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Neutrino Oscillations in the Early Universe – Cosmological Effects and Constraints

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Outline

Neutrino Oscillations Cosmological Effects

BBN Constraints on Neutrino Oscillations

in presence of L

in presence of ν_s

L effects and constraints in BBN with neutrino oscillations

Neutrino Oscillations Overview

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

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

The basic idea of oscillations is that mass eigenstates are distinct from the flavor eigenstates.

Solar neutrino problem, atmospheric neutrino anomaly and the results of terrestrial neutrino oscillations experiments were resolved by *flavor neutrino oscillations*.

✓ Combined neutrino oscillations data including reactor exps+LSND+MiniBooNe+Gallium: hint to 1 or 2 additional light 2 ν_s with sub-eV mass (in eq. before BBN),

Neutrino oscillations influence Universe processes.

Cosmology constrains oscillations b/n light $\nu_s \leftrightarrow \nu_e$.

$$P\,(\theta, \delta m^2, E, t)$$

Oscillations imply

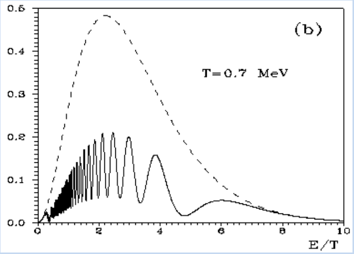
✓ non-zero neutrino mass and mixing

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

$$\Omega_\nu = \frac{3m_0}{93.14h^2\ \mathrm{eV}} \Rightarrow \boxed{0.001 < \Omega_\nu}$$

Flavor neutrino is HDM and hinders the formation of structure at small scales: $\boxed{0.001 < \Omega_\nu < 0.02}$

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



$N_e < N_{eq}$

L change

✓ additional species may be brought into equillibrium sterile neutrino

Neutrino Oscillations Overview

- Vacuum oscillations: Cosmological effect of fast oscillations *Dolgov 1981*
  Cosmological effect of active-sterile non-equilibrium oscillations *Kirilova 1988*
- Matter oscillations: 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

$P(\theta, \delta m^2, E, t, T, L)$

Notzold&Raffelt 88

In the Sun $L \gg Q/M^2_W$

$V_f = QT^3/(M^2_W \delta m^2) - L\, T^3/\delta m^2$ for neutrino

$V_f = Q\ldots. \qquad +L\ \ldots\ldots\ldots$ for antineutrino

$Q=-bET \qquad L=-aL_\alpha$

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

In the adiabatic case the effect of the medium can be hidden in matter oscillation parameters:

$$\sin^2\theta_m = \sin^2\theta/[\sin^2\theta + ((Q/M^2_W \pm L)T^3/\delta m^2 - \cos 2\theta)^2]$$

In general the medium suppresses oscillations.

A possibility of enhanced oscillation transfer *Wolfenstein, 1978; Miheev,Smirnov 1985*

if $(Q/M^2_W \pm L)T^3 = \cos 2\theta \delta m^2$ mixing in matter becomes maximal independent of mixing in vacuum

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

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

Evolution of oscillating neutrino

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

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

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

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

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

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

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

H*$_0$ *is free neutrino Hamiltonian

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

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

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

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

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*

Neutrino Oscillations Cosmological Effects

❖ Flavor Matter Oscillations

Oscillations favored by the atmospheric and solar neutrino data establish an equilibrium between active neutrino species before BBN epoch. No considerable influence on BBN, CMB, CNB.

Account for flavor oscillations : 113 /cm^3 instead 112 in SCM. But might be important for L.

❖ Active-sterile oscillations $\nu_a \leftrightarrow \nu_s$ may have considerable cosmological influence!

✓ *Dynamical effect: Excite additional light particles into equilibrium*

$\rho \sim g_{eff} T^4$

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

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. 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

BBN with $\nu_a \leftrightarrow \nu_s$ *effective after* ν_a *decoupling and* $\delta N_s<1$ *- strong sp distortion*

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

D.K&Chizhov,96; Foot&Volkas 95,96; Shi 96; di Bari 2003; DK 2012

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

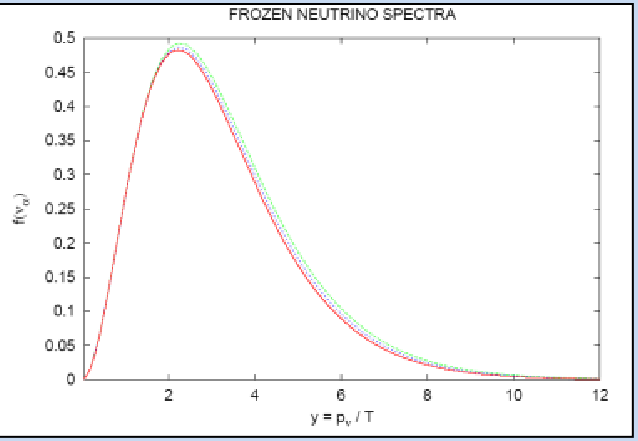
BBN is a sensitive to additional species and to distortions in neutrino distribution

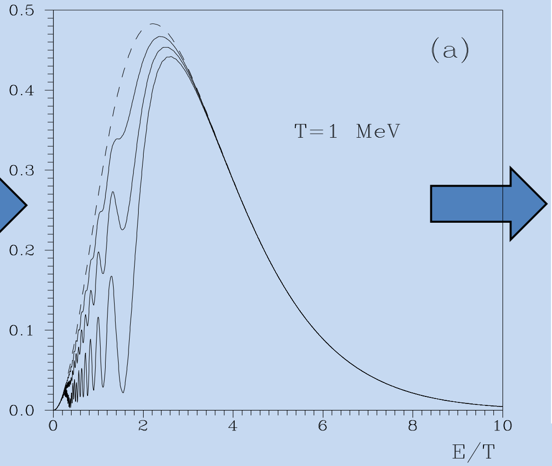
BBN stringent limits on oscillation parameters.

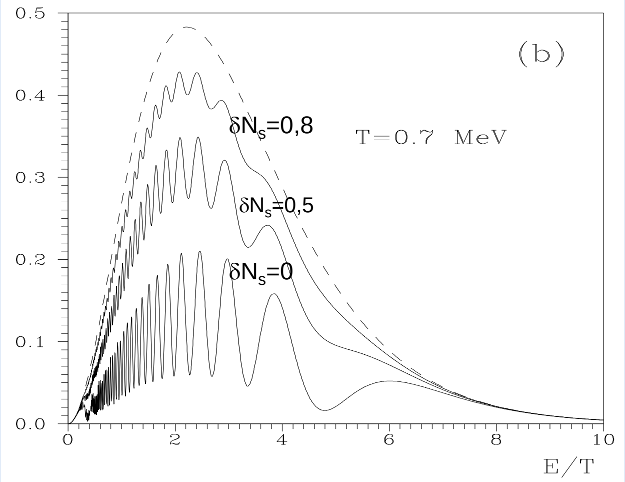
- Active-sterile oscillations proceeding after decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ may strongly distort neutrino distribution and deplete electron neutrino.

