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Neutrinos in Cosmology, in Astro, Particle and Nuclear Physics

BBN constraints on neutrino and CNB

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Big Bang Nucleosynthesis constraints on neutrino and Cosmic Neutrino Background

OUTLINE

- Relic neutrino predicted by standard cosmological model
- Deviations from the equilibrium Fermi-Dirac neutrino spectrum caused by neutrino oscillations
- BBN constraints on neutrino
- Effect of active-sterile oscillations on Universe dynamics and nucleon kinetics during BBN
- BBN constraints on neutrino oscillation parameters
  - Role of initial population of inert neutrino
  - Role of lepton assymmetry
- Conclusions

Relic Neutrino Background

T>> 1 MeV equilibrium due to weak interactions

$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$

$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$

$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$

$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$

$$\Gamma \sim G_F^2 E_\nu^2 N_\nu \gg H \sim \sqrt{g_{eff} G} T^2$$

As the Universe expands, particle densities are diluted and temperatures fall.
Weak interactions become ineffective to keep neutrinos in good thermal contact with the e.m. plasma.

$T_{dec}(\nu_e) \sim 2$ MeV $T_{dec}(\nu_{\mu,\tau}) \sim 3$ MeV $\Gamma \sim G_F^2 E_\nu^2 N_\nu \sim H \sim \sqrt{g_{eff} G} T^2$

Since decoupling neutrino were free streaming, i.e. cosmological neutrino background.

- $T \sim m_e$, $e^+e^- \to \gamma\gamma$, photons but not the neutrinos were heated $T_\nu = (4/11)^{1/3} T_{cmb}$.
  CNB today is expected with temperature ~ 1.9 K, $n_\nu = 3/11\, n_{cmb}$

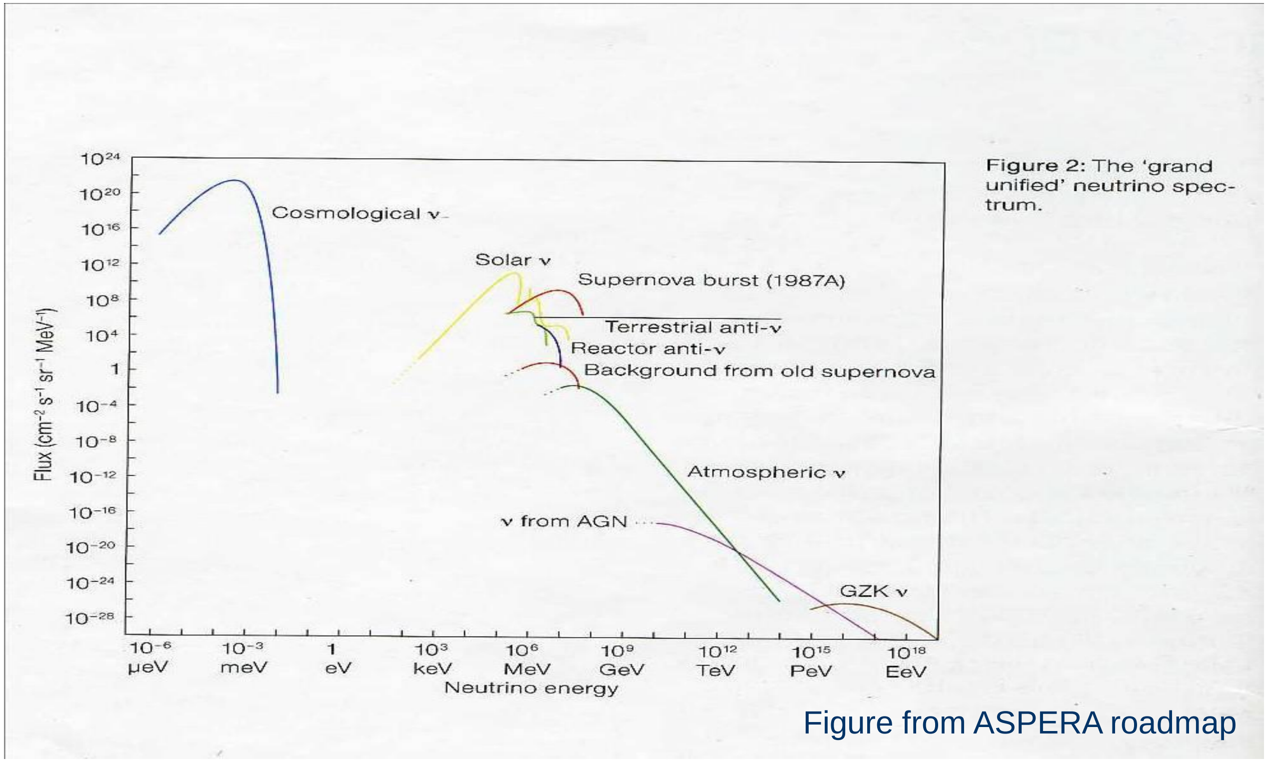
*S*ince **T_{dec}(ν)** is close to **m_e,** neutrinos shared a small part of the entropy release) *:*
neutrino species – 3.046 instead of 3 (not observable by present observational data)

