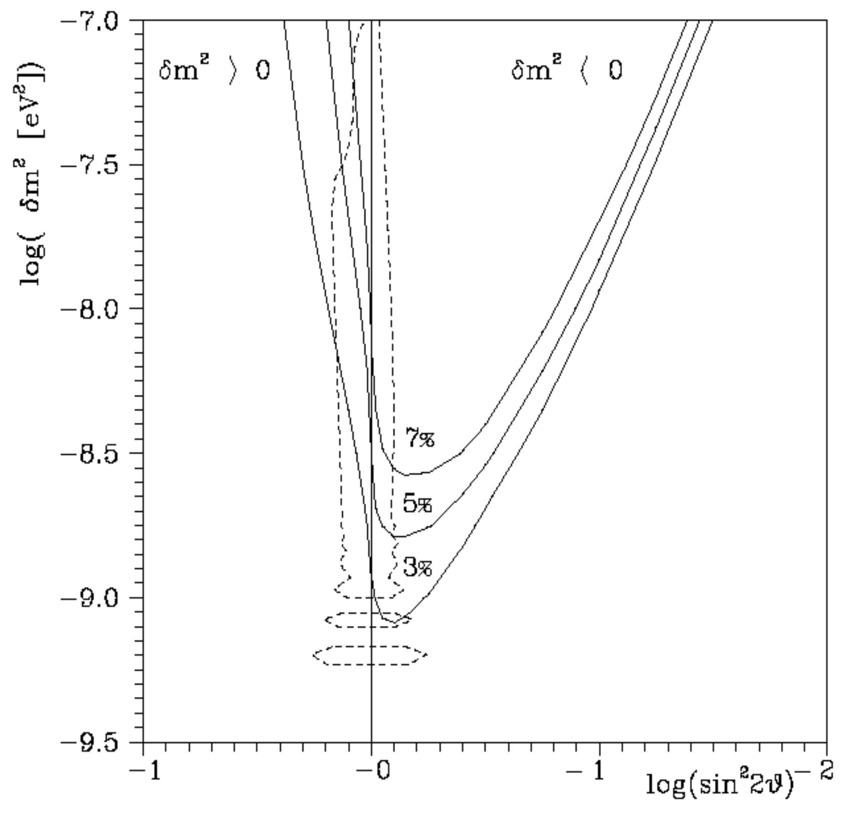
Previous BBN constraints on $\nu_e \leftrightarrow \nu_s$

- We have calculated combined iso-helium contours for 3-7% ^{4}He overproduction, accounting for all oscillations effects on BBN, for initial population δN_s=0, for non-resonant $\delta m^2<0$ and resonant $\delta m^2>0$ cases
- We have derived cosmological constraints on oscillations parameters δm^2 and $\sin^2 2\theta$.

Y_p=0,2565 ± 0.001(stat)± 0,005(syst)

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

DK, Chizhov NPB2000,2001



re-population of active neutrino slow,
spectrum distortion considerable

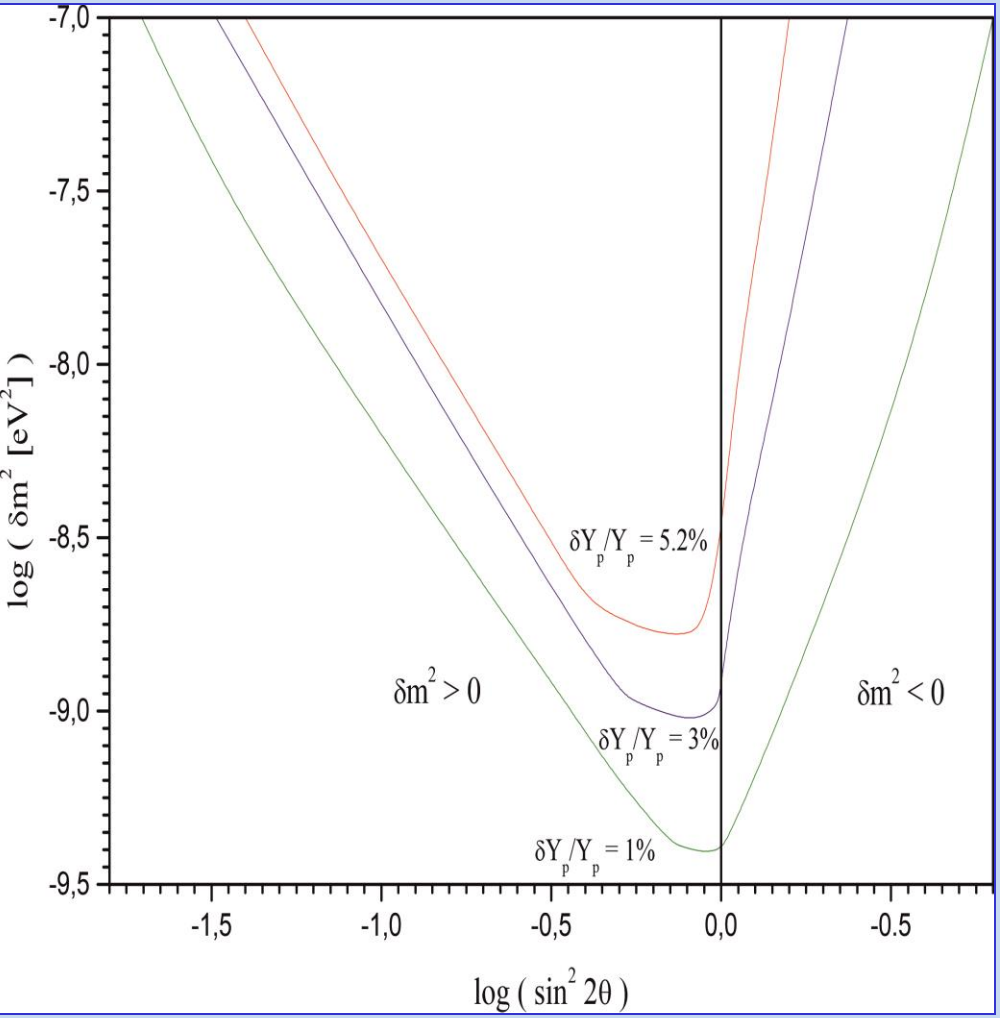
Fit to BBN constraints corresponding to
$\delta Y_p/Y_p$=3%:

$$\delta m^2 \left(\sin^2 2\theta\right)^4 \leq 1.5\times 10^{-9} eV^2 \quad \delta m^2 > 0$$

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

- ✓ BBN constraints are by 4 orders of magnitude more stringent than experimental ones
- ✓ Excluded electron-sterile solution to LSND , LMA and LOW active-sterile solutions (1990, 1999) years before experimental results.

Updated BBN constraints on neutrino oscillation parameters



DK, Panayotova, Chizhov 2924, Symmetry

Recently the primordial ^{4}He was determined with better accuracy

Y_p= 0.2453±0.0034

Hence, it is possible to obtain more stringent BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillations.

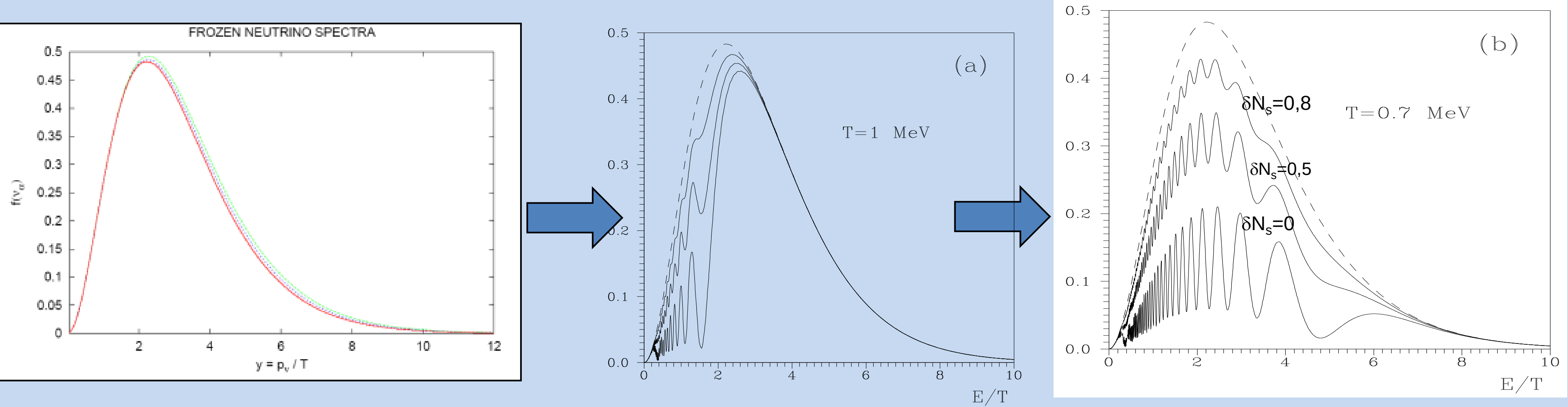
- We have provided numerical analysis of 135 BBN models with neutrino oscillations with different oscillation parameters.
- We present the updated BBN contraints on neutrino $\nu_e \leftrightarrow \nu_s$ oscillations parameters, based on
- 1-3% ^{4}He uncertainty.

We have updated the data on baryon density and the neutron life time.

- Active-sterile oscillations proceeding after decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ may strongly distort neutrino distribution and deplete electron neutrino.

