V INTERNATIONAL SYMPOSIUM
ON SYMMETRIES IN SUBATOMIC PHYSICS (SSP2012)
Groningen, The Netherlands, June 18-22, 2012

LEPTON ASYMMETRY AND NEUTRINO OSCILLATIONS INTERPLAY

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Outline

Interplay between L and ν oscillations
L cosmological effects
Big Bang Nucleosynthesis constraints on L
L and excess radiation density in the Universe

D.Kirilova ,JCAP 2012 ; D.Kirilova ,PNPP 2010

DK&M.Panayotova, JCAP 2006;

DK&Chizhov,NPB 98; DK &M.Chizhov,PLB,97

Lepton Asymmetry

Lepton asymmetry of the Universe

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

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

may be orders of magnitude bigger than the baryon one, $\beta = (n_b - n_{\bar{b}}) / n_\gamma \sim 6.10^{-10}$
which is measured with great precision (CMB, BBN).

Though usually assumed $L \sim \beta$, big L may reside in the neutrino sector $L \sim \sum_i L_{\nu_i}$
(universal charge neutrality implies $L_e = \beta$) .

CNB has not been detected yet, hence L is 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

Cosmic Microwave Background

Large Scale Structure, etc.

Lepton Asymmetry Effects

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

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

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

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

Lesgourgues&Pastor, 99

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

⟹ influence BBN, outcome is L sign dependent

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

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

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

- L changes the decoupling T of neutrino, etc.

We studied the interplay between L and neutrino active-sterile oscillations in the early Universe and their effect on BBN.

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

- Two different cases of L were explored:

  relic ($L>10^{-10}$) and generated by oscillations.

The evolution of the lepton asymmetry was numerically studied.
Numerical analysis of L influence on oscillations was provided in the full range of model oscillation parameters and a wide range of L values.
Primordial production of He-4 was calculated in case of relic L and in case of asymmetry generated by oscillations.
Modified BBN constraints on oscillation parameters in presence of L were presented.

Neutrino Oscillations Effects

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

✓ Dynamical effect: Excite additional light particles into equilibrium δN_s

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

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

✓ Distorting the neutrino energy spectrum from the equilibrium FD form

$$\Gamma \sim G_F^2 E_\nu^2 N_\nu$$ *DK 88, D.K&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; D.K&Chizhov,96; Shi 96

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

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

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

Asymmetry - 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&Volkas 96*

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

- ✓ Asymmetry effects neutrino oscillations

  suppresses them

  Foot&Volkas, 95; Kirilova&Chizhov 98

  enhances them

  Kirilova&Chizhov 98 ; Kirilova 2010, 2012

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

L influence on neutrino

- 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, μ, τ

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

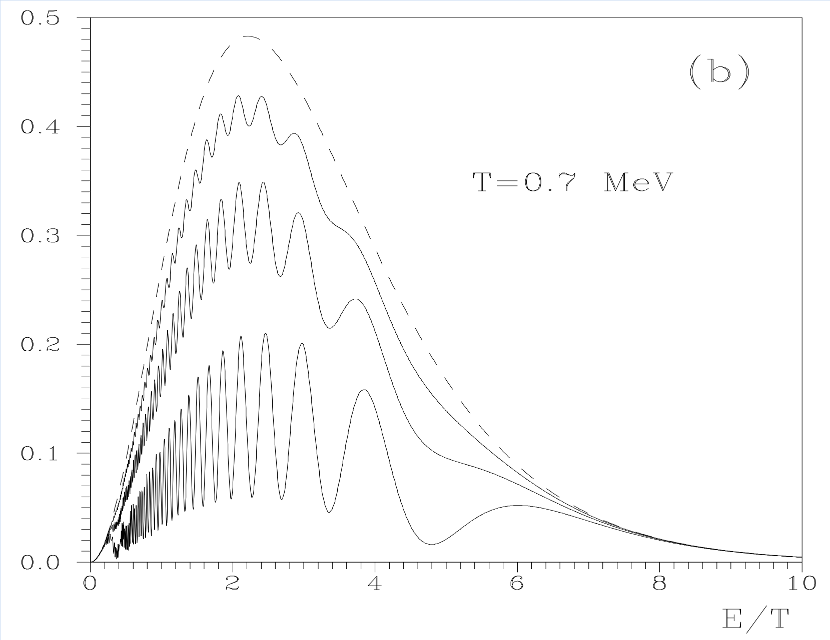
for Q<L at $\delta m^2 <0$ resonant for antineutrinos, $\delta m^2 >0$ – for neutrinos

L effect on oscillating neutrino

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

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

- Active-sterile oscillations proceeding after decoupling may strongly distort neutrino energy spectrum. *Kirilova 88, Kirilova&Chizhov 97*



Kirilova,IJMPD,2004

Precise description of neutrino momenta distribution is needed, which further complicates the numerical task.

In the analysis 1000 bins were used to describe neutrino distribution in non-resonant case, and up to 10 000 in the resonant case.