Dolgov, Hansen & Semikoz,1997,Mangano et al,02,05

- Today relic neutrino (CNB) is expected to be the most numerous particle after CMB photons.

$$n_\nu = 339.3\ \text{cm}^{-3} \qquad n_{cmb} = 411\ \text{cm}^{-3} \qquad \Omega_\nu = \frac{3m_0}{93.14 h^2\ \text{eV}^2}$$

Though numerous, CNB direct detection is very difficult because it is an extremely elusive particle due to its weak interactions and extremely low energy expected for neutrinos today.



Indirect CNB detection is possible due to its effect on BBN,CMB, LSS.
CMB&LSS feel the total neutrino density. BBN is precise probe also of neutrino energy distribution, mass differences and mixing, chemical potential, etc.

Neutrino in Standard Cosmological Model

- The lepton asymmetry is zero (*an assumption*).
- Neutrino spectra have the equilibrium Fermi-Dirac distribution (*an assumption*).

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

❖ **Neutrino contribution to the energy density of the Universe**

Effective number of relativistic neutrino species

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

N_{eff} is *not exactly* 3 for standard neutrinos if non-instantaneous decoupling is considered, N_{eff} =3.046.

Deviations from FD distribution

- Electron-positron annihilation – negligible effect

- Flavor oscillations *Dolgov 1981 ;Mangano et al, 2005*

  number density of one neutrino species 113 per cubic cm instead 112 in SCM.

  Flavor oscillations with parameters favored by the atmospheric and solar neutrino data establish an equilibrium between active neutrino species before BBN epoch.

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

- Non-zero lepton asymmetry *Terasawa, Sato 88; Wagoner et al.*

  Neutrino-antineutrino asymmetry – strongly constrained by BBN in all sectors because of flavor oscillations <0.07 *Dolgov et al. 2002*

- Active-sterile oscillations proceeding after decoupling may strongly distort neutrino energy spectrum *DK, 1988; DK&Chizhov PLB 96*

- Decays of neutrino and into neutrinos

- Mixed statistics, etc.

Neutrino spectrum distortion by $\nu_a \leftrightarrow \nu_s$

$\Gamma_{osc} \sim \frac{\delta m^2}{E}$ and $\delta N_s<1 \Rightarrow \nu_e$ energy spectrum distortion

$\Rightarrow \nu_e$ depletion $N_\nu \sim \int dE E^2 n_\nu(E)$ *D.K.,1988; D.K. M.Chizhov, 1996,97*

$\Rightarrow$ neutrino-antineutrino asymmetry growth *Foot,Volkas,1996; D.K. M.Chizhov,1996*

In case of oscillations effective after ν decoupling

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

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

and provided that the sterile state is not in equilibrium ($\delta N_s<1$), spectrum distortion, and correspondingly neutrino depletion, is considerable for a wide range of oscillation parameters.