Kirilova 88, Kirilova&Chizhov PLB,97

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

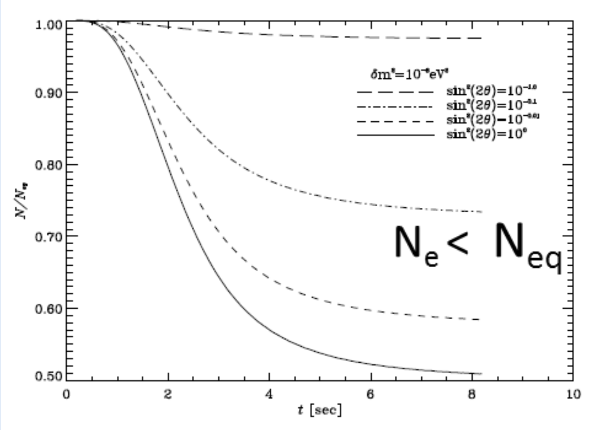






Kirilova,IJMPD,2004

The distortion due to active-sterile oscillations and the kinetic effect caused δN_k depends on the degree of initial population of $\nu_{s.}$



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.

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.

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 $\nu_e \leftrightarrow \nu_s$

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

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

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

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

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

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.

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

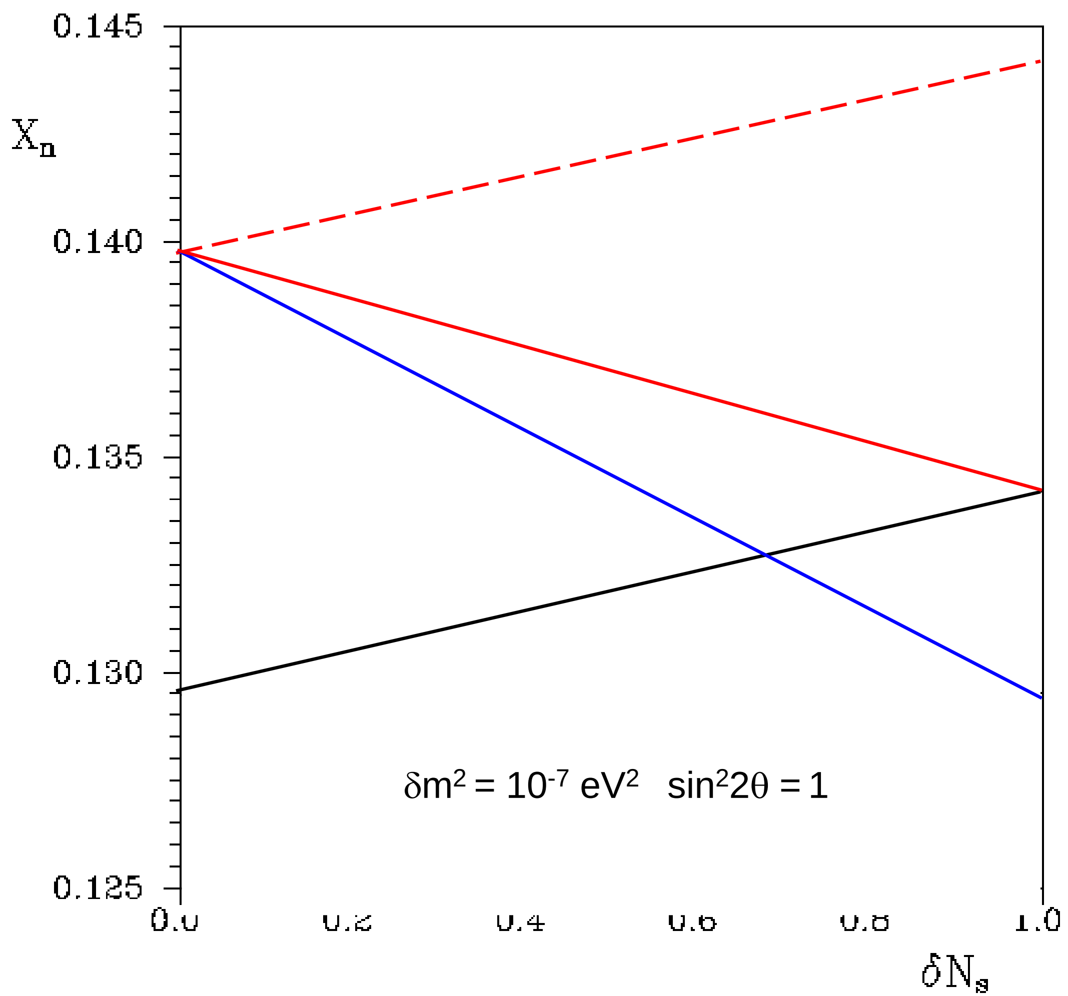
The interplay b/n dynamic and kinetic effects

$\delta N_{k,0} > 1$

Kinetic effect dominates

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

$\delta N_{k,0}\, \delta N_s > \delta N_s$



total effect decreases

kinetic effect decreases

dynamic effect increases

$\delta Y_p \sim 0.013\ \delta N_{eff}$

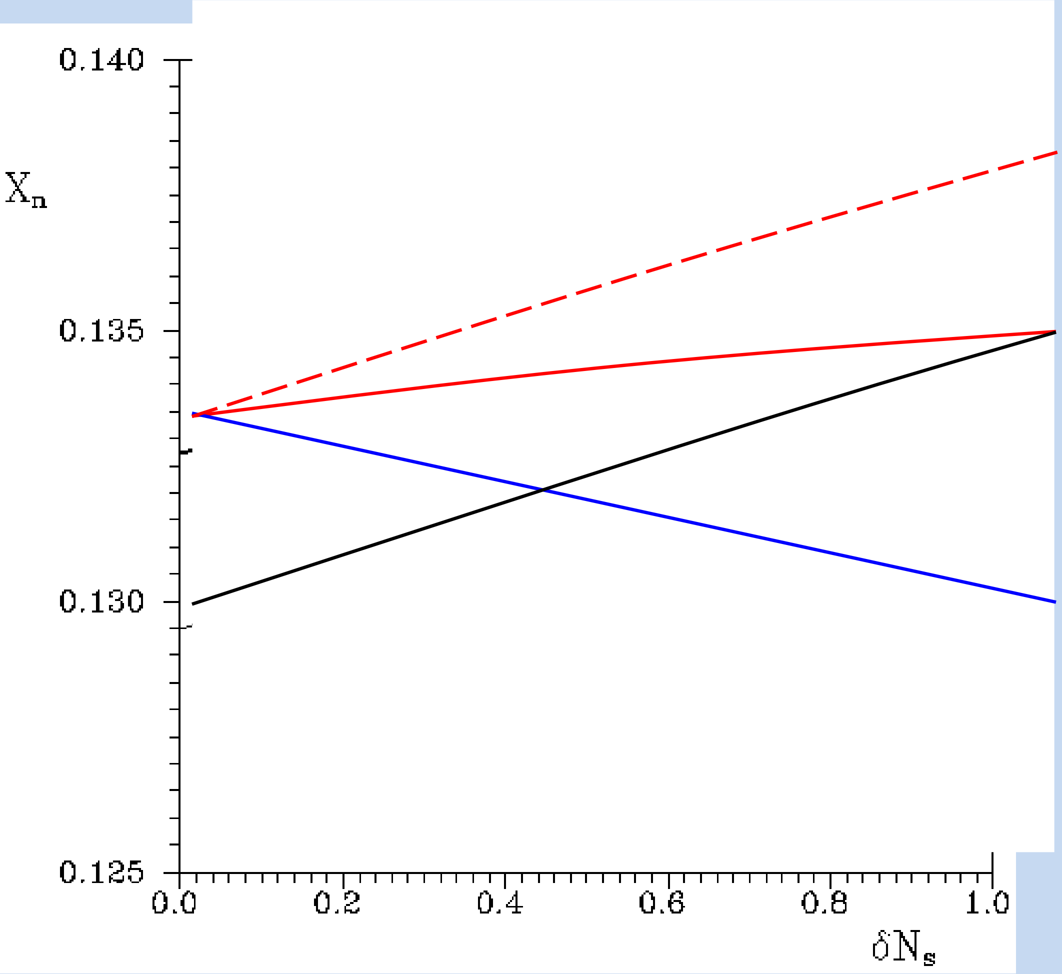
^{4}He overproduction decreases with δN_s, constraints relax compared to $\delta N_s = 0$ case.