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

- The medium influences the propation 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*

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

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

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

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

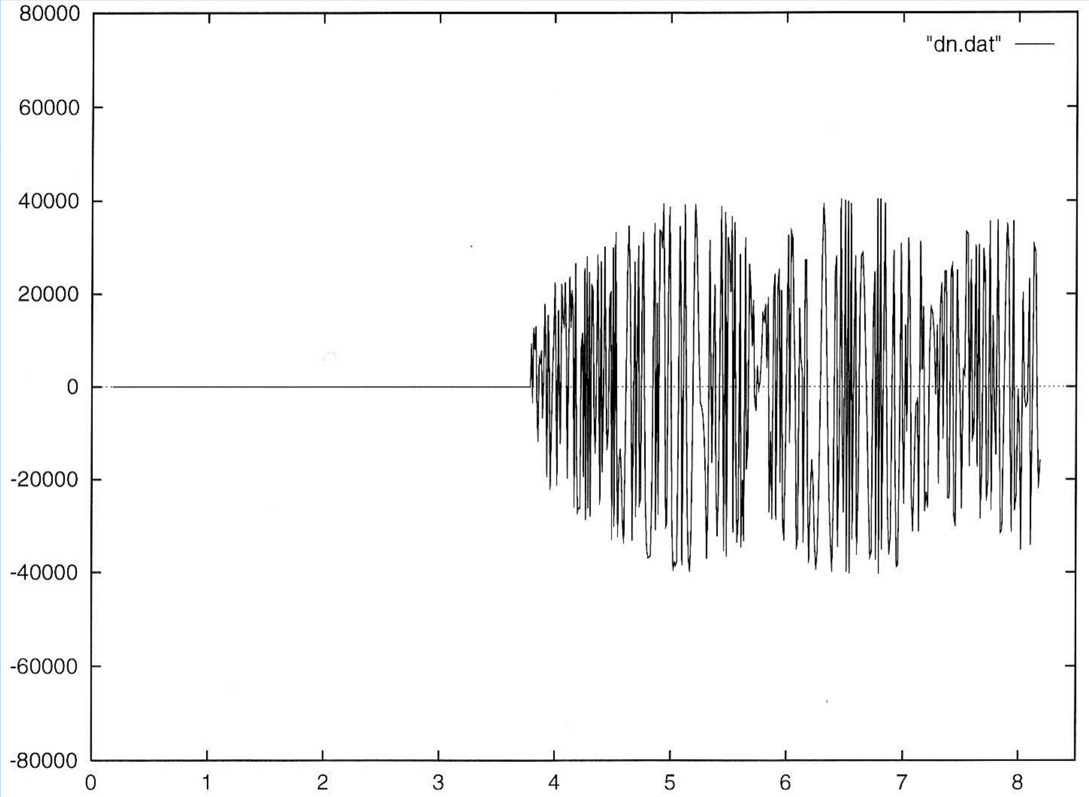
Oscillations generated lepton asymmetry

In the region $\delta m^2 \sin^4 2\theta < 10^{-7} eV^2$ evolution of L is dominated by ν oscillations.

L has rapid oscillatory behavior. The region of parameter space for which large generation of L is possible: $|\delta m^2| \sin^4 2\theta \leq 10^{-9.5} eV^2$

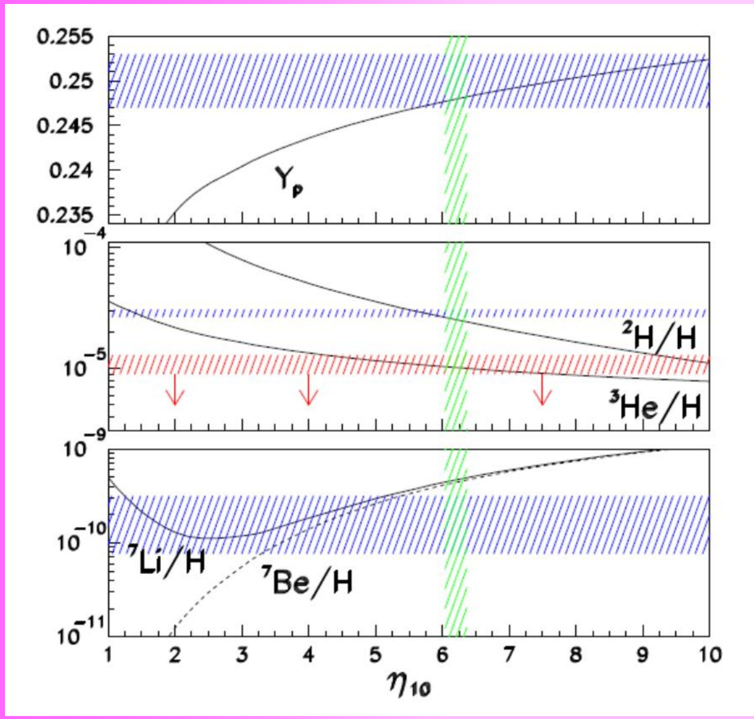
Generation of L by 4-5 orders of magnitude is found possible: $L \sim 10^{-5}$