Evolution of oscillating neutrino $\nu_e \leftrightarrow \nu_s$

Approach: follow the evolution of neutrino for each momentum; account for oscillations, expansion and interactions with the medium simultaneously *DK 1988, Chizhov, DK, 1997*

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

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

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

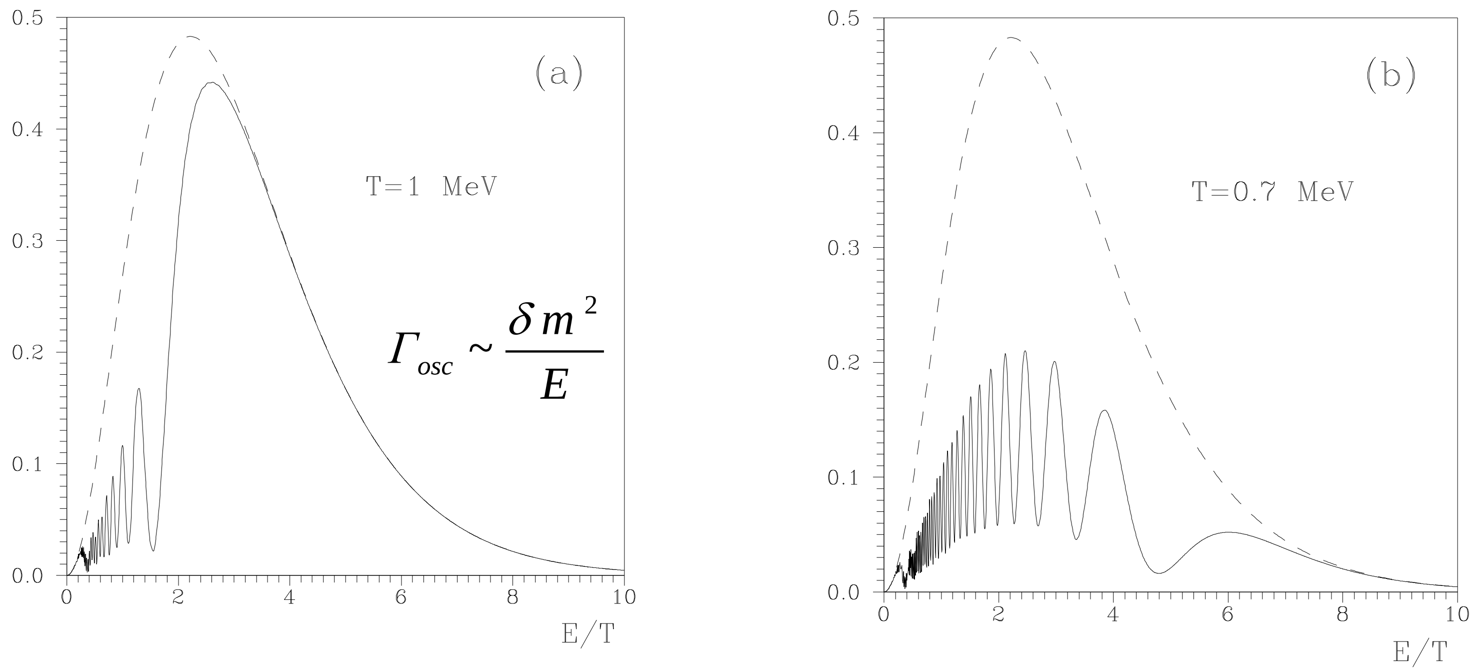
$$Q \sim E_\nu T \qquad L \sim 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} \qquad L_{\nu_e} \sim \int d^3p \left(\rho_{LL} - \bar{\rho}_{LL}\right)/N_\gamma$$

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

The evolution of spectrum distortion

Numerical solutions for matter neutrino oscillations

The non-equilibrium initial condition $\delta N_s<1$ leads to considerable and continuous deviations from the equilibrium neutrino FD distribution.



The distortion concerns first low energetic part of the spectrum because the oscillations become effective first to low energy neutrinos. Soon after, the whole spectrum is distorted from its equilibrium FD form. The spectrum distortion of the active neutrino for a wide range of oscillation parameters persists during the nucleons freezing period.

