Standard Model and Beyond
Corfu, September, 2018

BBN Cosmological Constraints on Beyond Standard Model Neutrino

Daniela Kirilova

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

Mihail Chizhov Mariana Panayotova

Outline

- BBN - the deepest reliable early Universe probe and beyond Standard Model test

- Neutrino beyond SM and BBN constraints
  inert neutrino, number of families,
  neutrino oscillations
  lepton asymmetry

- Neutrino oscillations - lepton asymmetry interplay
  L effects on neutrino oscillations
  neutrino oscillations effects on L
  L change BBN constraints on neutrino oscillations
  constraints on L by BBN with active-sterile oscillations
  DR problem solution

Big Bang Nucleosynthesis

George Gamow

1904 – 1968

In 1946–1948 develops BBN theory.
In the framework of this model
predicts CMB and its T.

Theoretically well established - based on
well-understood SM physics
Precise data on nuclear processes rates
from lab expts at low E (10 KeV – MeV)
Precise observational data on light elements abundances
Predicted abundances in good overall agreement
with the ones inferred from observational data

Most early and precision probe for physical conditions in early Universe and for new physics at BBN energies.

Universe baryometer
the best speedometer at RD stage
the most exact Universe leptometer

Baryon fraction, N_{eff}, L, etc. measured by CMB

The Primordial Abundances of Light Elements

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

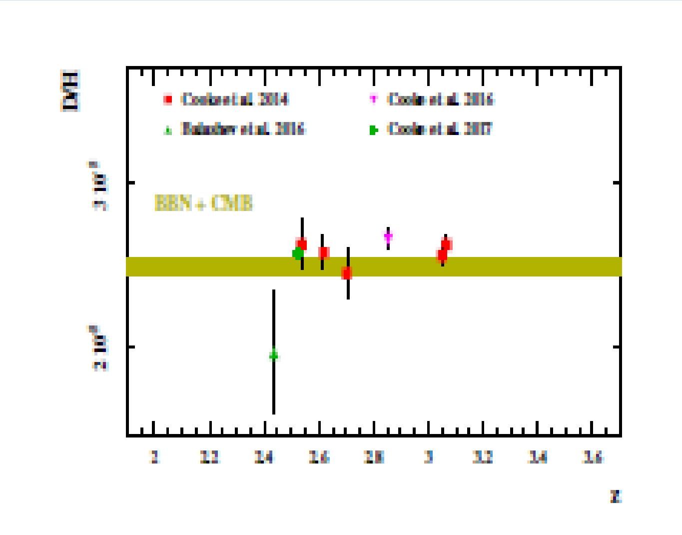
- D is measured in high z low-Z H-rich clouds absorbing light from background QSA.

Observations

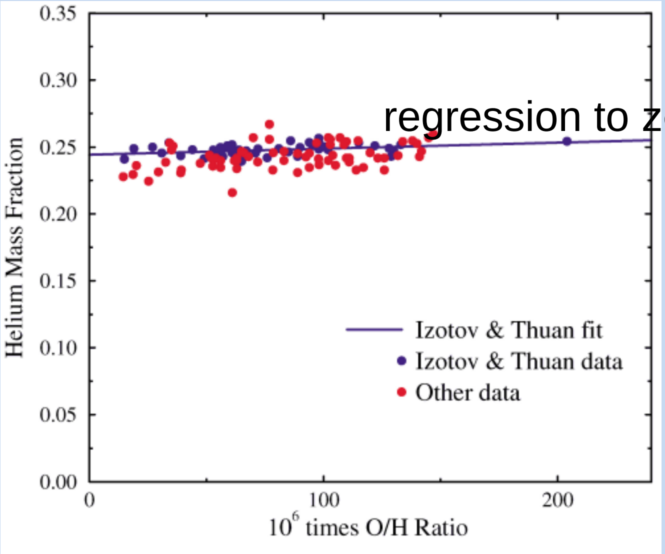
in systems least contaminated by stellar evolution.

- He in clouds of ionized H (H II regions), the most metal-poor blue compact galaxies.

lCooke et al. (2014-2017)



Izotov&Thuan



Account

for galactic chemical evolution

Y_p=0,2565 ± 0.001(stat)± 0,005(syst)

,

Peimbert,2016;Aver et al. 2015

Y_p=0,245± 0,003

Pitrou et al. 2018

Y_p=0,24709± 0,00017

New QSA observations:

D/H=(2.527±0.03) 10^{-5}

Cooke et al. 2017

Li in Pop II (metal-poor) stars in the spheroid of our Galaxy, which have Z<1/10 000 $Z_{☼}$).

Sbordone et al. 2010

Li/H=(1.58±0.31) 10^{-10}

During BBN 4 light elements D, He-3, He-4, Li-7 and tiny traces of Be-9, B-10, B-11 up to CNO were produced (1 s – 20 m, MeV – Kev)

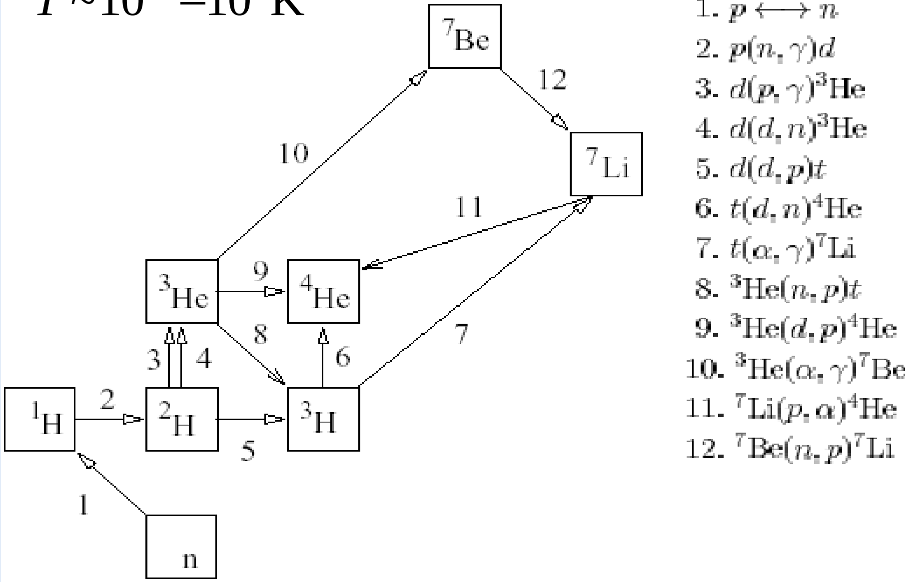
The primordially produced abundances depend on:

- ✓ baryon-to-photon ratio CMB measured now
- ✓ relativistic energy density (effective number of neutrino)

$$\rho_\nu + \rho_X(?) \equiv N_\nu \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma \qquad N_{eff} = 2.984 \pm 0.08 \quad \textit{LEP}$$

- ✓ n lifetime: 879.5±0.8s *Serebrov et al. 2017*

$T \sim 10^{10} - 10^9$ K



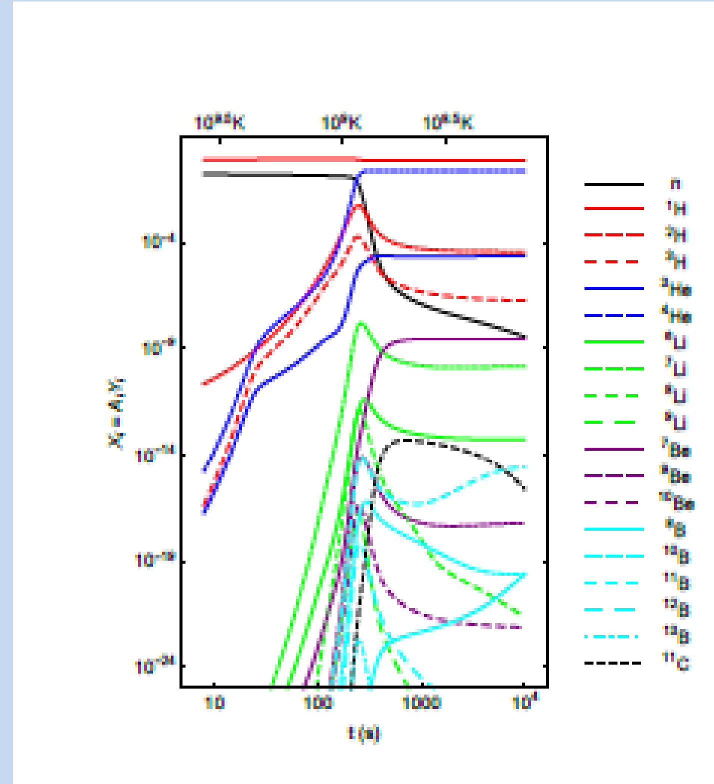


FIG. 25 *Left* : Evolution of light elements abundances. *Right* :

Pitrou, Coc et al. 2018
Cyburt et al, 2016

Over 400 reactions are considered
NACRE compilation
Angulo et al.99, Xu et al. 2013

More and more precise BBN codes used:

PArthENoPe *Pisanti et al. 2008, Cosiglio et al. 2017*
AlterBBN *Arbey, 2012*
PRIMAT *Pitrou et al. 2018*

Pitrou et al. 2018

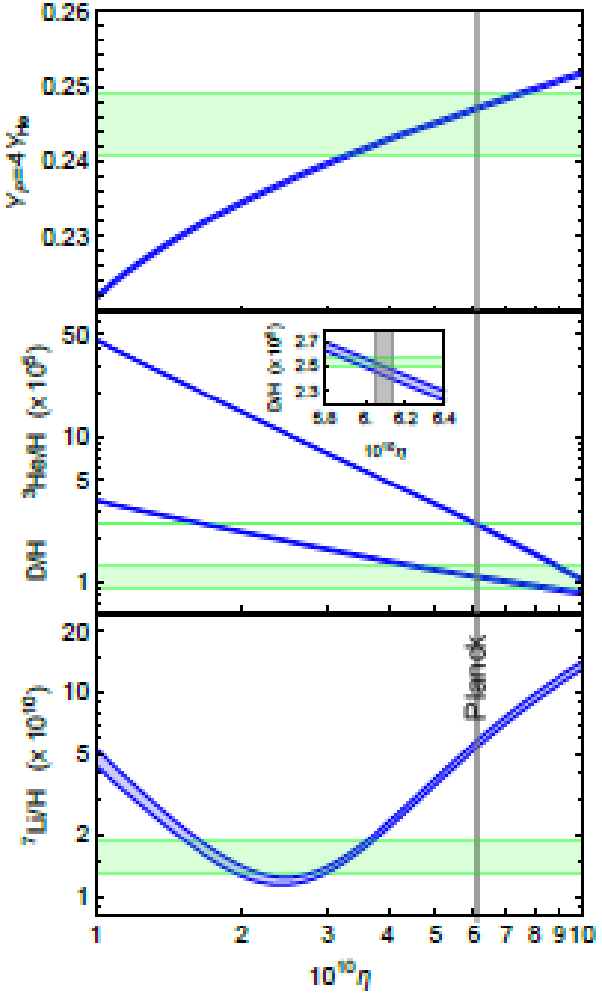


FIG. 26 *Top* : Dependence of $Y_P = 4Y_{^4He}$ in η and observational constraints. *Middle* : Dependence of deuterium (top curve) and ^3He (bottom curve) in η with observational constraints. The ^3H has been added since it decays radioactively in ^3He. *Bottom* : Dependence of ^7Li in η with observational constraints. The ^7Be has been added since it decays radioactively in ^7Li. In all these plots, the width of the curves represents the $\pm\sigma$ uncertainty from nuclear rates and neutron lifetime.

BBN predictions **$Y_P(N_\nu,\eta)$, $X_D(N_\nu,\eta)$**

for $\Omega_B \sim 0.05$ and $N_\nu = 3$ are in agreement with observational data.

Y_T = 0,24709 ± 0,00017
D/H=(2.459 ± 0,036) 10^{-5}

The good concordance between observational data and predicted by theory abundances allows to use BBN as:

- a precision probe of physical conditions in the Universe (barometer, speedometer, etc)
- a test of beyond SM physics

BBN is the earliest and most precision probe of early Universe physics.

The primordially produced abundances of the light elements as functions of **η**.

Observational data (horizontal bands) compared with theory predictions for He-4 (top), D and He-3 (middle) and Li-7 (bottom) .Vertical band gives baryon density measured by CMB (Planck).