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



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

BBN with L and ν oscillations



Big Bang Nucleosynthesis

Theoretically well established

Precise data on nuclear processes rates from lab expts at low E (10 KeV – MeV)

Precise data on D, He, Li

Baryon fraction measured by CMB

COSMOLOGY

ASTROPHYSICS → **MICROPHYSICS**

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

The Best Speedometer at RD Stage

BBN probes neutrino oscillations

The Most Exact Leptometer

BBN – the best speedometer and leptometer

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

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

$\delta Y_{KH} \sim 0.013\ \delta N_{eff}$

Non-zero ΔN_{eff} will indicate extra relativistic component, like sterile neutrino, neutrino oscillations, L, neutrino decays, nonstandard thermal history, etc

$\Delta N_{eff} < 1.6$

$2.8 \le N_\nu \le 3.6$ (95% CL) *Iocco et al, 2009*

Using Y from IT10: $3.0 \le N_\nu \le 4.5$ (95% CL)

$\Delta N_{eff} \sim 3$ (WMAP)

$\Delta N_{eff} \sim 0.4$ (Planck) (2 sigma)

- **Constrains chemical potentials and L**

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

ξ_e kinetic effect

- **Constrains neutrino oscillations parameters**

BBN with $\nu \leftrightarrow \nu_s$ neutrino spectrum and densities differ, thus influencing kinetics of nucleons in BBN epoch, reducing weak processes rates overproducing He-4.

The abundance of helium is known with 5% accuracy. This allows to constrain $\nu \leftrightarrow \nu_s$

BBN Constraints on L

- BBN provides the most stringent constraint on L in case of combined variation of chemical potentials

In case neutrino oscillations degeneracies equilibrate due to oscillations before BBN

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

Serpico&Raffelt,2005

Iocco et al.,2009 $-0.021 \le \xi_\alpha \le 0.005$

Recent Y and WMAP7 data *Krauss, Lunardini, Smith 2010* relax the constraints*:* $-0.14 < \xi_{\nu e} < 0.12$

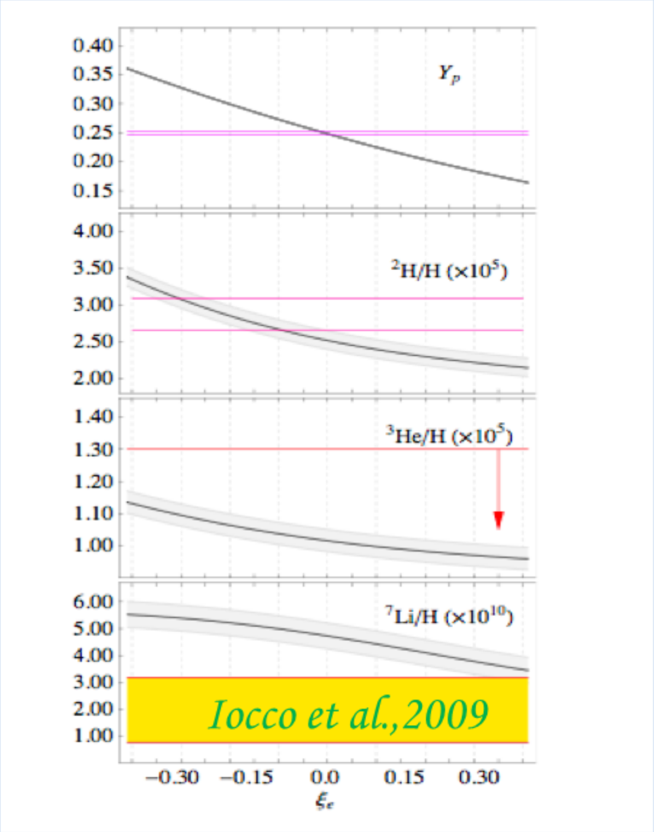
- Accounting for flavor oscillations and ν decoupling and $\sin^2\theta_{13} > 0.03$ $L < 0.1$ otherwise the bound may be relaxed

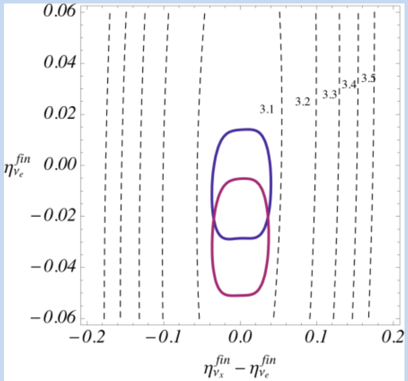
for $\theta_{13} = 0$ $-0.7 < L < 0.6$ *Miele et al.,2011*

CMB and LSS provide much looser bounds

- Recent measurement $\theta_{13} \sim 9^0$ → extra d.o.f. during BBN !