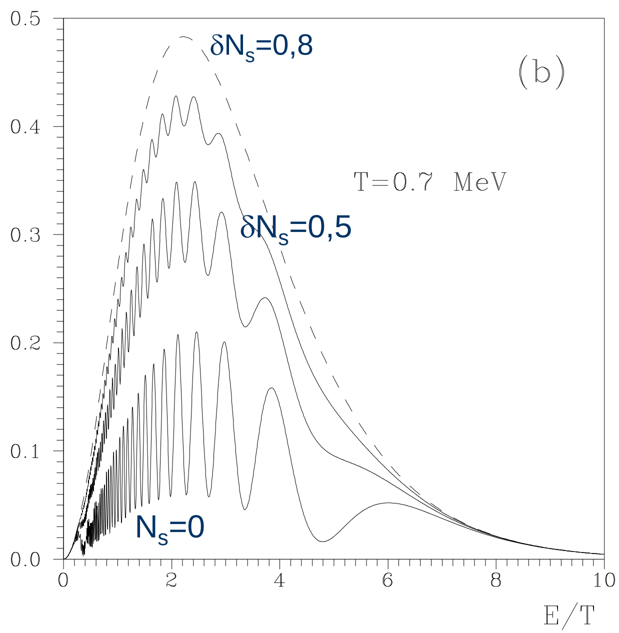
Spectrum distortion for non zero initial popuation of ν_s

Sterile neutrinos may be present at the onset of BBN epoch - may be produced in GUT models, in models with large extra dimensions, Manyfold Universe models, mirror matter models, or by oscillations in 4-neutrino mixing schemes, etc. The degree of population may be different depending on the production model.

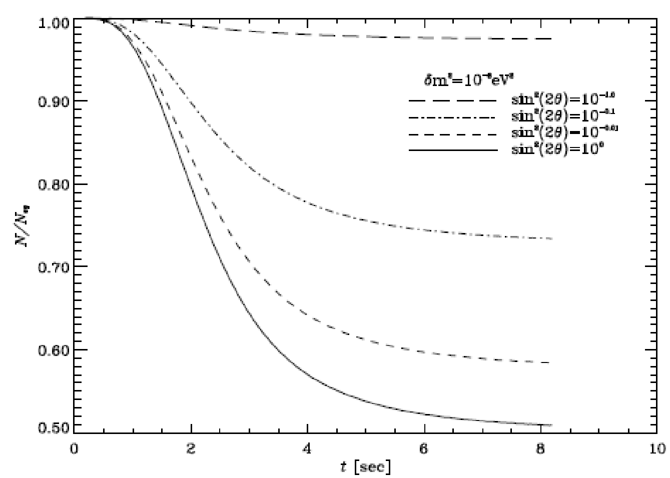
The distortion due to active-sterile oscillations and the kinetic effect caused δN_k depends on the degree of initial population of $\nu_{s.}$ The biggest effect $\delta N_{k,0}$ is achieved for $\delta N_s=0$, the effect decreases with δN_s .

DK, Int.J.Mod.Phys.D, 2004

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



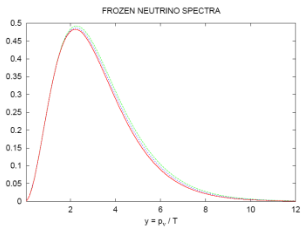
Spectrum distortion for different initial population of ν_s.: $\delta N_s=0$ – lowest curve, $\delta N_s=0{,}5$ and $\delta N_s=0{,}8$ – upper curve. The dashed curve shows the equilibrium spectrum.

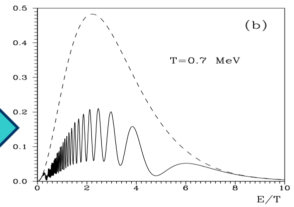


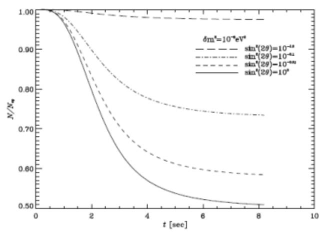
Due to nonequilibrium oscillations the number density of neutrinos are depleted and their distribution differ from equilibrium FD one.