Kirilova 88, Kirilova&Chizhov PLB,97

$$n_\nu^{eq} \neq \exp(-E/T)/(1+\exp(-E/T))$$



Kirilova,IJMPD,2004,2007

Role of sterile neutrino:

dynamical effect– increasing H(g) but suppressing the osc kinetic effect

$\delta N_k \sim \delta N_{k,0} - \delta N_{k,0}\, \delta N_s$

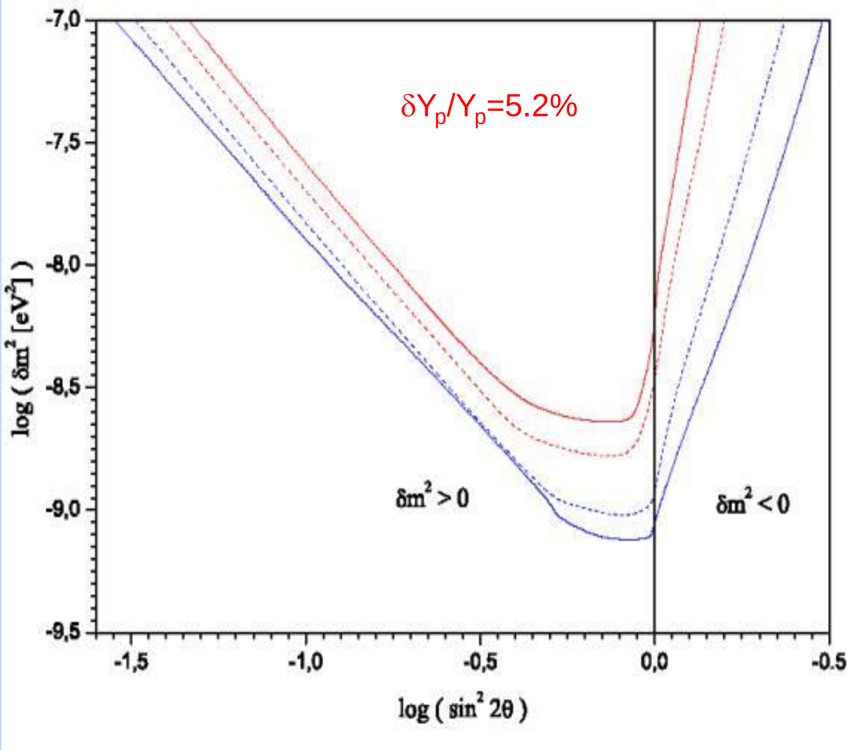
The distortion due to active-sterile oscillations and the kinetic effect caused δN_k depends on the degree of initial population of ν_s.

The effect decreases with δN_s. The biggest effect $\delta N_{k,0}$ is achieved for $\delta N_s=0$, the effect decreases with δN_s .

Generalized BBN constraints on $\nu_e \leftrightarrow \nu_s$

Additional ν_s population may strengthen or relax BBN constraints.

Constraint contours for 3 and 5% He-4 overproduction



Due to interplay b/n the effects of non-zero initial population of ν_s (partially filled) on BBN,

BBN bounds change non-trivially with δN_s:

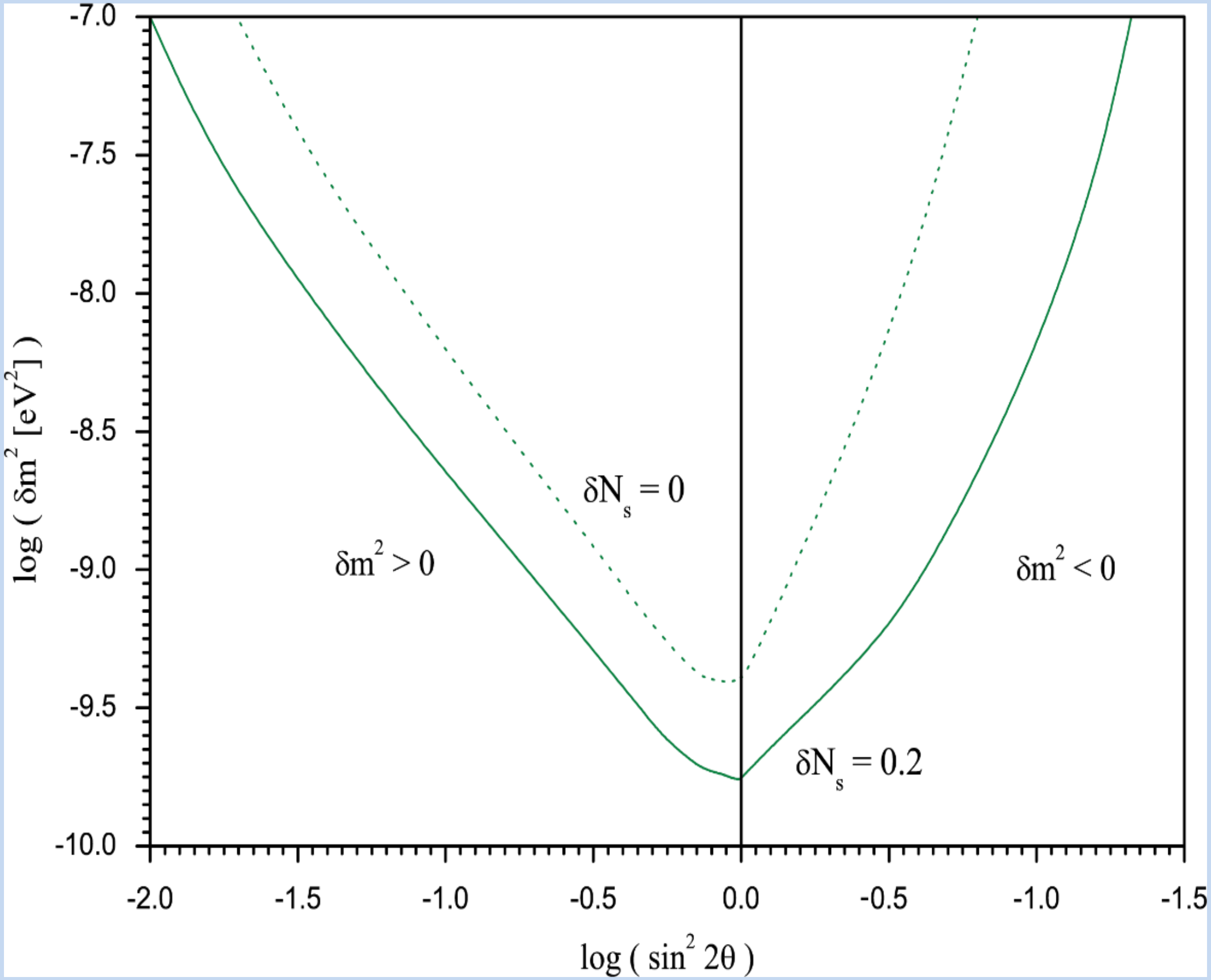
In case the dynamical effect dominates, He-4 overproduction is enhanced and BBN constraints strengthen.