$|L| < 0.1$





BBN with L for $\theta_{13} = 0$ ΔN <1.4

Mangano et al.,2011

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 $\nu_e \leftrightarrow \nu_s$

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

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

$\delta m^2 \leq 10^{-7} eV^2$ *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:

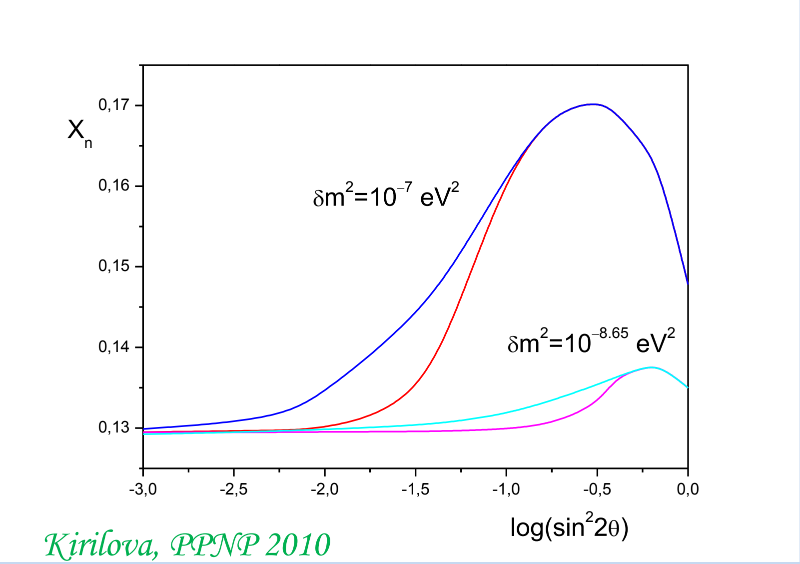
- Evolution of oscillating neutrino in the presence of L
- Evolution of nucleons and n/p freezing
- He-4 primordial production

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

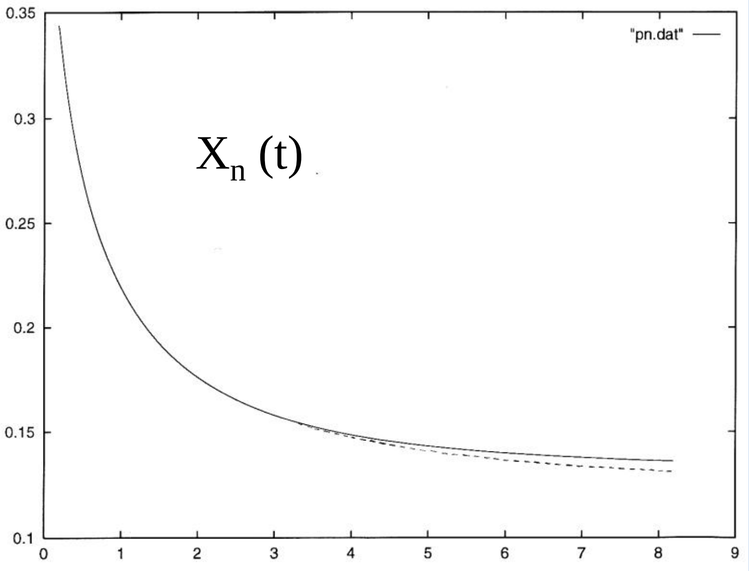
$\delta N = \delta N_{k,0} - \delta N_{k,0}\, \delta N_s + \delta N_s$ $\delta Y \sim 0.013\, \delta N$

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 calculated.



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.



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 the primordially produced He-4) decreases at small mixing parameters values due to L growth.

BBN constraints, accounting for L, on $\nu_e \leftrightarrow \nu_s$

He-4 is the preferred element: Y_p=0,2565 ± 0.001(stat)± 0,005(syst)

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

- ✓ 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, L..)

Barbieri, Dolgov 91 – depletion account

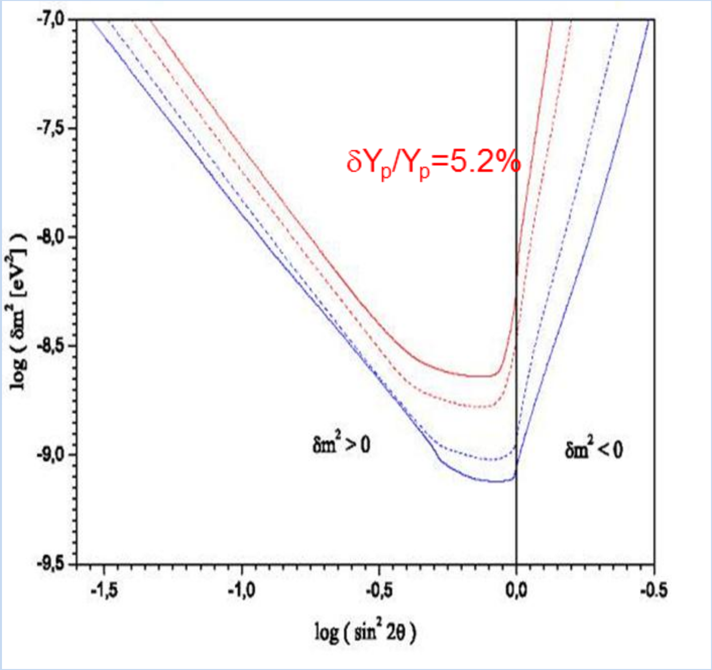
Enqvist et al. 92 – one p approx.