The interplay b/n dynamic and kinetic effects

$\delta N_{k,0} < 1$

Dynamic effect dominates

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



$\delta N_{k,0}\, \delta N_s < \delta N_s$

total effect increases

kinetic effect decreases

dynamic effect increases

In the instability region $|\delta m^2|\sin^4 2\theta \le 10^{-9.5} eV^2$ L grows
Generation of L up to 5 orders of magnitude larger than β is possible,
i.e. up to $L \sim 10^{-5}$ *DK&Chizhov , 2000; DK2013*

- Effect of relic L on oscillations and BBN
  relic initially present $L > 10^{-10}$ *DK&Chizhov , 98; DK2013*

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

Primordial production of He-4 was calculated.
BBN constraints on oscillation parameters in presence of L were obtained.

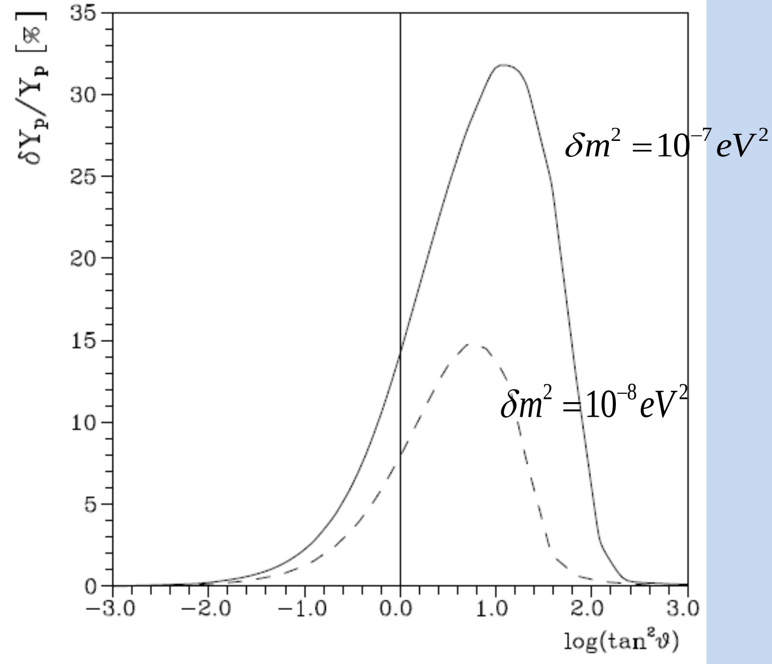
Maximum He-4 overproduction in BBN with oscillations due to spectrum distortion

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

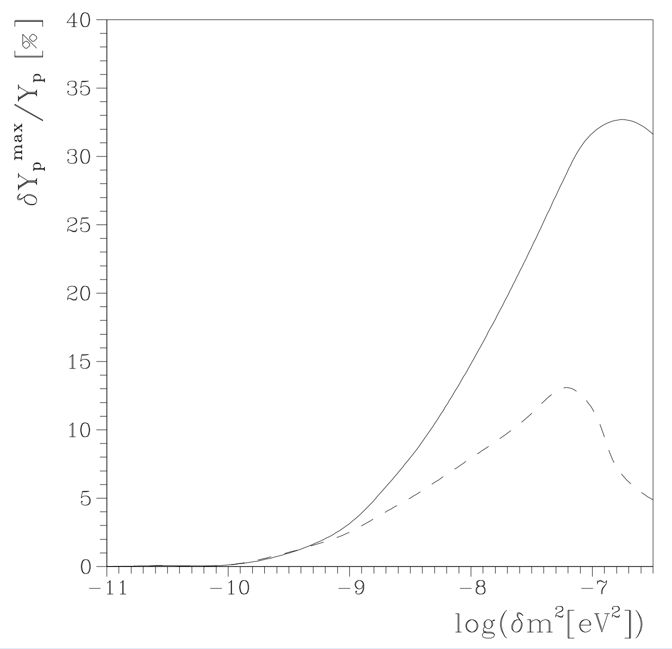
DK, Astrop.Phys.,2003

$\delta Y/Y \leq 32\%$ 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 neutrino oscillations

According to BBN 4 light elements: D, He-3, He-4, Li-7 produced during the hot stage of the Universe evolution, 1 s – 3 m 1 - 0.1 MeV.

The primordially produced abundances depend on:

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

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

- ✓ n lifetime

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

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

The Best Speedometer at RD Stage

The most exact leptometer

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

BBN limits neutrino oscillation parameters and neutrino-antineutrino asymmetry.

DK&Chizhov 98,2000, Dolgov&Villante 03, DK&panayotova, 2006, 2011; DK 07,12, 13

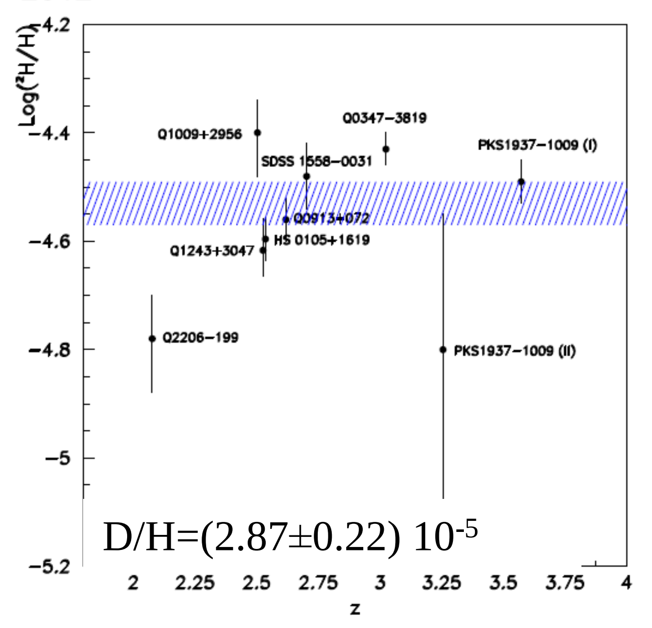
The Abundances of Light Elements

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

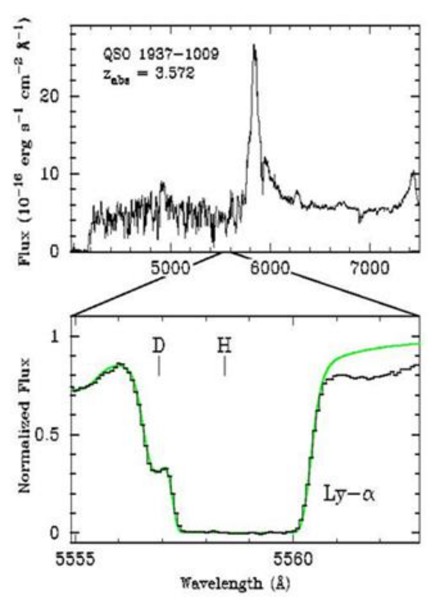
- D is measured in high z low-Z H-rich clouds absorbing light from background QSA.