CNB expected change

2 neutrino mixing:







CNB neutrinos may have the equilibrium number density or be depleted depending on the type of oscillations and their parameters.

$$N_e < N_{eq}$$

CNB neutrinos energy spectum strongly distorted from the equilibrium Fermi-Dirac one.

4 neutrino mixing:

$$\delta N_{k,4} < \delta N_{k,2}$$

Sterile state filles from ν_e , while ν_e is partially refilled for the sake of muon and tau neutrino

Flavor oscillations reestablish the equilibrium between the different neutrino flavors.Then CNB electron neutrinos will have less depleted number densities compared to the 2 neutrino case.

Flavor mixing decreases the depletion and spectrum distortion

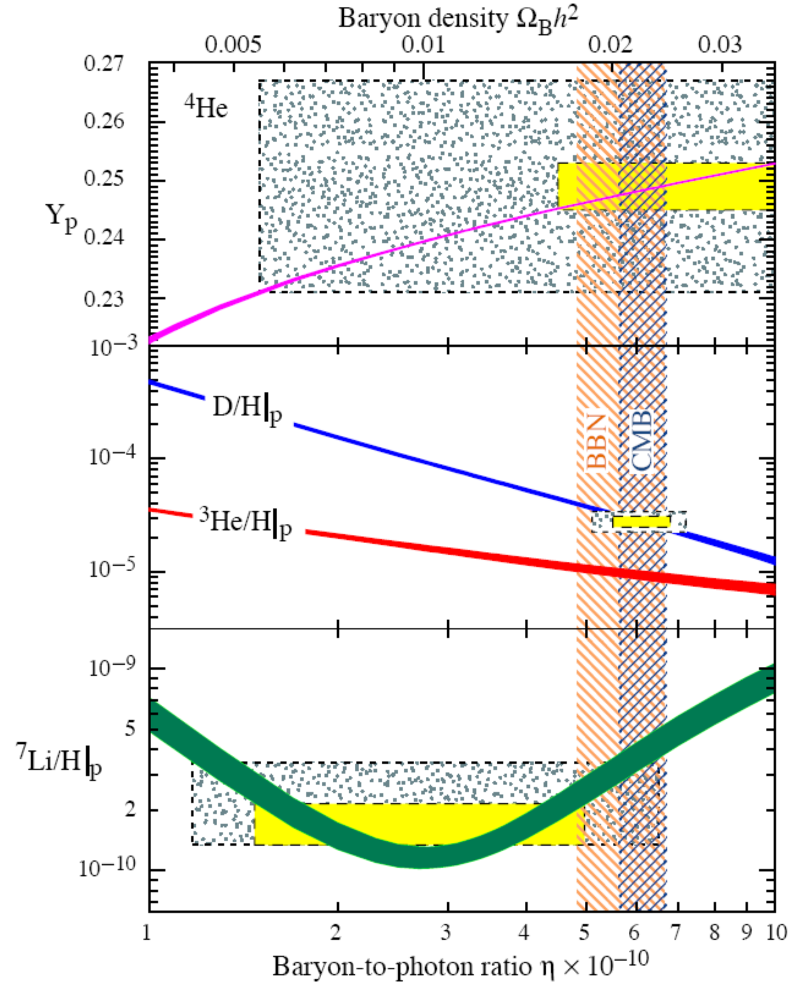
From the allowed range of the observables of the Universe, like baryonic density, light elements abundances, expansion rate, BBN, CMB spectrum, structure characteristics of the Universe, etc., it is possible to constrain neutrino characteristics.