BBN constrains physics beyond SM

- BBN depend on all known interactions - constrains modification of those
- Additional light (relativistic during BBN, i.e. m< MeV) particles species (generations) effecting radiation density (predicted by SUSY, string models, extradimensional models, DR, etc.)
- pre-BBN nucleon kinetics or BBN itself
- Additional interactions or processes relevant at BBN epoch (decays of heavy particles, neutrino oscillations)
- Depart from equilibrium distributions of particle densities of nucleons and leptons (caused by nu oscillations, lepton asymmetry, inhomogeneous distribution of baryons, etc.)
- SUSY, string models, extradimensional models, etc.
- etc

BBN Speedometer

Schwartzman 1969

Constraints on additional light species

BBN $2.3 < N_{eff} < 3.4$

$5.6 < \eta < 6.6$

Cyburt, 2016

$N_{eff} = 2.88^{+0.27}_{-0.27}$ (95%) *Pitrou, 2018*

4

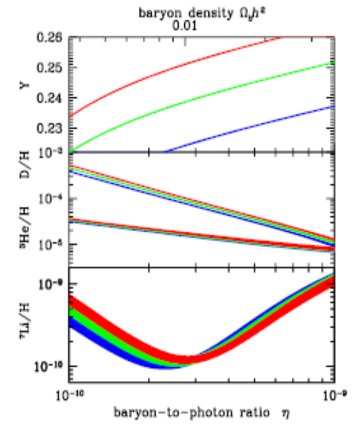


FIG. 7. The sensitivity of the light element predictions to the number of neutrino species, similar to Figure 1. Here, abundances shown by blue, green, and red bands correspond to calculated abundances assuming $N_\nu = 2, 3$ and 4 respectively.

Untill Plank CMB larger errors for ΔN_{eff} than BBN

Planck Collaboration 2015

$N_{eff} = 3.13^{+0.31}_{-0.31}$ (95%)

$N_{eff} = 2.88^{+0.16}_{-0.16}$ (95% Planck +D+He-4)

$N_{eff} = 3.01^{+0.15}_{-0.15}$ (95% Planck +BBN)

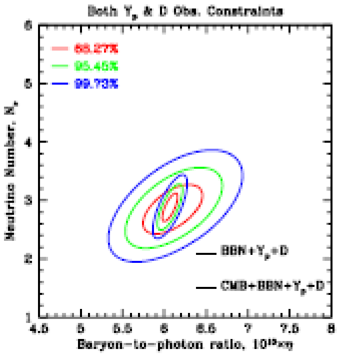


FIG. 10. The resulting 2-dimensional likelihood functions for the baryon to photon ratio (η) and the number of neutrinos (N_ν), marginalized over the helium mass faction Y_p, assuming different combinations of observational constraints on the light elements.

A maximum likelihood analysis *Cyburt, 2016*

BBN Speedometer

- **Constrains the effective number of relativistic species**

Non-zero ΔN_{eff} will indicate extra relativistic component, **$\Delta N_{eff} < 0.2\text{-}0.3$**

like sterile neutrino, neutrino oscillations, lepton asymmetry, neutrino decays, nonstandard thermal history, etc

- **Constrains sterile neutrino production, right handed bosons**

- **Constrains chemical potentials**

4

$$\Delta N_{eff} = 15/7[([\mu/T)/\pi]^4 + 2[(\mu/T)/\pi]^2$$

- **Constrains neutrino oscillations parameters**
- **Constrains supersymmetric scenarios (lightest particle neutralino or gravitino), string theory, large dimensions**
- **Constrains decaying particles, SUSY metastable particles (solution to Li problem?)**

Neutrino Oscillations Overview

$$\nu_m = U_{mf}\,\nu_f, \quad (f = e, \mu, \tau)$$

It has been observationally and experimentally proved that *neutrinos oscillate – flavor oscillations.*

✓ Combined neutrino oscillations data

including SBL reactor exps + LSND +MiniBooNe +Gallium (GALLEX, SAGE):

hint to light ν_s with eV mass and mixing with flavour neutrinos $\sin^2\theta$ [0.01-0.03]

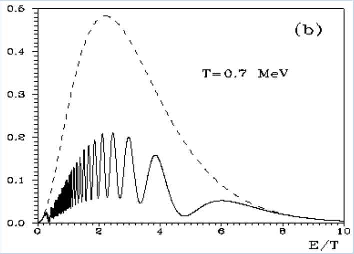
(in equilibrium before BBN),

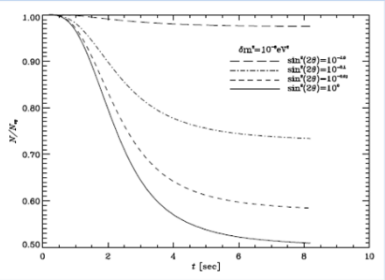
Oscillations imply

✓ non-zero neutrino mass and mixing

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

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





Neutrino anomalies are well described in terms of flavor neutrino oscillations, but sub-leading sterile oscillations may provide better fit.

✓ L change depletion $N_e < N_{eq}$

additional species may be brought into equillibrium

✓ sterile neutrino $N_{eff} > 3$

Neutrino oscillations influence Universe processes. BBN constrains $\nu_s \leftrightarrow \nu_e$.

Neutrino oscillations cosmological effects

❖ **Active-sterile oscillations** considerable cosmological influence

✓ Dynamical effect: Excite additional light particles into equilibrium δN_s

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

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

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

✓ Distort the neutrino energy spectrum from the equilibrium FD form

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

DK 88, DK&Chizhov 96

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)

Foot&Volkas 95,96; DK&Chizhov 96,97,2000

BBN is a sensitive probe to additional species and to distortions in the neutrino distribution.
BBN limits oscillation parameters.

DK&Chizhov 98,2000, Dolgov&Villante 03, DK04,07 ,DK&Panayotova, 2006, DK07

Evolution of oscillating neutrino

Kinetic eqs for density matrix of neutrinos in case of neutrino oscillations

$$i\frac{\partial\rho(t)}{\partial t} = Hp_\nu i\frac{\partial\rho(t)}{\partial p_\nu} + [\boldsymbol{H}_0, \rho(t)] + i\{\boldsymbol{H}, \rho(t)\}$$

vacuum flavor oscillations *Dolgov, 81*
vacuum electron-sterile oscillations *DK 88*
$O(G_F^2)$ breaking of coherence term

Kinetic eqs for matter neutrino oscillations *Rudzsky, 1990; Sigl,Raffelt,1993;McKellar,Thompson1994*

Evolution of *nonequilibrium light oscillating neutrino* $\nu_e \leftrightarrow \nu_s$ *DK, Chizhov, 1996*
effective after active neutrino decoupling $\delta m^2 \sin^4 2\theta \le 10^{-7}$ eV^2 *DK, Chizhov, PLB 1997*