In case the kinetic effect dominates He-4 overproduction decreases with δN_s increase and BBN constraints relax.

DK&Panayotova JCAP2006;IJMP DK07

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

Updated BBN constraints on neutrino oscillation parameters for $\delta N_s \neq 0$



Primordial He-4 and D were determined with high accuracy:

$Y_p = 0.24709 \pm 0.00017$ Pitrou et al. 2018
$D/H = (2.527 \pm 0.03)\ 10^{-5}$ Cooke et al., 2017
which lead to better accuracy

$N_{eff} = 2.88 \pm 0.27$ (95%).

Additional relativistic during BBN sterile neutrino ν_s is strongly constrained.
DK&Panayotova, 2023, DK, Panayotova, Chizhov 2924, Symmetry

Contemporary BBN constraints on $\nu_e \leftrightarrow \nu_s$ neutrino oscillations parameters corresponding to 1% He-4 overproduction and $\delta N_s=0$ (upper curve) and $\delta N_s=0.2$ (lower curve).
BBN constraints strengthen with the increase of initial population of ν_s

BBN with L

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 orders of magnitude bigger than the baryon one, $\beta = (n_b - n_{\bar{b}}) / n_\gamma \sim 6.10^{-10}$

Though usually assumed $L \sim \beta$, big L 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 L may be measured/constrained only indirectly through its effect on other processes, which have left observable traces in the Universe:

light element abundances from Big Bang Nucleosynthesis , CMB, LSS, etc.

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

Dolgov,2002

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

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

Lepton Asymmetry Effects

- Dynamical - Non-zero L increases the radiation energy density

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

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

leading to faster expansion, delaying matter/radiation equality epoch …

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

Lesgourgues&Pastor, 99

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

- Direct kinetic - $|L\nu_e| > 0.01$ effect neutron-proton kinetics in pre-BBN epoch

⇨ 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 changes the decoupling T of neutrino

❖BBN provides the most stringent constraint on L in case *neutrino oscillations degeneracies equilibrate due to oscillations before BBN*

Dolgov et al., NPB, 2002 , Serpico&Raffelt,2005, Iocco et al.,2009, Mangano et al., 2012

❖Improvement on D and He measurement – stringent BBN constraints:

$|\xi_\nu| < 0.016 (68\% CL)$ $L < 0.01$

BBN with L and v oscillations

Indirect Lepton Asymmetry Effects

We studied the interplay between tiny L and neutrino oscillations in the early Universe and their effect on BBN for the specific case:

$\nu_1 = \nu_e \cos\theta + \nu_s \sin\theta$
$\nu_2 = - \nu_e \sin\theta + \nu_s \cos\theta$ $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ eV^2

effective after active neutrino decoupling

- The evolution of the L was numerically studied. Different cases of L were studied:

relic initially present $L>10^{-11}$ and dynamically generated by oscillations

✓ Neutrino active-sterile oscillations change neutrino-antineutrino asymmetry of the medium

suppress pre-existing asymmetry *Barbieri&Dolgov 90.91; Enqvist et al. 1992,*

enhance L (MSW resonant active-sterile oscillations) $\theta_m(\delta m^2, \theta, L, T, ..)$

L enhancement in MSW resonant active-sterile neutrino oscillations $\delta m^2 < 10^{-7}$eV^2 in the collisionless case *Kirilova&Chizhov 96;DK 2012*

Indirect Lepton Asymmetry Effects

- L<<0.01 influence *on neutrino* by:

✓ changing neutrino number densities

✓ neutrino evolution

✓ changing neutrino distribution and spectrum distortion

✓ changing neutrino oscillations pattern (suppressing or enhancing them)

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

L influence on oscillations was explored in the full range of model oscillation parameters and a wide range of L values.