BBN CONSTRAINTS ON NEUTRINO

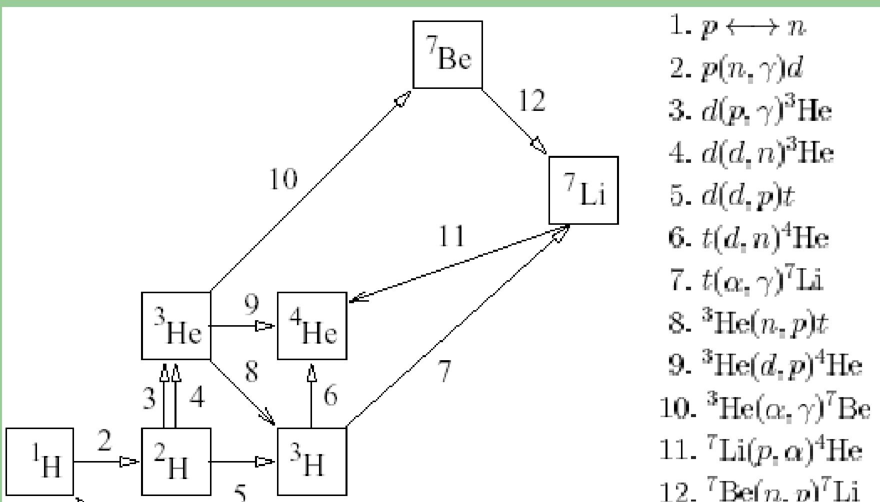
BBN CONSTRAINTS ON NEUTRINO OSCILLATIONS

BBN theory

According to the Standard Big Bang Nucleosynthesis 4 light elements: D, He-3, He-4, Li-7 were produced during the early hot stage of the Universe evolution



The primordially produced abundances of these elements are functions of only one parameter - the baryon-to-photon ratio η. (now determined by CMB anisotropy measurements)



$$\mathrm{D/H}|_p = (2.78 \pm 0.29) \times 10^{-5}$$

$$Y_p = 0.249 \pm 0.009$$

$$0.017 \le \Omega_b h^2 \le 0.024$$

BBN is the most early and most precision probe for physical conditions in the early Universe, and for constraining new physics, relevant at $T \sim 10^{10}$K

BBN theory predictions are in excellent agreement with the observational data, spanning 9 orders of magnitude!

The Abundances of Light Elements

$$D/H|_p = (2.78 \pm 0.29) \times 10^{-5}$$

- D measured in highredshift, low-metallicity quasar absorption systems

$$Y_p = 0.249 \pm 0.009$$

- He in clouds of ionized hydrogen (H II regions), the most metal-poor

  of which are in dwarf galaxies.

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

- Pop II (metal-poor) stars in the spheroid of our Galaxy, which have metallicities going down to at least 10−*4* and perhabs 10−*5* of the Solar value

$$0.017 \leq \Omega_b h^2 \leq 0.024$$

concordance between theoretically predicted and extracted from observed primordial abundances

^{4}He – the preferred element

The most reliable and abundant data now available are for that element. He-4 is abundantly produced (25% by mass), precisely measured (3-5 % uncertainty) and calculated (0.1% uncertainty) and has simple post-BBN chemical evolution.

- Observed in HII low metalicity regions of dwarf galaxies
- Extrapolated towards zero metalicity

Y_p=0,2421± 0,0021 *Izotov, Thuan 2000*

Y_p=0,2429± 0,009 *Izotov, Thuan 2004*

Y_p=0,2472± 0,0012 *Izotov, Thuan 20007* *(93 spectra of 86 low-metalicity HII regions)*

Y_p=0,245± 0,013 *Olive, Skillman 2004*

Y_p=0,2491± 0,0091 *Olive, Skillman 2004*

Y_p=0,2384± 0,0025 *Peimbert et al 2002*

Y_p=0,2474± 0,0028 *Peimbert, Luridiana. Peimbert 2007, new atomic data*

dispersion of determinations

$$Y_{\rm p} = 0.249 \pm 0.009.$$

Determinations indicate 3-5% uncertainty (systematic errors)

Possibly it is related with the evaluation of ionization level, stellar absorption *Sasselov, 95 ,Luridiana, 2002*

The primordial abundance Y_p, predicted from SBBN, is calculated with great precision: the theoretical uncertainty is less than 0.1% within a wide range of baryon density.