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

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

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

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

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

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

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

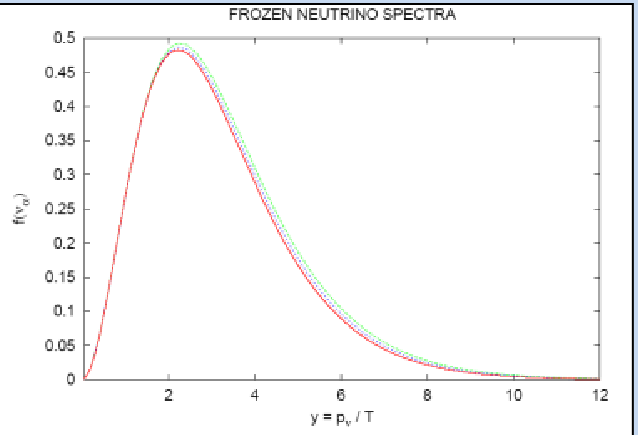
Approach: *follow the evolution of neutrino for each momentum and account for oscillations, expansion, neutrino forward scattering and interactions with the medium simultaneously.*

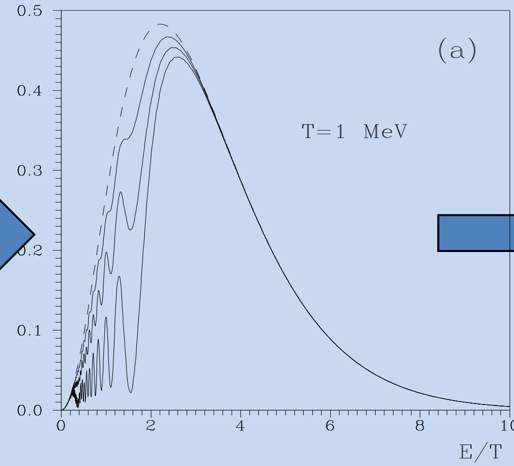
Even for fast oscillation case <p> approximation – not suitable, L growth overestimated.
Approximate solutions of L(t) were developed. *Foot&Volkas 97, Bell,Volkas&Wang,99*

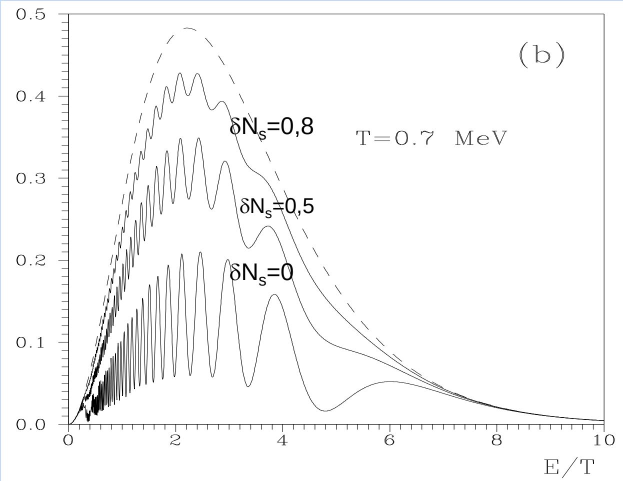
- Active-sterile oscillations proceeding after decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ may strongly distort neutrino distribution and deplete electron neutrino.

Kirilova 88, Kirilova&Chizhov PLB,97

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

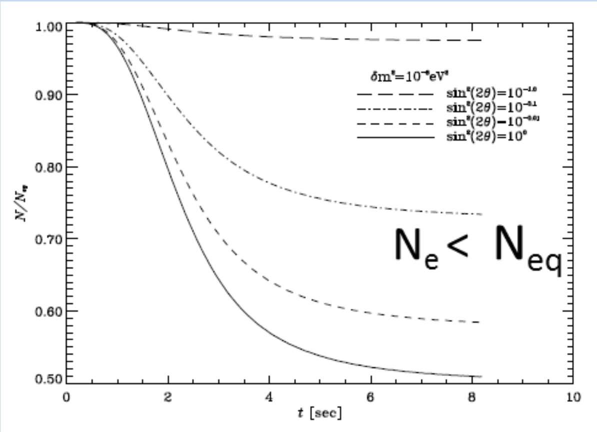






Kirilova, IJMPD, 2004

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.

Precise description of neutrino momenta distribution:

1000 bins used to describe it in non-resonant case

up to 10 000 in the resonant case.

- *Active-sterile oscillations before neutrino decoupling* slightly influence active neutrino distributions, because the states are refilled due to interactions with the plasma and bring sterile neutrino into equilibrium.

BBN with late $\nu_e \leftrightarrow \nu_s$ and L

❖ In BBN with $n_e \leftrightarrow n_s$ 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 $\nu_e \leftrightarrow \nu_s$

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

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

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

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

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

Numerical analysis:

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

Oscillations and L dynamical and kinetic effect on BBN were explored.

$\delta N = \delta N_{k,0} - \delta N_{k,0}\, \delta N_s + \delta N_s$ $\delta Y \sim 0.013\, \delta N$

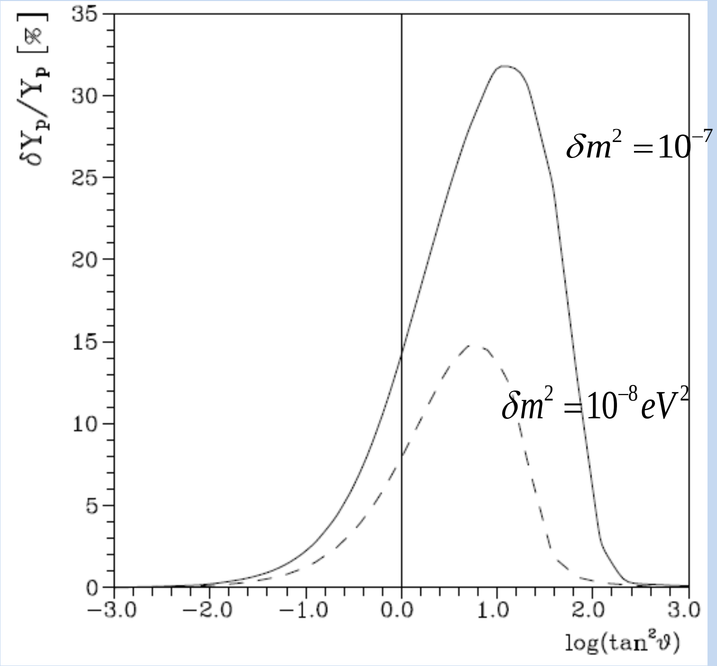
Maximum He-4 overproduction in BBN with oscillations due to spectrum distortion

may be much bigger than 5% due to kinetic effects.