Kirilova, Chizhov 97, 2000 spectrum distortion and L growth account

Dolgov, Villante, 2003 - spectrum distortion

Kirilova, Panayotova, 2006 – δN_s effect

Kirilova, 2010, 2012 – relic L and oscillations generated L



DK&Panayotova JCAP 2006;DK IJMPD 07

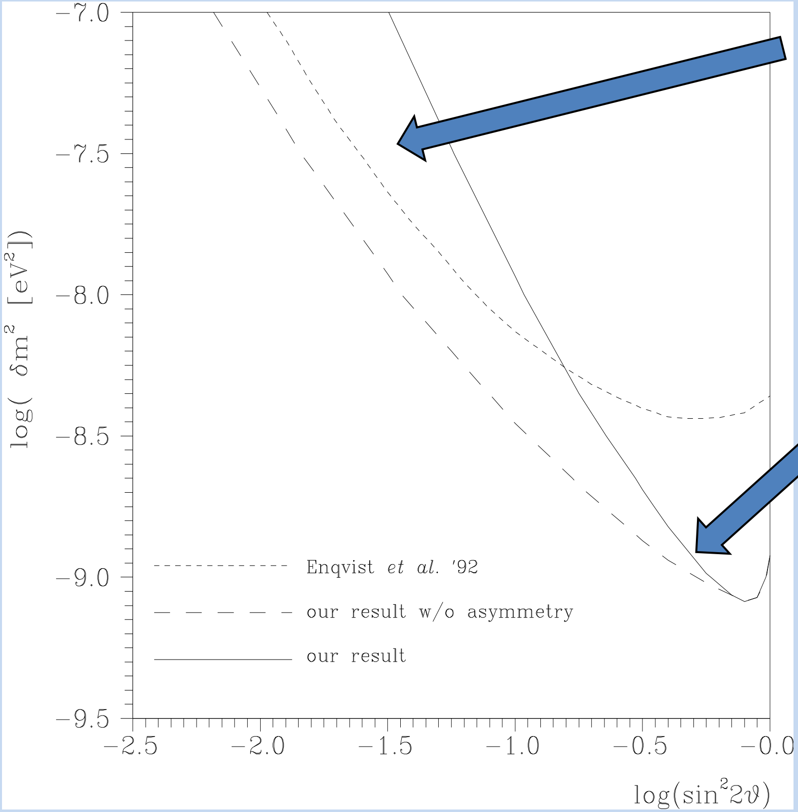
Additional inert population may strengthen or relax BBN constraints.

BBN with nonequilibrium oscillations leads up to 32% He overproduction, i.e. N<9.

BBN constraints on the basis of the He-4 data in case proper account for spectrum distortion, δN_s and asymmetry growth due to oscillations were obtained.

Oscillations generated L effect on BBN constraints

❖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.

Thus, if the mixing is small the generated asymmetry may partially suppress the oscillations and the inert neutrino may equilibrate only partially .

Relic L and BBN with oscillations

Small $10^{-8} < L << 0.01$, 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)

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

$L > 0.1(\delta m^2)^{2/3}$ suppresses oscillations

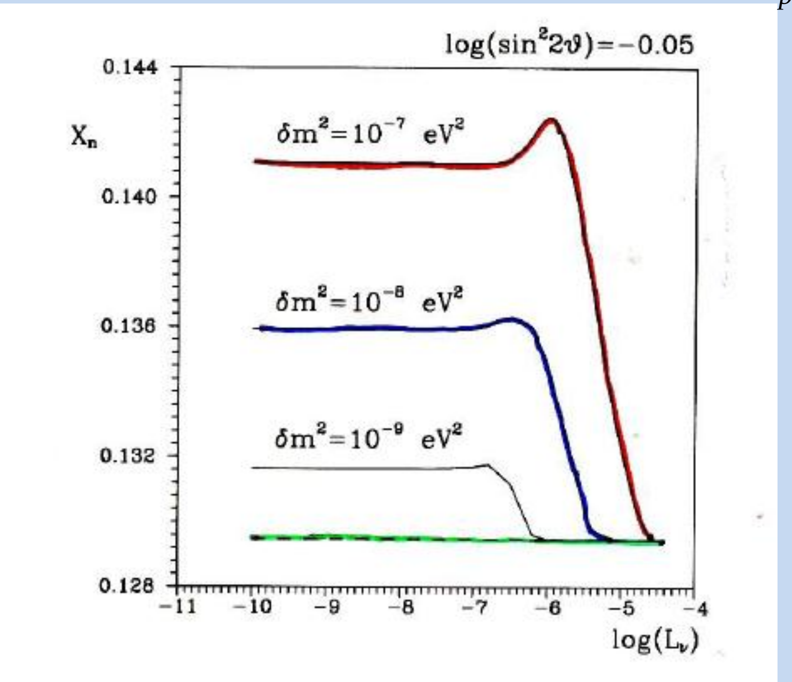
$L > (\delta m^2)^{2/3}$ inhibit oscillations.