Y_p=0,2482± 0,0007

^{4}He production

- T > 1 MeV

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

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

- T < 1 MeV

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

$$\Gamma \sim G_F^2 T^5 \qquad H \sim \sqrt{g_{eff}}\, G T^2 \qquad g_{eff} = \frac{11}{2} + \frac{7}{4} N_\nu = 10{,}75$$

$$T_f \sim \left(\frac{g_{eff} G}{G_F}\right)^{1/6} \sim 0{,}7 MeV \qquad \left(\frac{n}{p}\right)_f \sim e^{-\frac{\Delta m}{T_f}} \sim \frac{1}{6} \qquad \Delta m = 1.293 MeV$$

- T < 80 KeV

$$p + n \rightarrow D + \gamma \qquad D + D \rightarrow {}^4He + \gamma$$

$$(X_n)_f = \left(\frac{N_n}{N_{nuc}}\right)_f = \frac{\left(\frac{n}{p}\right)_f}{1 + \left(\frac{n}{p}\right)_f} \qquad Y_p = 2(X_n)_f\, e^{-\frac{t}{\tau_n}} \sim 0.24 \qquad \tau_n = 885{,}7 s$$

$$\Delta Y_{BBN} \simeq 0.013 \Delta N_\nu$$

^{4}He is the best speedometer.

BBN constrains additional species.

Shvartsman 1969

BBN constraints on neutrino

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

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

$$\Delta Y_{\rm BBN} \simeq 0.013 \Delta N_\nu$$

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

$\Delta N_{eff} < 1$ (0.3)

CMB $1 < N_{eff} < 8$

WMAP,ACBAR,CBI,BOOMERANG

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

$\Delta N_{eff} \sim 0.2$ (Planck)

- **Constrains lepton asymmetry**

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

$\mu/T < 0.07$

BBN + LMA restricts chemical potential of all neutrino flavors

- **Constrains sterile neutrino decoupling** T_R > 130 MeV **production, right handed bosons**
- **Constrains neutrino magnetic moment** $\mu_\nu < 310^{-10}\mu_B$
- **Constrains neutrino oscillations parameters**

Cosmological constraint on new coupling constant

- Constrains sterile neutrino decoupling, new coupling constant strength

From $\Delta N_\nu < 1$ at BBN epoch, and entropy conservation constraint on T_R decoupling of right-handed neutrino is obtained:

$$\left(\frac{g_*(T_R)}{g_*(T_L)}\right)^{4/3} > 3; \quad g_*(T_R) > 2.28 \times 10.75 = 24.5,$$

which corresponds to T_R > 130 MeV. On the other side T_R depends on G_T :

(in case of 3 light right-handed neutrinos)

$$\frac{\Gamma_R}{H} = \left(\frac{T_R}{T_L}\right)^3 \left(\frac{G_T}{G_F}\right)^2 \sim 1; \quad G_T \leq 10^{-2} G_F$$

Enough big to explain *anomalies* in radiative pion weak decay and two pion decay of tau lepton.

M.Chizhov,1993,2006-08; DK&Chizhov, 2009

Neutrino oscillations effects

- Mixing b/n different flavors influence neutrino spectra and BBN negligibly. *Dolgov ,1981*

Flavor Matter Oscillations corresponding to the regions 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 flavour oscillations : 113 per cubic cm instead 112 in SCM.

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

✓ BBN with fast $\nu_a \leftrightarrow \nu_s$: δN_s increase
effective before ν_a decoupling - effect BBN and CMB

✓ BBN with $\nu_a \leftrightarrow \nu_s$ ν_e spectrum distortion
effective after ν_a decoupling and $\delta N_s<1$ BBN, CNB effect

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

Dolgov 81. DK 88, Barbieri, Dolgov 90, Kainulainen 91, Enqvist et al.,92, Foot&Volkas 95,96; D.K&Chizhov,96-98,2000-01, Dolgov&Villante 03; DK 04, DK&Panayotova 06, DK 07,08

Main Oscillations effects on BBN

$\nu_a \leftrightarrow \nu_s$

Dynamical effect – production of additional neutrino species. Additional degree of freedom enhances the energy density

and drives expansion faster.