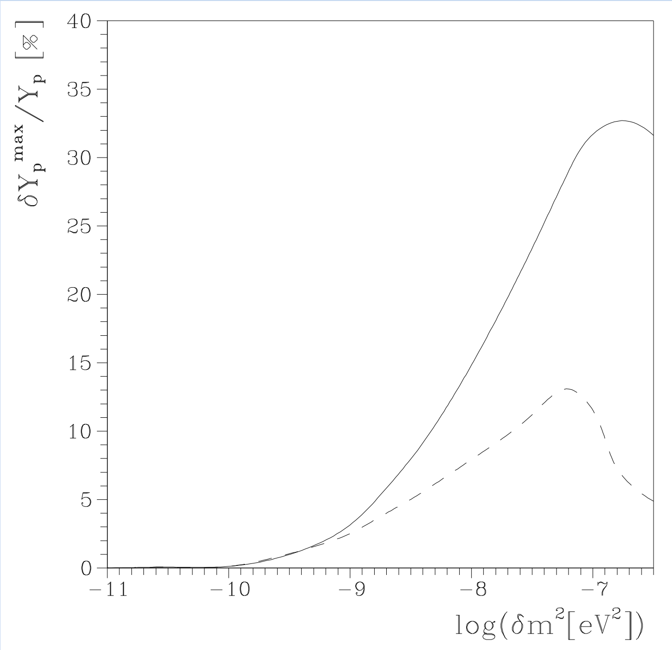
DK , Astrop.Phys.,2003

$\delta Y/Y \leq 32\%$ for resonant oscillations $\delta N_{k,0} \leq 6$

$\delta Y/Y \leq 14\%$ for non-resonant oscillations $\delta N_{k,0} \leq 3$



Dependence of maximum overproduction on the mixing



Dependence of maximum overproduction on mass

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.

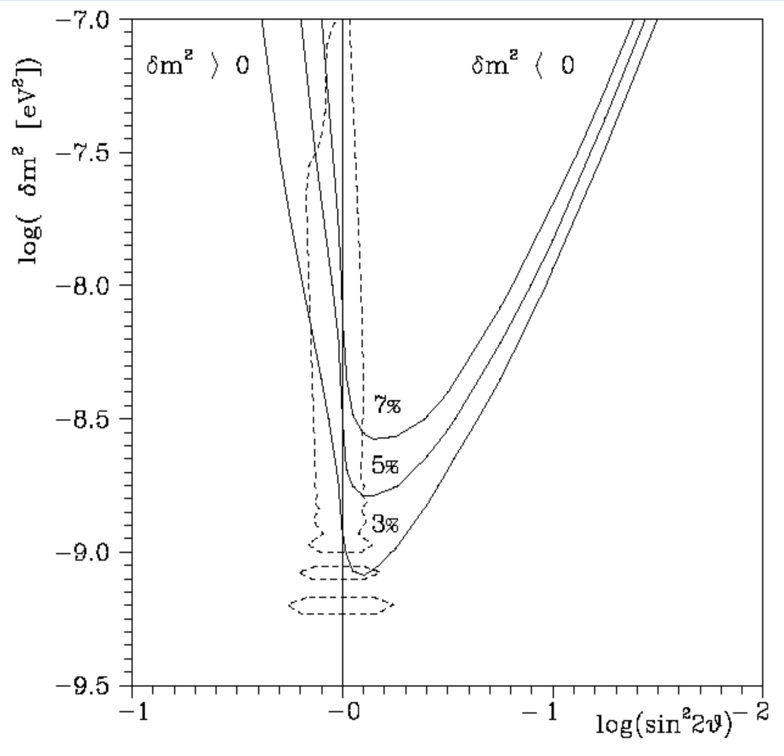
BBN constraints on $\nu_e \leftrightarrow \nu_s$

Y_p=0,2565 ± 0.001(stat)± 0,005(syst)
Izotov&Thuan, 2010 *93 Sp of 86 low Z HII*

He-4 is the preferred element:

- ✓ abundantly produced,
- ✓ precisely measured
- ✓ 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..)



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

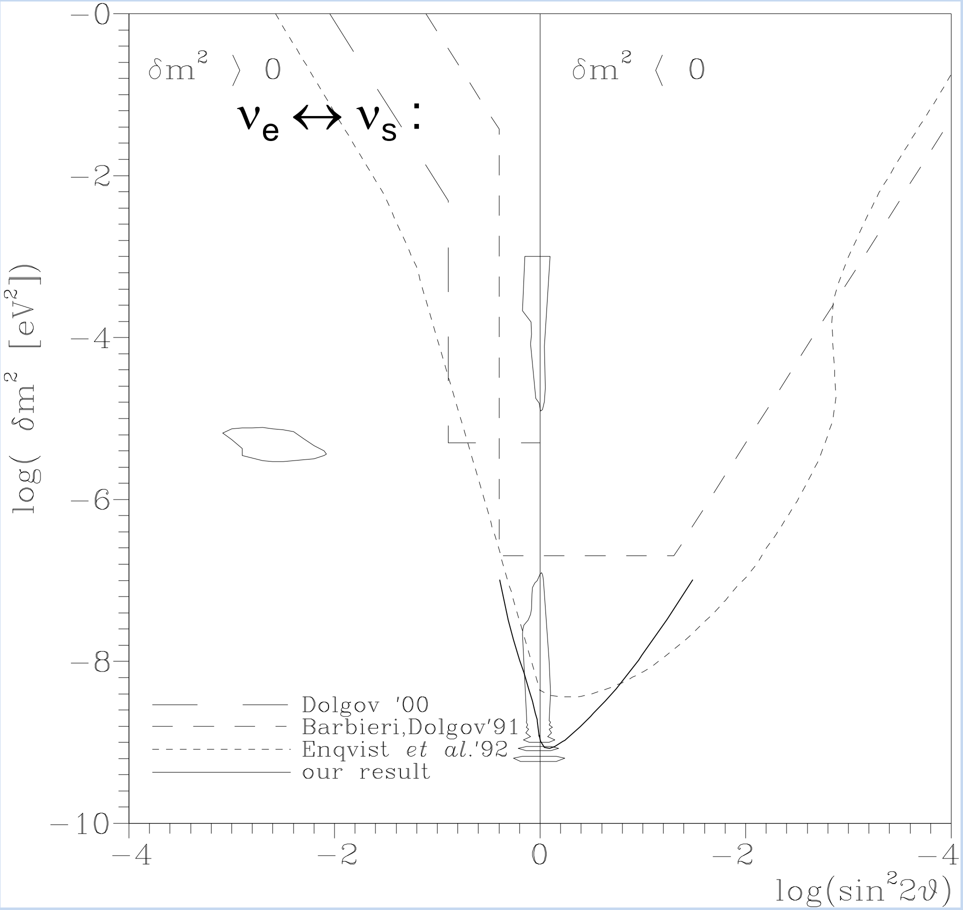
$$\delta m^2 \left(\sin^2 2\theta\right)^4 \leq 1.5\times10^{-9} eV^2 \quad \delta m^2 > 0$$