L effects neutrino oscillations

suppresses them *Foot&Volkas, 95; Kirilova&Chizhov 98*

enhances them *Kirilova&Chizhov 98*

We have numerically studied that interplay and determined the parameter range for which L is able to enhance, suppress or inhibit oscillations *DK 2018*.

- L<<0.01 influence *indirectly BBN* kinetics - $L > 10^{-8}$ influence n/p kinetics and BBN via neutrino BBN with electron-sterile oscillations feels and constrains tiny L

DK&ChizhovNPB98,2000; DK PNPP, 2010, JCAP2012, 2018

Evolution of neutrino in presence of $\nu_e \leftrightarrow \nu_s$ and L

- The medium influences the propagation of neutrino. The evolution of the oscillating ν and ν_s, accounting simultaneously for Universe expansion, neutrino oscillations and neutrino forward scattering is described by:

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

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

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

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

$Q \sim E_\nu T \qquad L \sim 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} \qquad L_{\nu_e} \sim \int d^3p\left(\rho_{LL} - \bar{\rho}_{LL}\right)/N_\gamma$ $\qquad g_{eff} = 10.75 + \frac{7}{4}\delta N_s \qquad \delta N_s = N_\nu - 3$

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

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

BBN with neutrino oscillations and L

❖ In BBN with $\nu_e \leftrightarrow \nu_s$ and L 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.

Evolution of nucleons in the presence of $\nu_e \leftrightarrow \nu_s$

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

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

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

$2\ MeV \geq T \geq 0.3\ MeV$ $\quad$ $10^{-11} < L < 0.01$

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

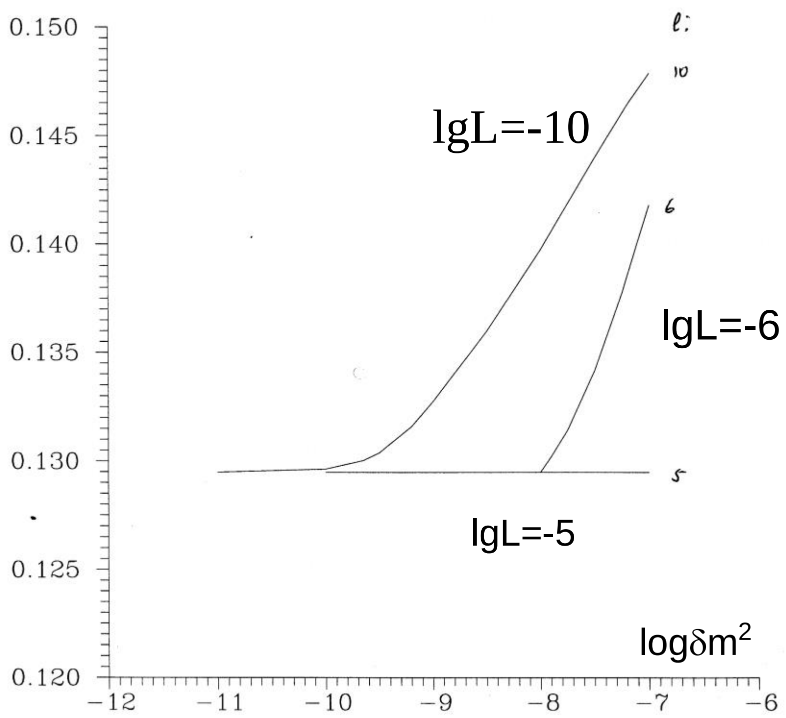
Numerical analysis:

- Evolution of oscillating neutrino in the presence of L
- Evolution of nucleons and n/p freezing
- He-4 primordial production

BBN with late neutrino oscillations and tiny lepton asymmetry

Numerical analysis of $Y_p\left(\delta m^2, \theta, L\right)$ dependence has been provided for the entire parameter range of mixing parameters of the model and L.

Small $10^{-8} < L << 0.01$, that do not effect directly BBN kinetics, influence *indirectly* BBN via oscillations.



The dependences of helium production on the initial L on mass differences for three different values of L .

As is obvious from the figure L bigger than 10^{-5} leads to a total suppression of oscillations effect on BBN and hence, eliminates the BBN bounds on oscillation parameters.

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

This relation is an analytical fit to the exact constraints obtained numerically.