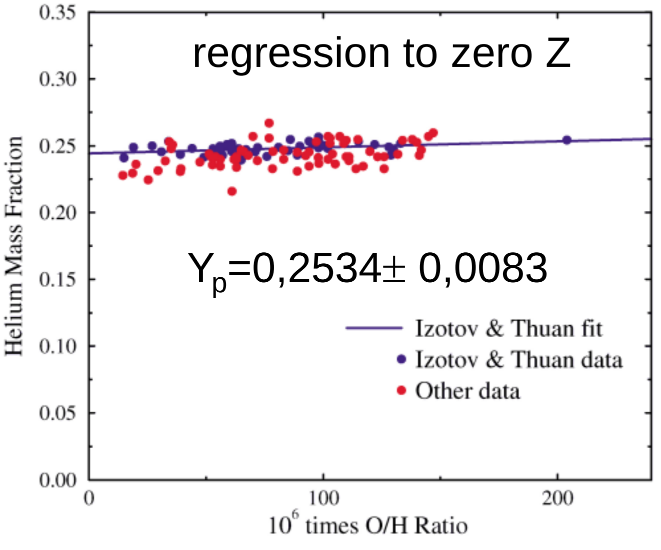
- He in clouds of ionized H (H II regions), the most metal-poor blue compact galaxies.

D from Iocco et al. PR472, 1 (2009); He from Aver et al. 2012



D/H=(2.87±0.22) 10^{-5}





regression to zero Z

Y_p=0,2534± 0,0083

Observations

in systems least contaminated by stellar evolution.

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

$$\mathrm{Li/H}|_{\mathrm{p}} = (1.7 \pm 0.02^{+1.1}_{-0}) \times 10^{-10}.$$

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.

BBN speedometer

BBN constrains the effective number of relativistic species

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

$\delta Y \sim 0.013\ \delta N_{\rm eff}$

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

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

4

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

$3.0 \le N_\nu \le 4.5$ (95% CL)

Steigman 2012 1208.0032 $Y=0.2565 \pm 0.006$ $N_{\rm eff} = 3.71^{+0.47}_{-0.45}$

consistent with $\Delta N_{\rm eff} = 0$ 95% C.L. $\Delta N_{\rm eff} \sim 1$ favored $\Delta N_{\rm eff} \sim 2$ disfavored at > 95% C.L.

Nollett&Holder, 2011 $N_{\rm eff} = 3.53^{+0.66}_{-0.63}$ (CMB, D)

Mangano, Serpico, 1103.1261 *(Aver et al.)* $Y<0.2631$ at 95% C.L $N_{\rm eff} < 4.04$ (4.2 CMB: η)

BBN disfavors two additional sterile neutrino species if they are thermalized at BBN epoch.

CMB and BAO constraints

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

Planck Collaboration arXiv: 1303.5076 *No evidence for extra relativistic neutrino species*

CMB: $N_{eff} = 3.361^{+0.68}_{-0.64}$ (95% Planck +WP+high l)

$N_{eff} = 3.30^{+0.54}_{-0.51}$ (95% Planck +WP+high l+BAO)

$N_{eff} = 3.52^{+0.48}_{-0.45}$ (95% Planck +WP+high l+H_0+BAO)

CMB tension b/n H direct measurements and CMB and BAO data relieved if extra radiation exists, best fit : $N_{eff} = 3.37$ (for low l power sp)

CMB+BBN simultaneous constraints

$N_{eff} = 3.41^{+0.3}_{-0.3}$ (68% Planck +WP+high l+Y(Aver et al.))
$N_{eff} = 3.02^{+0.27}_{-0.27}$ (68% Planck +WP+high l+D(Pettini+Cooke))

Simultaneous constraints on Y and N

$N_{eff} = 3.33^{+0.59}_{-0.83}$ (68% Planck +WP+high l)
$Y_p = 0.254^{+0.041}_{-0.033}$

CMB+BAO simultaneous constraints

However, simultaneous constraints on N_{eff} and the total neutrino mass or sterile neutrino mass:

- *massless sterile*

$N_{eff} = 3.29^{+0.67}_{-0.64}$ (95% Planck +WP+high l)
$\Sigma m_\nu < 0.60$ eV

Bounds tighten when BAO data are added:

$N_{eff} = 3.32^{+0.54}_{-0.52}$ (95% Planck +WP+high l+BAO)
$\Sigma m_\nu < 0.28$ eV

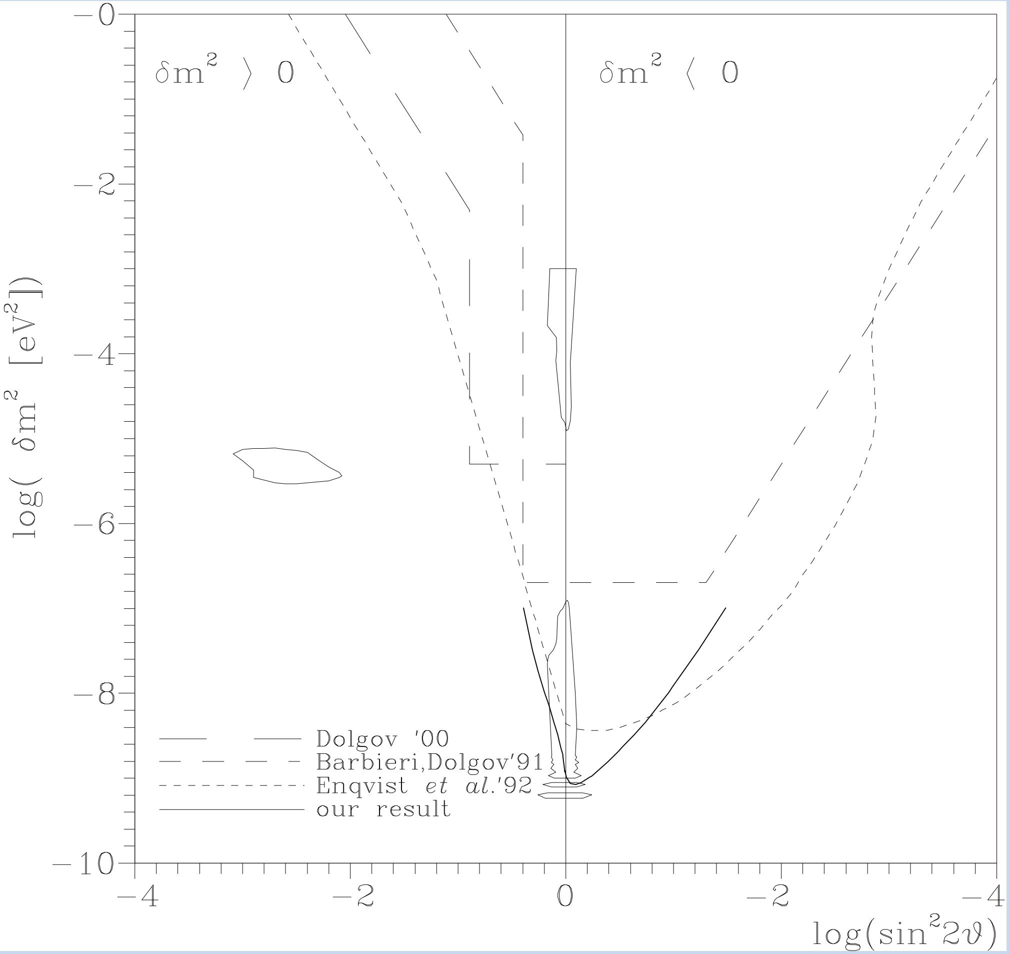
- *massive sterile* (MiniBoone, reactor and Gallium anomalies), $m_\nu = 0.06$ eV