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

DK, Chizhov NPB2000,2001;

BBN constraints on neutrino oscillations

BBN constraints on oscillations between initially empty ν_s and ν_a



Barbieri, Dolgov 91 – depletion account
Dolgov 2000 – dashed curve;
Enqvist et al. 92 – one p approx.
our result DK, Chizhov - spectrum distortion and L growth
Dolgov, Villante, 2003 - spectrum distortion

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

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

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

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

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

DK.,Chizhov 2001

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

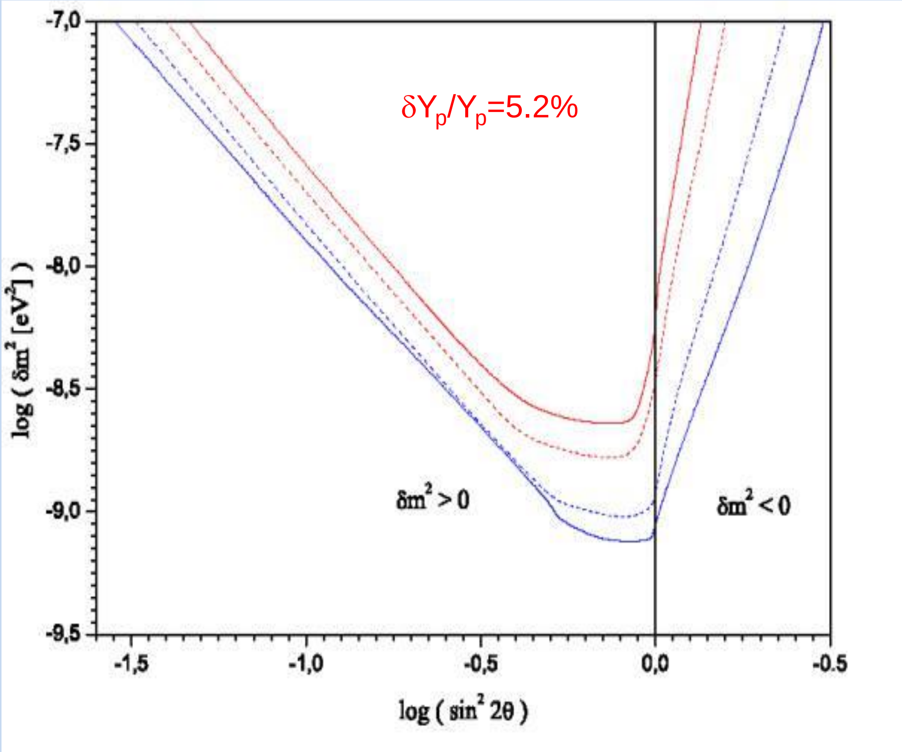
$$\delta m^2 < 8.2\times10^{-10} eV^2 \quad \text{large } \theta,\ \delta m^2 < 0$$

- ✓ 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.

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 2006;DK07

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

Lepton Asymmetry Effects

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

$$L = \sum_i \frac{1}{12\zeta(3)} \frac{T_{\nu_i}^{\,3}}{T_\gamma^{\,3}} (\xi_{\nu_i}^3 + \pi^2 \xi_{\nu_i}) \qquad \xi = \mu/T$$

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

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

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

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

Wagoner et al.1967

.Terasawa&Sato, 1988 …

Lesgourgues&Pastor, 99

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

- 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:

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

- Indirect kinetic - $0.01 > L \geq 10^{-8}$ effects neutrino evolution, its number density, spectrum distribution, oscillations pattern and hence n/p kinetics and BBN

DK&ChizhovNPB98,2000;DK PNPP, 2010, 2011, DK JCAP,2012.

BBN Constraints on L

❖ BBN provides the most stringent constraint on L. Accounting for the dynamical and direct kinetic effect and the equilibration of the degeneracies due to neutrino oscillations before BBN:

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

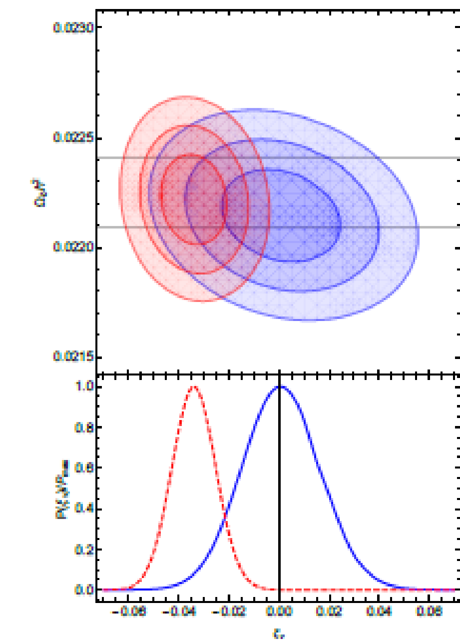


FIG. 28 *Top :* $P(\Omega_b h^2, \xi_\nu)$ with 68.27%, 95.45% and 99.73% contours. *Blue :* using the ^{4}He bounds (4). *Red :* using the bounds $Y_P = 0.2551 \pm 0.0022$ of Izotov et al. (2014). The gray horizontal bars are the $\pm\sigma$ CMB constraints on baryon abundance. *Bottom :* marginalized distribution for ξ_ν. Continuous line uses (4) whereas the dashed line uses the bounds $Y_P = 0.2551 \pm 0.0022$ of Izotov et al. (2014).

Steigman, 2012 ; Castorini et al. 2012 ; Mangano et al., 2013

❖ Improvement on D and He measurement – stringent BBN constraints

$$\xi_\nu = 0.001 \pm 0.016 \qquad |\xi_\nu| < 0.016(68\%CL)$$

CMB provide looser bounds $\xi_\nu = 0.002 \pm 0.06$

Pitrou et al., 2018

Interplay between L and active-sterile oscillations allows to constrain strongly L.

BBN with electron-sterile oscillations feels and constrains tiny L $L < (\delta m^2 / eV^2)^{2/3}$

Kirilova, JCAP 2012, Hyperfine Int. 2013

L oscillations interplay

- ✓ 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) *L-T=M*

  -L-T=M

L enhancement in MSW resonant active-sterile neutrino oscillations was first found for

$\delta m^2 > 10^{-5} eV^2$ in collisions dominated oscillations *Foot, Thompson&Volkas 96; Bell,Volkas&Wang,99*

$\delta m^2 < 10^{-7} eV^2$ in the collisionless case *Kirilova&Chizhov 96;DK 2012*

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

Flavor oscillations equalize L in different flavors before BBN *Dolgov et al., NPB, 2002*

- ✓ Relic L effects neutrino oscillations

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

  enhances them *Kirilova&Chizhov 98*

In BBN with neutrino oscillations spectrum distortion and L generation lead to different nucleon kinetics, and modified BBN element production.