Depending on its value, initial L may also change BBN bounds: It may relax them at large mixings and strengthen them at small mixings

Kirilova, PoS, 2018, 2023

BBN with late neutrino oscillations and tiny lepton asymmetry

L $>10^{-8}$ may considerably influence BBN:

L $\sim 10^{-7}$ enhances oscillations, while

higher L suppresses oscillations

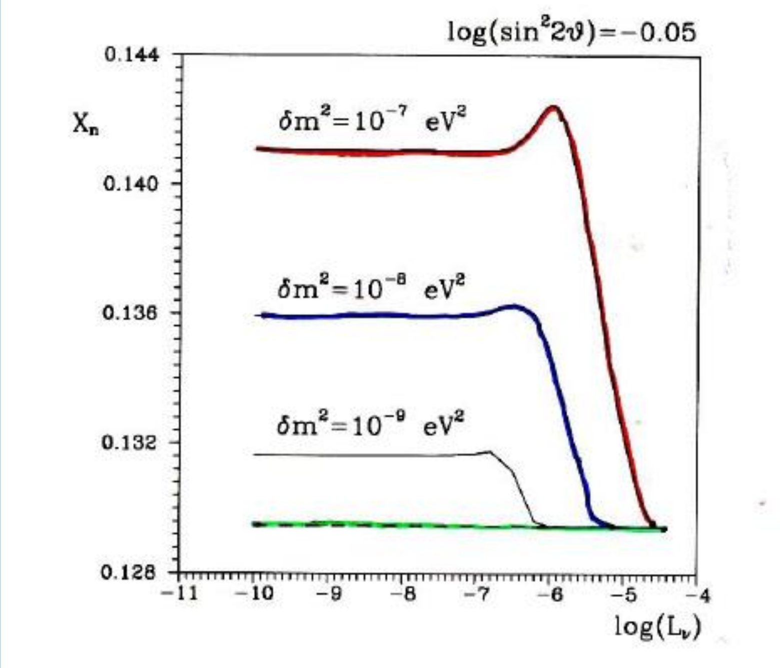
$L > (0.01\delta m^2)^{3/5}$ inhibit oscillations.

Small 10^{-8} <L<<0.01, not effecting directly BBN kinetics, influence *indirectly* BBN via oscillations.

L change primordial production of He

by enhancing or suppressing oscillations.

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



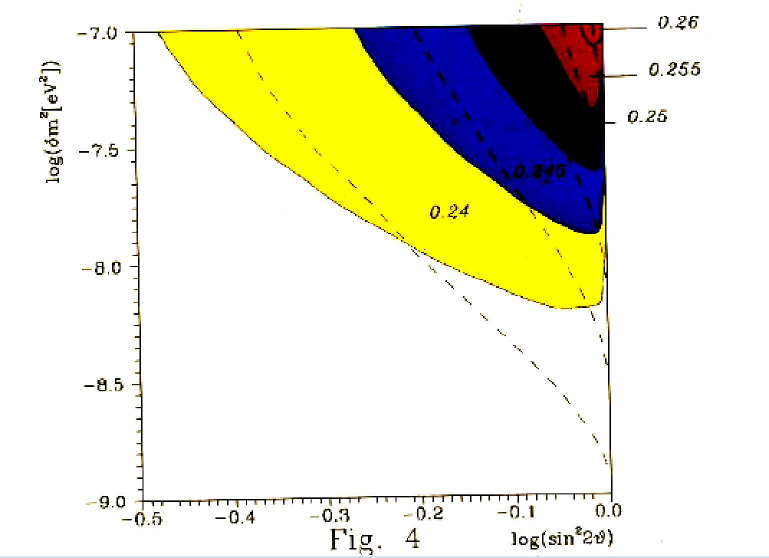


Fig. 4

L $=10^{-6}$ relaxes BBN constraints at large mixings and strengthen them at small mixing.

Kirilova&Chizhov NPB98, Kirilova JCAP 2012 , 2018

L may strengthen, relax or eliminate BBN constraints on oscillations.

In the last case, instead, the following approximate bound holds:

$$\delta m^2 (eV^2) < 100 L^{5/3}$$

Dark Radiation Problem

Neutrino oscillations data points to additional relativistic density in the early Universe, called dark radiation.

Reactor experiments+LSND+MiniBooNe+Gallium expt+SAGE Ice Cube, T2K, NOvA, NU4.

Combined neutrino oscillations data hint to oscillations with ν_s with $\Delta m^2_{41} = 0.01 - 1\ \mathrm{eV}^2$ mass

additional light sterile neutrino (in eq. before BBN), participating into oscillations with flavor neutrinos with higher mass differences values, than the ones required by solar and atmospheric neutrino oscillations experiments.

Oscillations with ν_s with eV mass and large mixing lead to thermalization of ν_s before ν_a decoupling, hence additional state speeds expansion and influences BBN.

BBN does not allow a thermalized light inert state. $N_{eff} < 3.2$

- Lepton asymmetry is capable to suppress ν oscillations ! *DK&Chizhov , NPB 98*

Solution: BBN with relic L – to suppress oscillations, so that new neutrinos are not thermalized.

Kirilova 2012, 2013; Mirizzi et al. 2012; Hannestad et al. 2012.

Numerical analysis of BBN with neutrino oscillations and L $L > (0.01\delta m^2)^{3/5}$

inhibit oscillations:

δm^2 =0.1 eV^2 $|L| > 0.016$

1 $L > 0.063$

The additional relativistic density might point to non-zero L, decaying particles during BBN, etc. Future experimental and observational data will choose among different possibilities.