$N_{eff} < 3.91$ (95% Planck +WP+high l for thermal sterile m<10 eV)
$m_s < 0.59$ eV

Bounds marginally compatible with fully thermalized sterile neutrino with sub-eV mass <0.5 eV necessary to explain oscillations anomalies

L needed to suppress thermalization of the sterile neutrino

Overview of BBN constraints on oscillations



Barbieri, Dolgov 91 – dashed curve depletion account
Dolgov 2000 – long dashed curve;
DK, Enqvist et al. 92 – dotted curve, mean p approx
DK,Chizhov 97 – spectrum distortion, asym growth
Dolgov, Villante, 2003 - spectrum distortion

Fits to BBN constraints

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

$\delta m^2>10^{-6}$ eV² nonres case Dolgov, Villante,03

$$\delta m_{es}^2 \sin^4 2\theta_{es} \le 3.16\times10^{-5} eV^2 \ln^2(1-\Delta N_\nu)$$

$$\delta m_{\mu s}^2 \sin^4 2\theta_{\mu s} \le 1.74\times10^{-5} eV^2 \ln^2(1-\Delta N_\nu)$$

$$\delta m^2 \sin^4 2\theta \le 10^{-7}$$ 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 2 of the possible solutions of the solar neutrino problem : LMA and LOW active-sterile solutions (1990, 1999) years before experimental results.
- ✓ Excluded electron-sterile solution to LSND

BBN constraints 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*

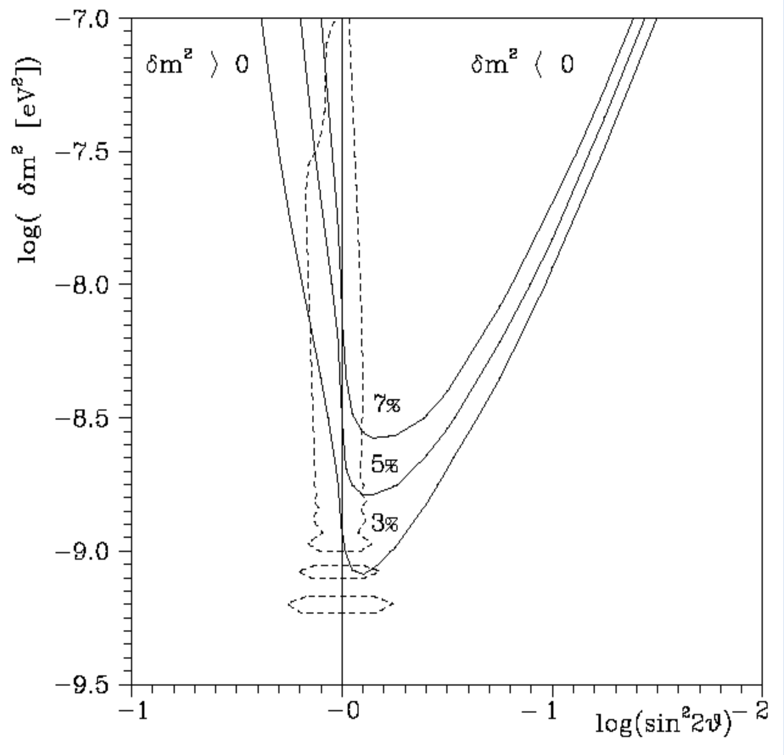
- ✓ abundantly produced,
- ✓ precisely measured
- ✓ precisely calculated (0.1% uncertainty)

Y_p=0,2482± 0,0007

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

$$Y_p = 2(X_n)_f \, e^{-\frac{t}{\tau_n}} \qquad (X_n)_f = \left(\frac{N_n}{N_{nuc}}\right)_f = \frac{\left(\frac{n}{p}\right)_f}{1+\left(\frac{n}{p}\right)_f}$$

$$\left(\frac{n}{p}\right)_f \sim e^{-\frac{\Delta m}{T_f}} \qquad T_f \sim \left(\frac{g_{eff}G}{G_F}\right)^{1/6}$$

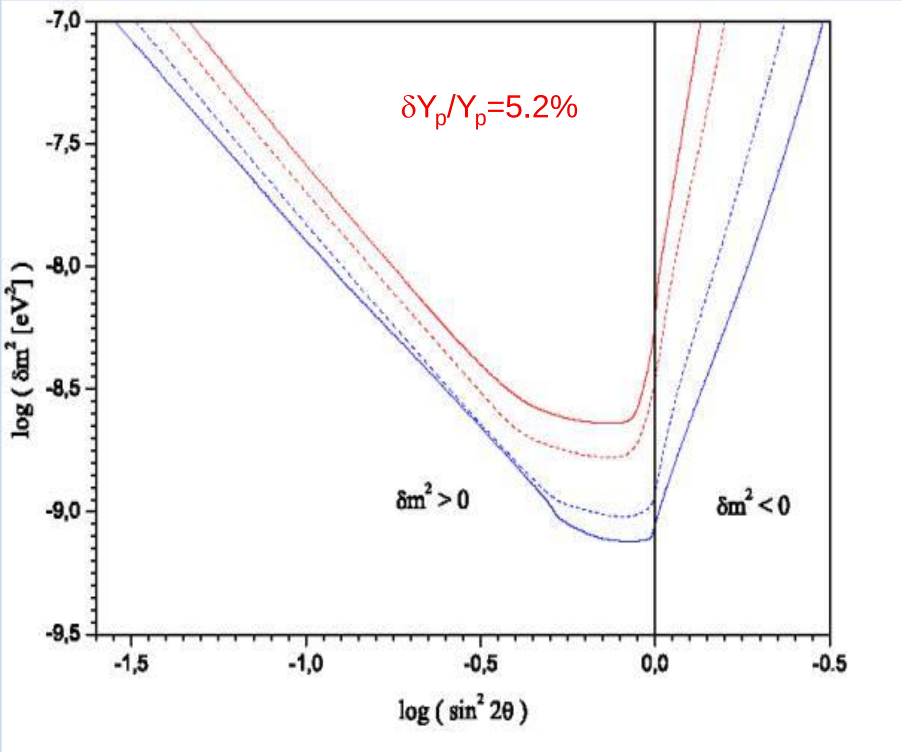


DK, Chizhov 2001

BBN constraints relaxed or strengthened?