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

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

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

Small L<<0.01 influence *indirectly* BBN via oscillations by:

- ✓ changing neutrino number densities
- ✓ 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

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

- Different cases of L were studied:

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

DK&Chizhov , NPB 96, 98, 2001 *DK PNPP 2010, JCAP2012, 2018*

The evolution of the L was numerically studied. L influence on oscillations was explored in the full range of model oscillation parameters and a wide range of L values. Primordial production of He-4 was calculated. Modified BBN constraints on oscillation parameters in presence of L were presented.

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

- Equations governing the evolution of the oscillating ν and ν_s, accounting simultaneously for Universe expansion, neutrino oscillations and neutrino forward scattering.

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

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

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

$\boldsymbol{H_0}$ *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 L term leads to coupled integro-differential equations and hard numerical task .
L term leads to different evolution of neutrino and antineutrino.

BBN with $\nu_e \leftrightarrow \nu_s$ 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 $\nu_e \leftrightarrow \nu_s$

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

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

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

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

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

Numerical analysis:

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

Oscillations and L dynamical and kinetic effect on BBN were explored.

$\delta N = \delta N_{k,0} - \delta N_{k,0}\, \delta N_s + \delta N_s$ $\delta Y \sim 0.013\ \delta N$

BBN with $\nu_e \leftrightarrow \nu_s$ and L

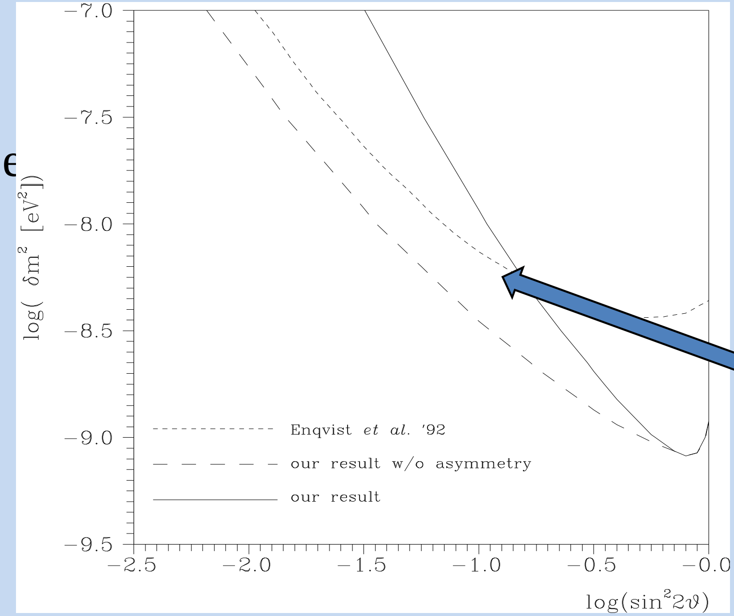
For $\delta m^2 \sin^4 2\theta < 10^{-7} eV^2$ evolution of L is dominated by oscillations and typically L has rapid oscillatory behavior.

The region of parameter space for which large enhancement of L is possible:

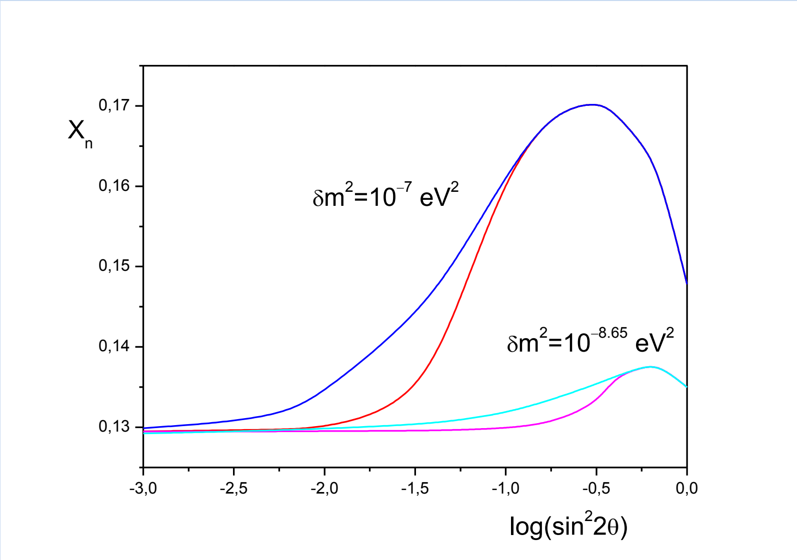
$$|\delta m^2| \sin^4 2\theta \le 10^{-9.5} eV^2$$

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

e



❖ In BBN with $\nu_e \leftrightarrow \nu_s$ neutrino spectrum distortion and asymmetry generation lead to different nucleon kinetics, and modified BBN element production.



X_n and correspondingly the primordially produced He-4 decreases at small mixing parameters values due to asymmetry growth.

DK, PNPP,2010; 2011

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

Relic L and BBN with $\nu_e \leftrightarrow \nu_s$

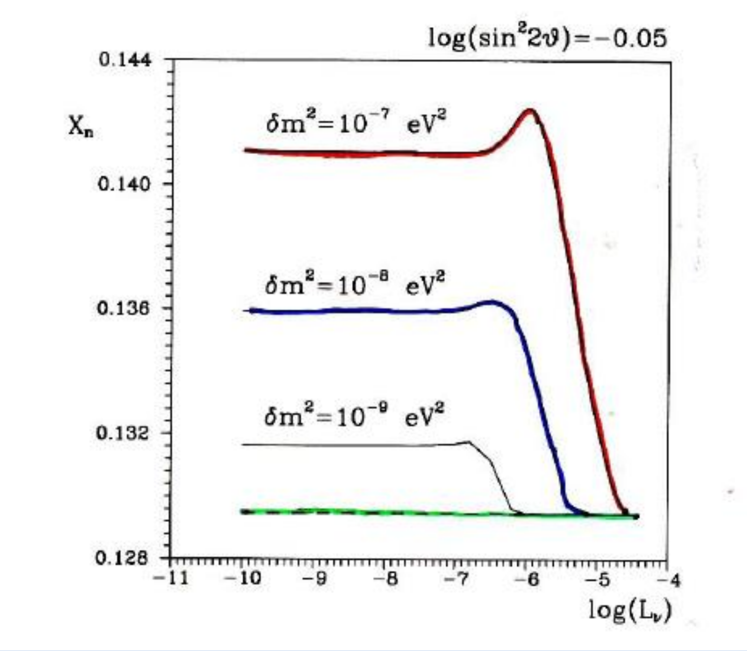
$L > 0.1(\delta m^2)^{2/3}$ suppresses oscillations — relaxes BBN constraints on oscillations

$L > (\delta m^2)^{2/3}$ inhibit oscillations. — eliminate BBN constraints on oscillations

enhances oscillations — strengthens BBN constraints

L change primordial production of He by enhancing or suppressing oscillations.