Recent observational indications for L

- EMPRESS survey of 10 extremely metal poor systems $<0.1Z_{Sun}$

and 51 galaxies $(0.1-0.4Z_\odot)$

Matsumoto et al, EMPRESS VIII, 2203.09617v.3, accepted Ap.J.

1-2σ deviation from SM, lower primordial He-4 value than the predicted

$Y_p=0.237^{+0.0034}_{-0.0033}$

Can be interpreted as a hint for L: : $\xi_{\nu e}=0.05^{+0.03}_{-0.02}$ 2σ $N_{eff}=3.11^{+0.34}_{-0.31}$

This analysis allows higher values of $N_{eff}=3.45$ 1 σ and can solve Hubble tension problem

PDG $Yp=0.245^{+0.003}_{-0.003}$ $\xi_{\nu e}=0.008\pm0.013$

In case of DR the preference for L>0 increases.

- It is interesting that this value of L is also close to the required L for solving the Hubble tension, see *Seto, Toda, PRD 2021*

$\xi_{\nu e}\sim 0.04$ and $0.3<\delta N_{eff}<0.6$

Escudero, M.; Ibarra, A.; Maura, V. Primordial lepton asymmetries from BBN and the CMB. *Phys. Rev. D* **2023**, *107*, 035024

- ξ_ν =0.043± 0.015

The evidence for a nonzero lepton asymmetry strengthens to 3σ

future CMB observations from the Simons Observatory and CMB-S4 will increase the significance for a nonzero lepton asymmetry to 4σ and 5σ respectively

Recent precise analysis accounting for non-instantaneous decoupling correction and neutrino spectrum distortions, give

- $0.032 \leq \xi_\nu \leq 0.052$ from EMPRESS data.

the non-instantaneous decoupling correction is given by $N_{eff} = 0.044 + 0.0102\,\xi_\nu^2$

Yuan-Zhen Li et al., 2024 e-Print: 2409.08280 [hep-ph]

- combined analysis with EMPRESS BBN, Planck CMB and BOSS

BAO data yields a tighter constraint $\xi\nu = 0.024 \pm 0.012$,

2 sigma significance for positive L!

Recent observational indications for L

D.K., Panayotova, M., Chizhov, E. Symmetry, 2024

On the basis of our analysis if $\xi_{\nu e}=0.05$ L~0.0342 we estimate that this L can suppress neutrino oscillations with

$\delta m^2(eV^2) < 100L^{5/3}$ ~0.36 eV^2

The dark radiation problem can be solved for the experiments obtaining mass differences $\delta m^2 \leq 0.36$ eV^2

Thus, the indicated by EMPRESS survey L may resolve the DR problem for $\delta m_{14}^2 < 0.36$ eV^2 .

if $\xi_{\nu e}=0.03$ L~0.02 $\delta m^2 \leq 0.15$ eV^2

if $\xi_{\nu e}=0.02$ L~0.013 $\delta m^2 \leq 0.078$ eV^2

These indication for L values point to much larger lepton asymmetry than the baryon asymmetry of the local universe.

Note: Large *B*/*L* ratio can arise in MSSM if the two asymmetries are both generated through the Affleck–Dine mechanism, but along different directions of the MSSM scalar potential.

Summary

- We analyzed the model of BBN with $\nu_e \leftrightarrow \nu_s$ neutrino oscillations. Late active-sterile oscillations may considerably distort neutrino spectrum and produce neutrino-antineutrino asymmetry. We derived stringent BBN constraints on neutrino oscillations parameters corresponding to the present 1% accuracy of He-4 determination. The dependence of the BBN constraints on neutrino oscillations parameters on the initial population of sterile neutrino and lepton asymmetry L in the Universe was also studied.
- Helium may be both overproduced or underproduced with the increase of the initial population of ν_s depending which effect dominates (dynamical or kinetic). Additional partially filled sterile state may lead to strengthening as well as to relaxation of the BBN constraints.
- The numerical analysis of the interplay between small lepton asymmetry <<0.01 , either relic (initially present) or dynamical (generated by MSW neutrino oscillations) and $\nu_e \leftrightarrow \nu_s$ oscillations occurring after ν_e decoupling allowed to determine the parameter range for which L is able to enhance, suppress or inhibit oscillations. In particular L as small as 10^{-8} may be felt by BBN through neutrino oscillations.
- Large L may provide relaxation of BBN constraints on oscillations, by suppressing oscillations and causing incomplete thermalization of the sterile neutrino. Large enough L alleviates BBN constraints on oscillation parameters. New stringent cosmological constraints on L are derived in the model of BBN with neutrino oscillations.
- A solution to the DR problem is proposed in model of neutrino oscillations and L. The value of L needed to solve DR problem is found close to L hinted by EMPRESS, and close to L needed to solve Hubble tension problem. This L is much bigger than the baryon asymmetry value.

Thank you for your attention!