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.

BBN constraints relaxed or strengthened?

Additional ν_s population relax BBN constraints.

Constraint contours for 5% He-4 overproduction

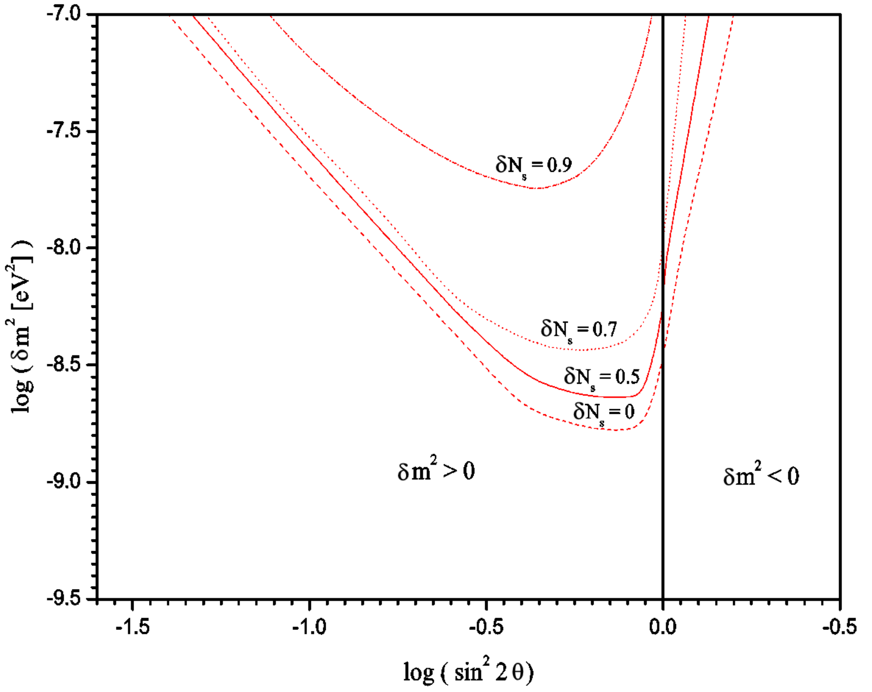


Fig.1 - The resonant ($\delta m^2>0$) and non-resonant ($\delta m^2<0$) iso-helium contours for $\delta Y_p/Y_p=5.2\%$ and $\delta N_s=0$ – dashed contour, $\delta N_s=0.5$ – solid contour, $\delta N_s=0.7$ – dotted contour and $\delta N_s=0.9$ – dotted-dashed contour are presented .

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

DK&Panayotova JCAP 2006;DK IJMPD 07,

BBN constraints on L

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

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

$\xi = \mu/T$

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

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

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.

- Non-zero L increases the radiation energy density $\Delta N_{\text{eff}} = 15/7[([\mu/T)/\pi]^4 + 2[(\mu/T)/\pi]^2\}$
- $|L_{\nu e}| > 0.01$ effect neutron-proton kinetics in pre-BBN epoch
- 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, 2011, DK JCAP,2012.

❖Accounting for flavor oscillations and ν decoupling and $\sin^2\theta_{13} > 0.03$ $L < 0.1$

Dolgov et al., NPB, 2002 ; Serpico&Raffelt,2005 ; Miele et al.,2011

❖ BBN with electron-sterile oscillations feels and constrains tiny L

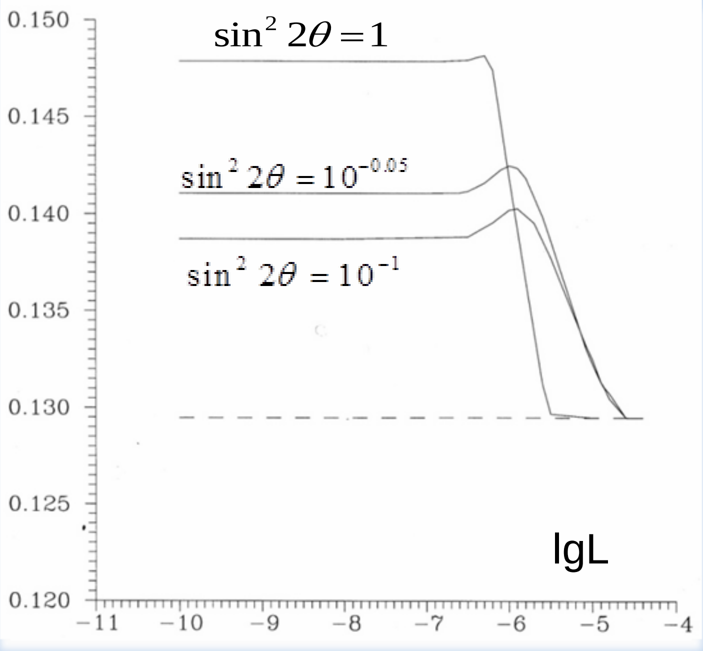
Constraints on L in case of presence of electron-sterile oscillations $L < (\delta m^2)^{2/3}$

Kirilova, Hyperfine Int. 2013

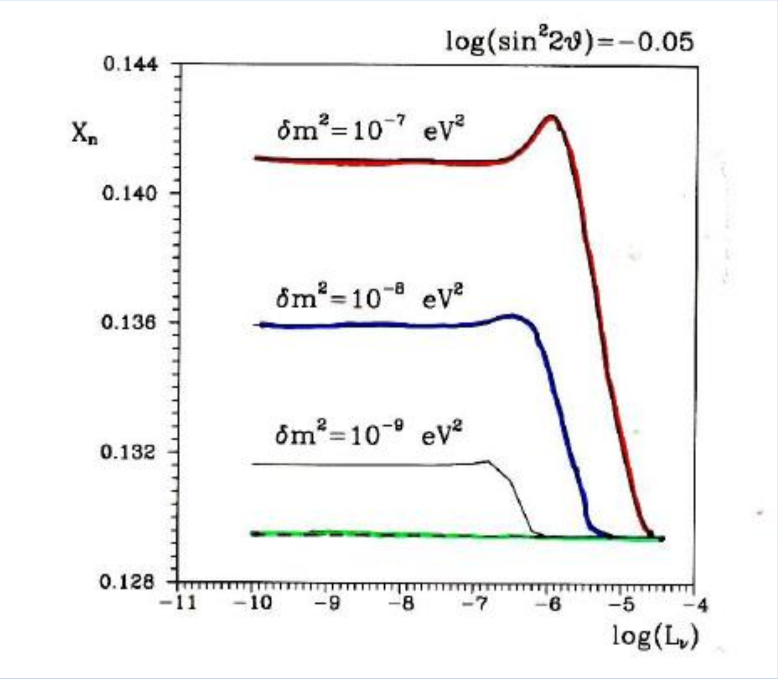
BBN with neutrino oscillations and relic L

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

Kirilova JCAP 2012



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



The dependences of helium production on L
(for different mass differences) .