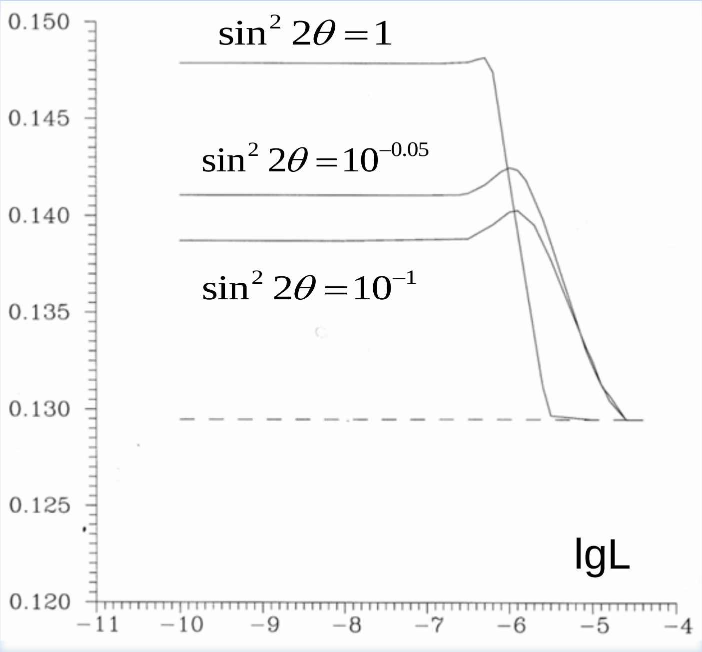
L change primordial production of He by enhancing or suppressing oscillations.

- L change primordial production of He by enhancing or suppressing oscillations.
- He can feel extremely small L: down to 10^{-8}

BBN with oscillations is the best known leptometer.

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





Relic L and BBN constraints on oscillations

- Relic L> 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: $\delta m^2(eV^2) < L^{3/2}$

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

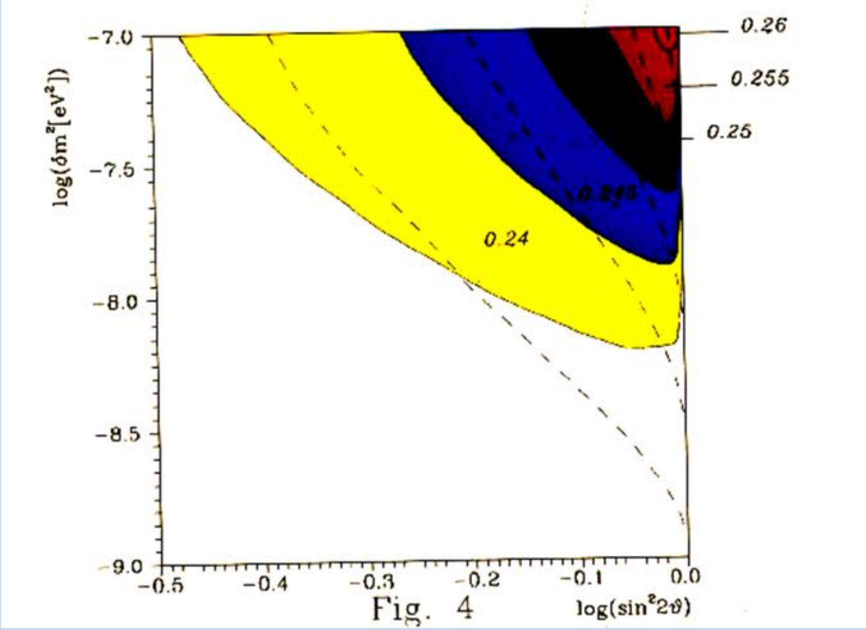
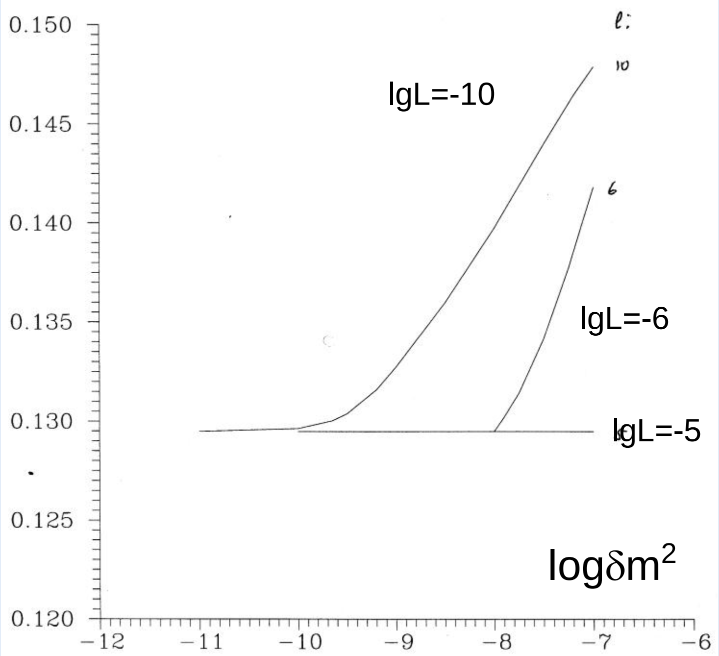