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
- L can enhance neutrino oscillations

  DK&Chizhov , NPB 98
- L may be generated by MSW resonant neutrino oscillations in the early Universe in act
  sterile oscillations

L 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 have found qualitatively new effects of $\nu_e \leftrightarrow \nu_s$ oscillations

(i) neutrino oscillations may strongly distort neutrino energy distribution, therefore precise description of neutrino momenta distribution is needed

(ii) an interplay between L and oscillations is observed: oscillations can suppress L or amplify it, L depending on its value it can suppress oscillations or lead to their resonant enhancement.

The latter is a result of a new type of resonance of neutrino oscillations – spectral resonance, which we have found numerically accounting for the neutrino energy distribution in *Kirilova D., Chizhov M., Neutrino Degeneracy Effect on Neutrino Oscillations and Primordial Helium Yield, Nucl.Phys.B 534, pp.447-463, 1998.*

Note: This effect, discussed qualitatively later in Shi X., Fuller G. M., 1999, Phys. Rev. Lett., 82, 2832 and applied as sterile neutrino dark matter production mechanism, is called Shi-Fuller mechanism.

Обилие на леките елементи

Основен проблем: Първичните обилия не се наблюдават директно (химична еволюция след КН).

Наблюдения

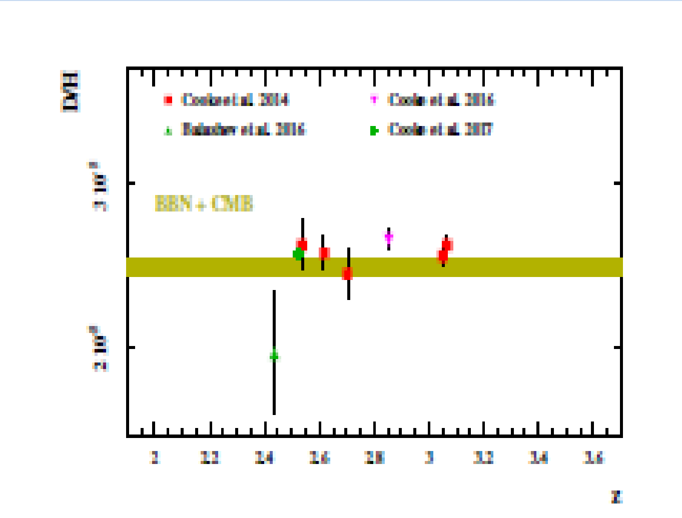
в системи минимално повлияни от химична еволюция.

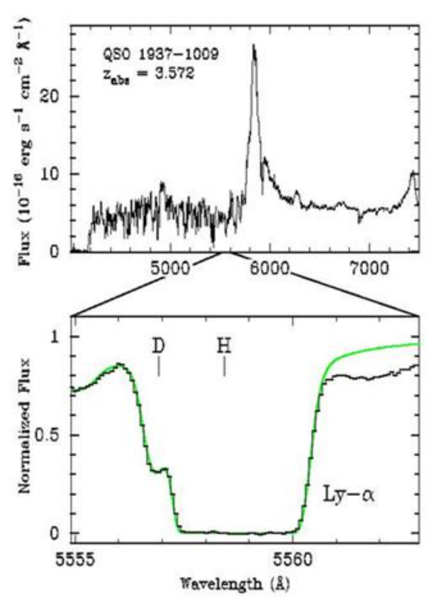
ICooke et al. (2014-2017)

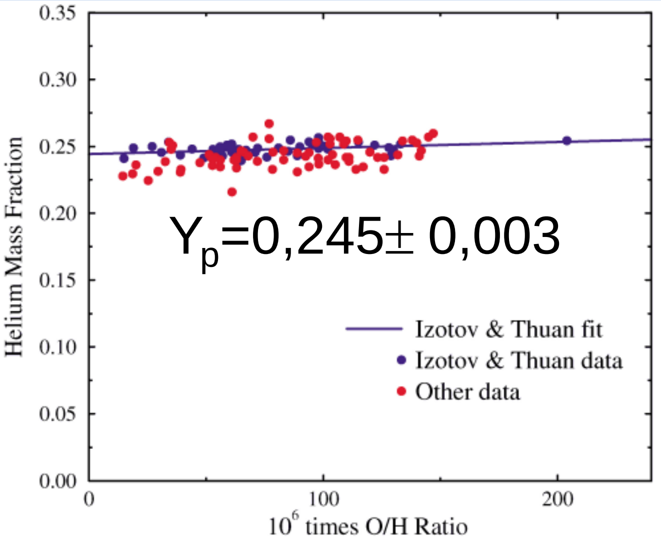
- D се измерва в далечни, нискометалични системи поглъщащи излъчването от далечни квазари. 16 QSA

- He - в H II области на галактики джуджета с ниска Z.

екстраполация към Z нула







Корекции

на галактичната химична еволюция

- Li - в Pop II (бедни на метали $Z<1/10\,000\ Z_{☼}$) звезди от сфероидалната компонента на Галактиката

Valerdi, 2020; Aver, 2021

$D/H=(2.527±0.03)\ 10^{-5}$

$Y_p=0,245± 0,003$

$Li/H=(1.58±0.31)\ 10^{-10}$

Cooke et al. 2018, Fields et al. 2021

Sbordone et al. 2010