BBN with neutrino oscillations and relic L

BBN with oscillations can feel extremely small L: down to 10^{-8}

BBN with oscillations is the best known leptometer.

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

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

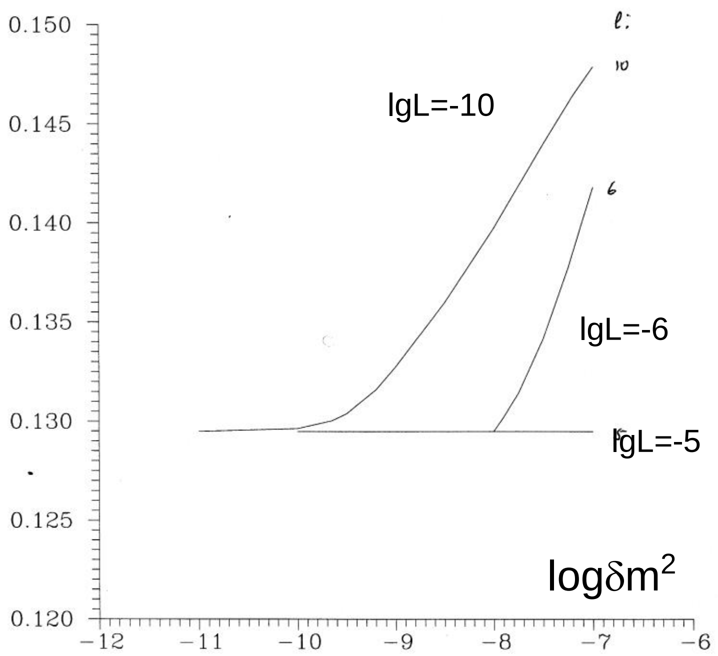
L change primordial production of He

by enhancing or suppressing oscillations.

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

Kirilova JCAP 2012

Relic L may relax BBN constraints at large mixings and strengthen them at small mixing.



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

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

In the last case, instead, the following approximate bound holds: $\delta m^2(eV^2) < L^{3/2}$

Constraints on L in case of electron-sterile oscillations with δm^2 $L < (\delta m^2)^{2/3}$

$\delta m^2 = 10^{-5} eV^2$ $L < 10^{-3.3}$

Summary

- In case of active-sterile oscillations the number densities of flavor neutrinos may be reduced, their energy spectrum may be distorted and neutrino-antineutrino asymmetry can be changed, in particular it can be generated by resonant oscillations.
- BBN is very sensitive to spectrum distortion and L. In case of late non-equilibrium oscillations spectrum distortion is the major effect of neutrino oscillations on BBN.

  BBN constraints on oscillations parameters in case of non-equilibrium oscillations do exist even if He-4 uncertainty were over 5%. BBN provides the most stringent constraint on δm^2 .
- BBN bounds on N_{eff} are strengthened in case of neutrino oscillations.
- BBN constraints on neutrino oscillations depend nontrivially on the population of sterile neutrino and L. Additional initial population of the sterile state not always leads to strengthening of constraints (as can be naively thought) it may relax them.
- BBN bounds on L depend on the presence of neutrino oscillations. They

  strengthen considerably in case of presence of active-sterile oscillations.
- L<< 0.01, either relic or generated by neutrino oscillations (not having direct effect on nucleons kinetics during BBN, invisible by CMB) , still may influence BBN.

  $L \geq 10^{-8}$ may be felt by BBN with late electron-sterile oscillations.
- Lepton asymmetry is able to enhance, suppress or inhibit oscillations. Large enough L may provide relaxation of BBN constraints on oscillations, by suppressing oscillations and causing incomplete thermalization of the sterile neutrino.

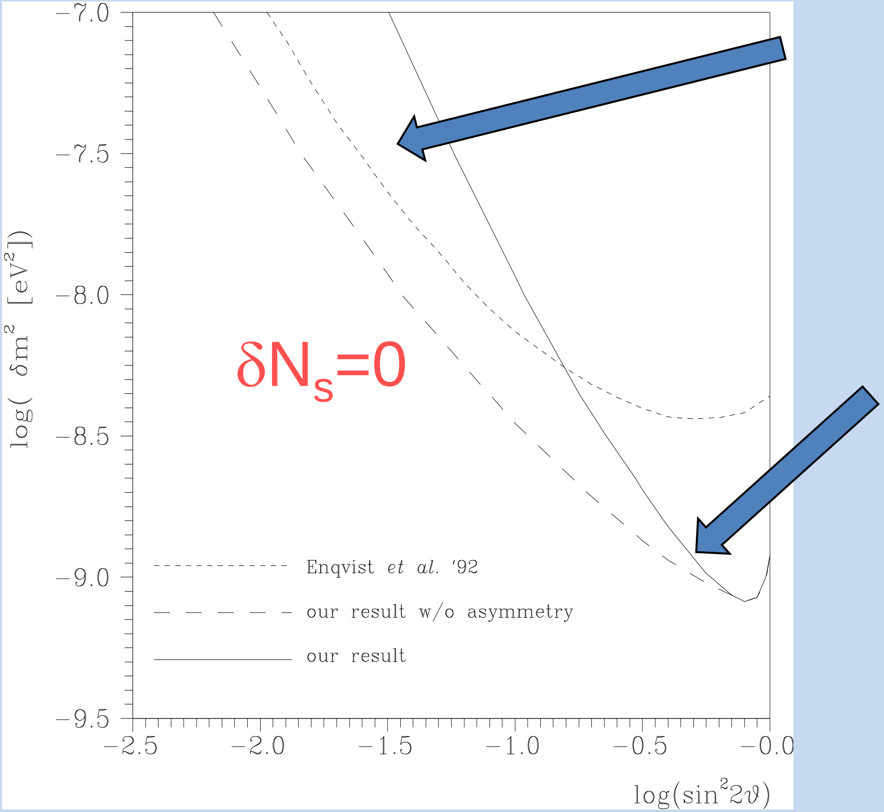
  Thus 1+3 oscillations models might be allowed by BBN with L.

Благодаря за вниманието!

Thanks for the attention!

Effect of dynamical L and distortion of ν_e distribution on constraints

- Oscillations change 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 at 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 by orders of magnitude.