Fig. 4

L may relax BBN constraints at large mixings and strengthen them at small mixing.
Kirilova&ChizhovNPB98, Kirilova JCAP 2012



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

Excess radiation density

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

ΔN_{eff} measures any relativistic component, including inert neutrino brought into equlibrium, oscillations, LA, decays, etc.

✓ Cosmological indications suggesting additional relativistic density:

N_{BBN}=3.8+0.8-0.7 N_{CMB}=4.34+/- 0.87 N_{SDSS}=4.78+1.89-1.79

Y=0.2565+/-0.001+/-0.005 *WMAP7+BAO+HST Komatsu et al. 2011*

A IT2010 68% CL 95% confidence

Y=0.2561+/-0.01 *Aver et al. 2010*

WMAP7+BAO+HST+ACT Keisler et al. 2011: 3.86+/-0.42

+SPT Dunkley et al. 2011 4.56+/-0.75

Excess radiation density

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- ✓ Cosmological indications suggesting additional relativistic density:

  $N_{BBN}=3.8+0.8-0.7$ $N_{CMB}=4.34+/- 0.87$ $N_{SDS}=4.8+1.9-1.8$

- ✓ Combined neutrino oscillations data (including MiniBoone and LSND):

  require 1 or 2 additional light sterile neutrino (in eq. before BBN),
  participating into oscillations with flavor neutrinos with higher mass differences values,
  than ones required by solar and atmospheric neutrino oscillations experiments.

Excess radiation density

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require 1 or 2 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.

Recent analysis 3+1 and 3+2 : Hint of oscillations with 2 ν_s with sub-eV mass

Reactor experiments+LSND+MiniBooNe+Gallium expt

$\delta m^2{}_{41} \sim 0.5eV^2$,

$\delta m^2{}_{51} \sim 0.9eV^2$

Kopp, Maltoni,Schwetz, arXiv: 1103.4570

- Neutrino oscillations effect early Universe processes.

Does cosmology favour light ν_s ? L role?

Excess radiation density

✓ Does cosmology allow these additional neutrinos?

What other explanations of the excess density exist?

CMB, galaxy clustering and and SNIa data allow 3+2 models.

if neutrinos are in sub-eV range *Hamann et al. 2010; Giusarma et al. ,arXiv: 1102.4774*
Hamann et al. 2011:

eV neutrinos are disfavored in SCM – too much HDM

Modified cosmological models: additional radiation

w, $\xi_{\nu e} \sim +0.06$ $n/p \sim e^{-\xi}$

BBN current He and D data allow 1 new d.f. Modfied BBN may be necessary.
Excess radiation cannot be explained by degenerate BBN *Mangano et al. 2011*
BBN hardly allows two thermalized light inert states.

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

The additional relativistic density might point to L, additional sterile neutrino states, neutrino active-sterile oscillations, decaying particles during BBN, etc.

Future experimental and observational data will choose among different possibilities.

Planck data is expected to constrain the radiation content at CMB formation with precision $\Delta N \sim 0.26$, i.e. it will be able to check the extra radiation.

Summary

- Considerable L generation in active-sterile Mikheyev-Smirnov-Wolfenstein oscillations, effective after neutrino decoupling, is found.

  The region in the oscillation parameter space of considerable L growth was determined.
- We provided a detail numerical analysis of the interplay between lepton asymmetry

  L << 0.01, either relic or generated by active-sterile neutrino oscillations, and neutrino oscillations for the case of oscillations after electron neutrino decoupling. The evolution of L growth in case of small mass differences and relatively big mixing angles was studied in more detail.
- The parameter range for which relic L is able to enhance, suppress or inhibit oscillations is determined.
- Cosmological influence of small L, which do not have direct effect on nucleons kinetics during BBN, is discussed. Such small asymmetries are invisible by CMB, but may be felt by BBN:

  L as small as 10^{-8} may be felt by BBN via oscillations.
- The effect of the dynamically generated and initially present L on BBN with oscillations was studied.

Summary

- Relic L 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 L alleviates BBN constraints on oscillation parameters.

- Dynamically generated asymmetry relaxes BBN constraints at small mixing angles.

- SBBN hardly allows two thermalized light inert states. 2+3 oscillations models - allowed by modified BBN with L, because large enough L provides relaxation of BBN constraints, suppressing oscillations and leading to incomplete thermalization and relaxation of limits on inert neutrino.

The additional relativistic density might point to L, additional sterile neutrino states, neutrino active-sterile oscillations, decaying particles during BBN, etc.

Future experimental and observational data will choose among different possibilities.