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



DK&ChizhovNPB98, DK, JCAP 2012

Constraints on δm^2 in case L eliminates standard BBN constraints on neutrino oscillations:

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

Constraints on L in case of electron-sterile oscillations with $\delta m^2 = 10^{-5} eV^2$

$$L < 10^{-3.3}$$

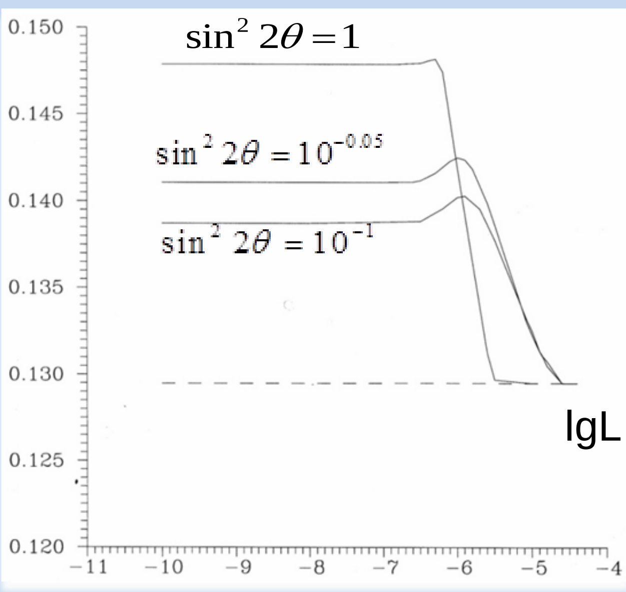
Relic L and BBN with $\nu_e \leftrightarrow \nu_s$

$Y_p\left(\delta m^2, \theta, L\right)$ $10^{-11}<L<0.01$

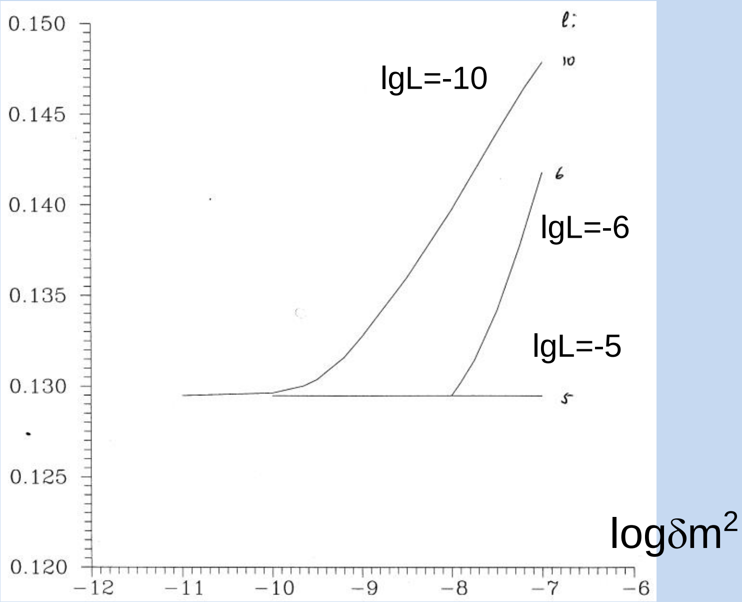
Kirilova 2018

BBN with oscillations can feel extremely small L: down to 10^{-8} .It is precise leptometer.

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



The dependences of helium production on relic L (for different mixing) .



The dependences of helium production on δm^2 (for different L) .

Summary

- Fruitful interplay b/n cosmology and particle physics exists.
  Cosmology can predict the influence of BSM characteristics and test them. In particular, BBN is the earliest and the most reliable probe of beyond SMP. It «measures» neutrino mass differences, number of neutrino species, neutrino oscillations patameters, deviations from equilibrium, baryon density, L, new interactions, etc.
- BBN is the most sensitive speedometer. Stringent BBN constraints on additional light particle species N_{eff} exist. These are used to constrain SUSY, string, extradim, etc. BBN bounds on N_{eff} is strengthened in case of neutrino oscillations.
- BBN is a very sensitive leptometer. BBN bounds on L are changed in case of neutrino oscillations, $|L|<0.01$. L as small as 10^{-8} may be felt by BBN via electron-starile neutrino oscillations.
- BBN constrains neutrino oscillations parameters. Constraints exist even if He-4 uncertainty were over 5%. BBN provides the most stringent constraint on δm^2 . BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ oscillations allows to put constraints on ν oscillation parameters for He-4 uncertainty up to 32%(14%) in resonant (non-resonant) case, provided ν_s was not in equilibrium.
- BBN constraints on neutrino oscillations parameters depend nontrivially on the population of ν_s and L in the Universe. Additional initial population of ν_s not always leads to strengthening of constraints, it may relax them.
  Relic L may provide relaxation or enhancement of BBN constraints on oscillations.
  Oscillations generated L relaxes BBN constraints at small mixings.

Благодаря за вниманието!

Thanks for the attention!

Oscillations in the Early Universe medium

- The thermal background of the early Universe influences the propagation of ν.

Differences in the interactions with the particles from the plasma lead to different average potentials for different neutrino types V_f $f= e, \mu, \tau$

Notzold&Raffelt 88

In the Sun L>>Q

$V_f = Q - L$ for neutrino

$V_f = Q + L$ for antineutrino

$Q = -bET^4 / (\delta m^2 M^2_W)$ $L = -aET^3 L_\alpha / (m^2)$

- In the early Universe, E>10 MeV, Q>L if L is of the order of B.

In the adiabatic case the effect of the medium can be hidden in matter oscillation parameters: $\sin^2\theta_m = \sin^2\theta / [\sin^2\theta + (Q \pm L - \cos 2\theta)^2]$

In general the medium suppresses oscillations.

When $Q \pm L = \cos 2\theta$ mixing in matter becomes maximal independent of mixing in vacuum - enhanced oscillation transfer.

for Q>L $\delta m^2 < 0$ resonant oscillations both for neutrino and antineutrino

for Q<L at $\delta m^2 < 0$ resonant for antineutrinos, $\delta m^2 > 0$ – for neutrinos