Planck 2013 results

arXiv:1303.5062

Planck results for neutrino physics:

No evidence for extra relativistic neutrino species

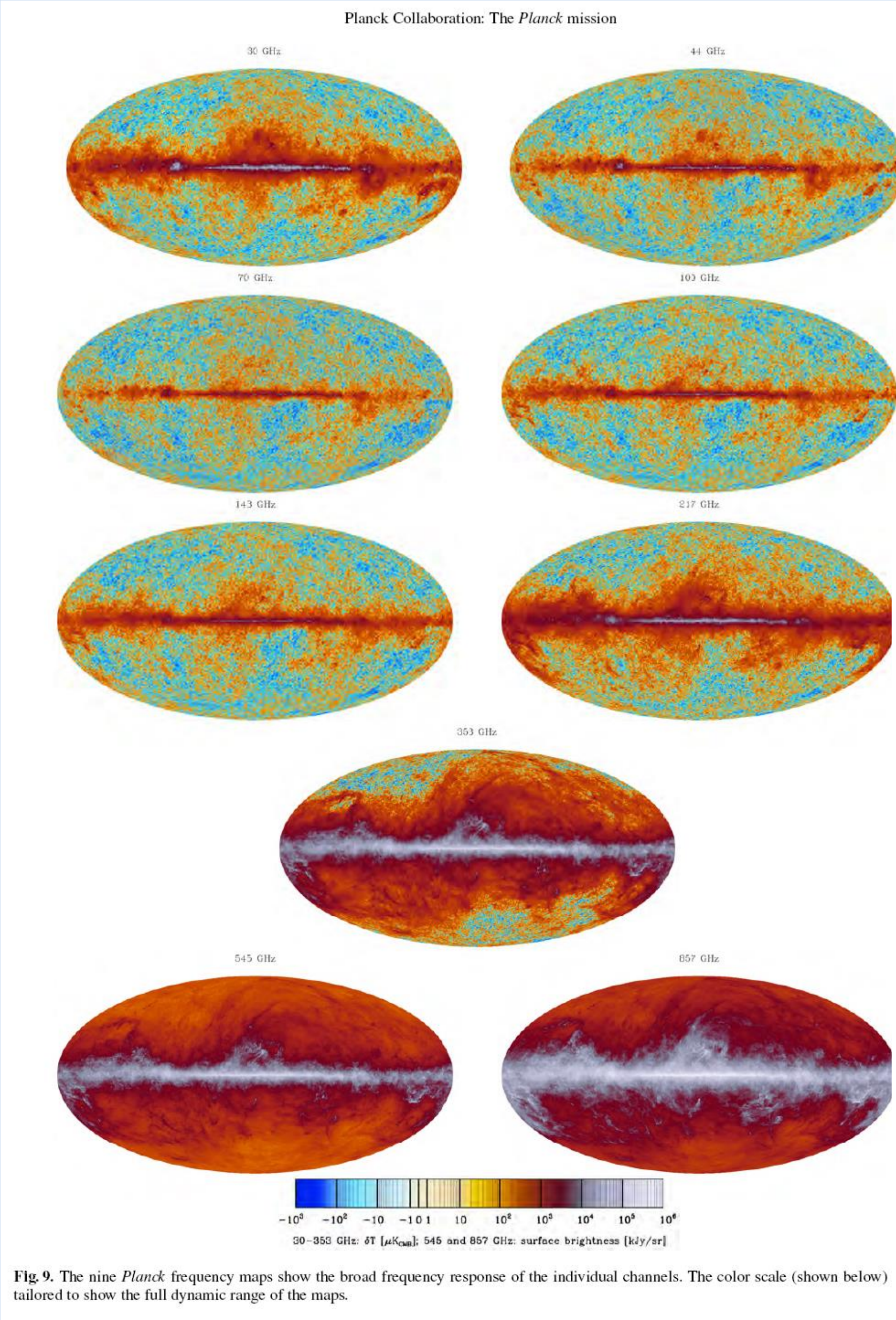
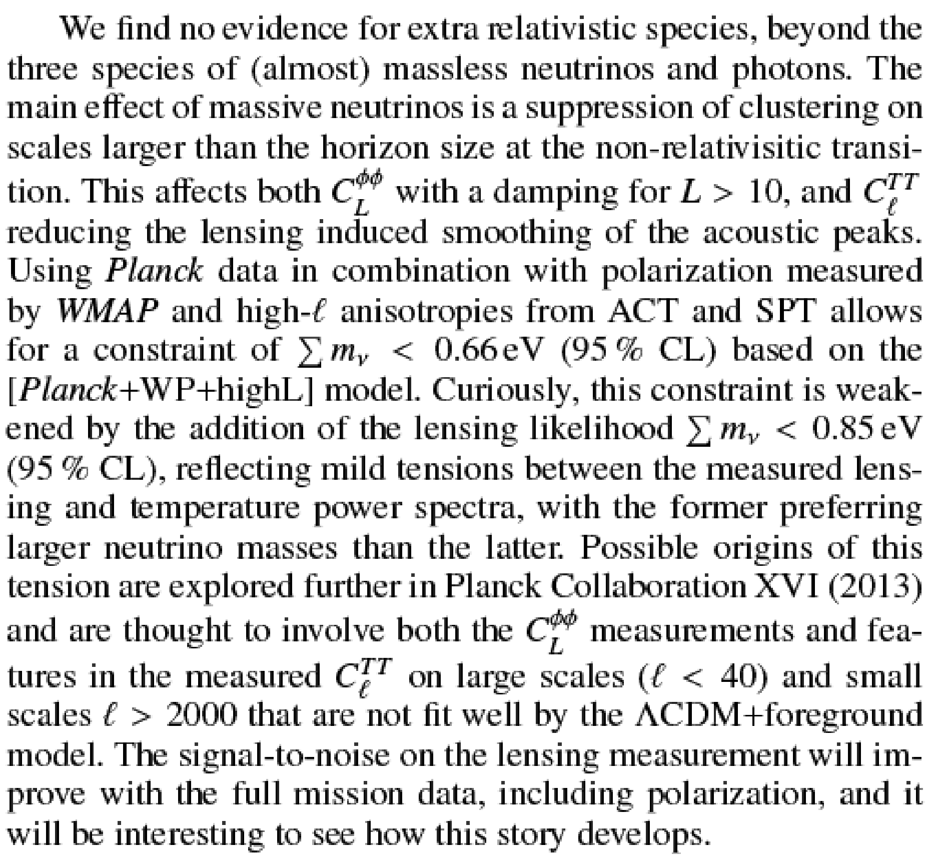

Planck Collaboration: The *Planck* mission

Fig. 9. The nine *Planck* frequency maps show the broad frequency response of the individual channels. The color scale (shown below) tailored to show the full dynamic range of the maps.


We find no evidence for extra relativistic species, beyond the three species of (almost) massless neutrinos and photons. The main effect of massive neutrinos is a suppression of clustering on scales larger than the horizon size at the non-relativisitic transition. This affects both $C_L^{\phi\phi}$ with a damping for $L > 10$, and C_ℓ^{TT} reducing the lensing induced smoothing of the acoustic peaks. Using *Planck* data in combination with polarization measured by *WMAP* and high-ℓ anisotropies from ACT and SPT allows for a constraint of $\sum m_\nu < 0.66\,\mathrm{eV}$ (95 % CL) based on the [*Planck*+WP+highL] model. Curiously, this constraint is weakened by the addition of the lensing likelihood $\sum m_\nu < 0.85\,\mathrm{eV}$ (95 % CL), reflecting mild tensions between the measured lensing and temperature power spectra, with the former preferring larger neutrino masses than the latter. Possible origins of this tension are explored further in Planck Collaboration XVI (2013) and are thought to involve both the $C_L^{\phi\phi}$ measurements and features in the measured C_ℓ^{TT} on large scales ($\ell < 40$) and small scales $\ell > 2000$ that are not fit well by the ΛCDM+foreground model. The signal-to-noise on the lensing measurement will improve with the full mission data, including polarization, and it will be interesting to see how this story develops.