Conclusions

Active-sterile oscillations may considerably distort neutrino spectrum and produce neutrino-antineutrino asymmetry, thus influencing BBN.
Small lepton asymmetry, relic or produced by active-sterile oscillations, has considerable indirect kinetic effect on oscillating neutrino.

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.
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.

Thanks for the attention!

Благодаря за вниманието!

^{4}He – the best speedometer

He-4 most abundantly produced (25%), most precisely measured (3-5 %) and calculated element (0.1% error) with simple post-BBN evolution.

$$Y_p = 2(X_n)_f e^{-\frac{t}{\tau_n}} \sim 0.24$$

$$\nu_e + n \leftrightarrow p + e^-$$

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

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

$$\tau_n = 885{,}7 s$$

$$\Delta m = 1.293 MeV$$

$$(X_n)_f = \left(\frac{N_n}{N_{nuc}}\right)_f = \frac{\left(\frac{n}{p}\right)_f}{1 + \left(\frac{n}{p}\right)_f}$$

$$H \sim \sqrt{g_{eff} G} T^2$$

$$\left(\frac{n}{p}\right)_f \sim e^{-\frac{\Delta m}{T_f}} \sim \frac{1}{6}$$

$$T_f \sim \left(\frac{g_{eff} G}{G_F}\right)^{1/6} \sim 0{,}7 MeV$$

$$\Gamma \sim G_F^2 T^5$$

$$g_{eff} = \frac{11}{2} + \frac{7}{4} N_\nu = 10{,}75$$

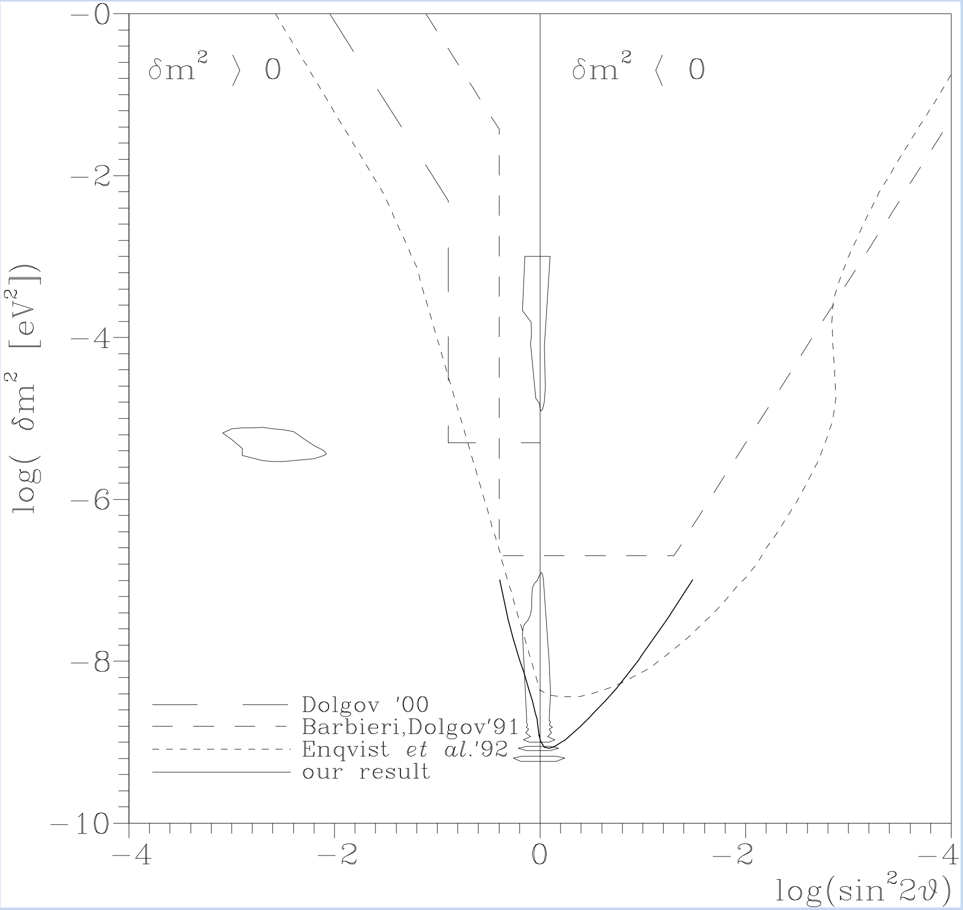
Y_T=(H(ρ(g)),Γ) = 0,2482± 0,0007

Y_o=0,256± 0,01

$\delta Y_{KH} \sim 0.013\ \delta N_{eff}$

BBN constraints on oscillations

BBN with neutrino oscillations between initially empty ν_s and ν_e



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

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

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

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

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

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

DK.,Chizhov 2001 – distortion and asymmetry growth account

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

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

- ✓ BBN constraints are by 4 orders of magnitude more stringent than experimental ones
- ✓ Excluded 2 LMA and LOW active-sterile solutions (1990, 1999) years before experimental results.