Dolgov ,1981

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

$T_f \sim g_{eff}^{1/6} \rightarrow$ ^4He overproduction

$$(X_n)_f = \left(\frac{N_n}{N_{nuc}}\right)_f = \frac{\left(\frac{n}{p}\right)_f}{1+\left(\frac{n}{p}\right)_f} \qquad Y_p = 2(X_n)_f e^{-\frac{t}{\tau_n}} \sim 0.24$$

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).

(1 additional $\nu \rightarrow \delta Y_p/Y_p =$ 5 %) oscillations dynamical effect

Effects of nonequilibrium $\nu_a \leftrightarrow \nu_s$

Kinetic effects : $\Gamma_{osc} \sim \frac{\delta m^2}{E}$ and $\delta N_s < 1$ $\Rightarrow$ ν_e energy spectrum distortion,

$\Rightarrow$ ν_e depletion, $N_\nu \sim \int dE E^2 n_\nu(E)$

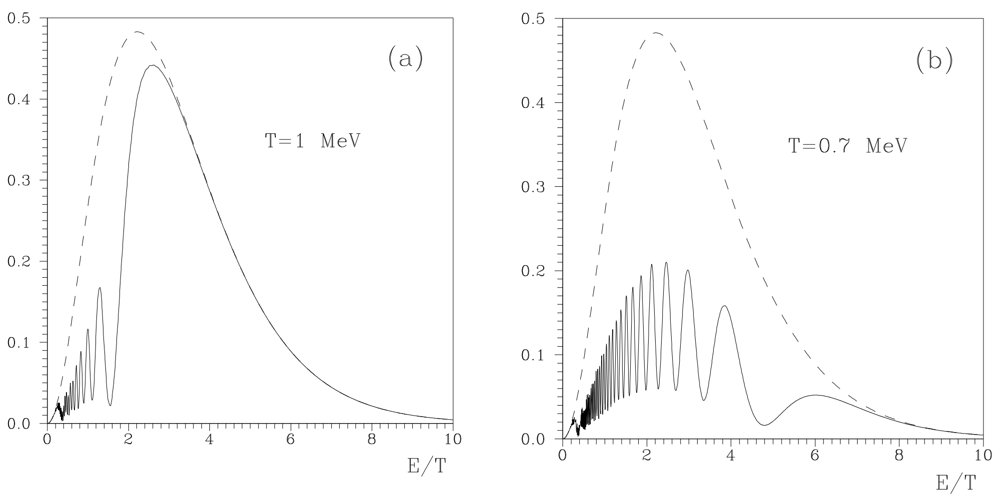
D.K.,1988; Barbieri,Dolgov, 1990,91
Enqvist et.al., 92; DK M.Chizhov, PLB ,1996,97

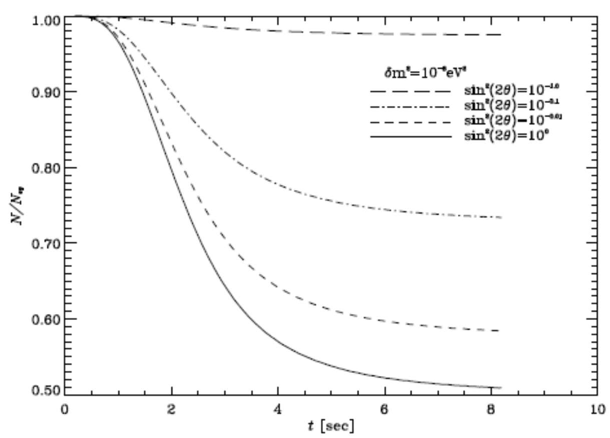
$\Rightarrow$ energy threshold effect

$\Rightarrow$ pre-BBN kinetics

$\Rightarrow$ neutrino-antineutrino asymmetry growth

Foot, Volkas,1996; DK M.Chizhov,1996
Dolgov et al., 2002





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

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

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

the numerical approach

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

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

$\delta m^2 \sin^4 2\theta \leq 10^{-7}$ *all mixing angles* θ $\quad 0 \leq \delta N_s \leq 1$

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

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

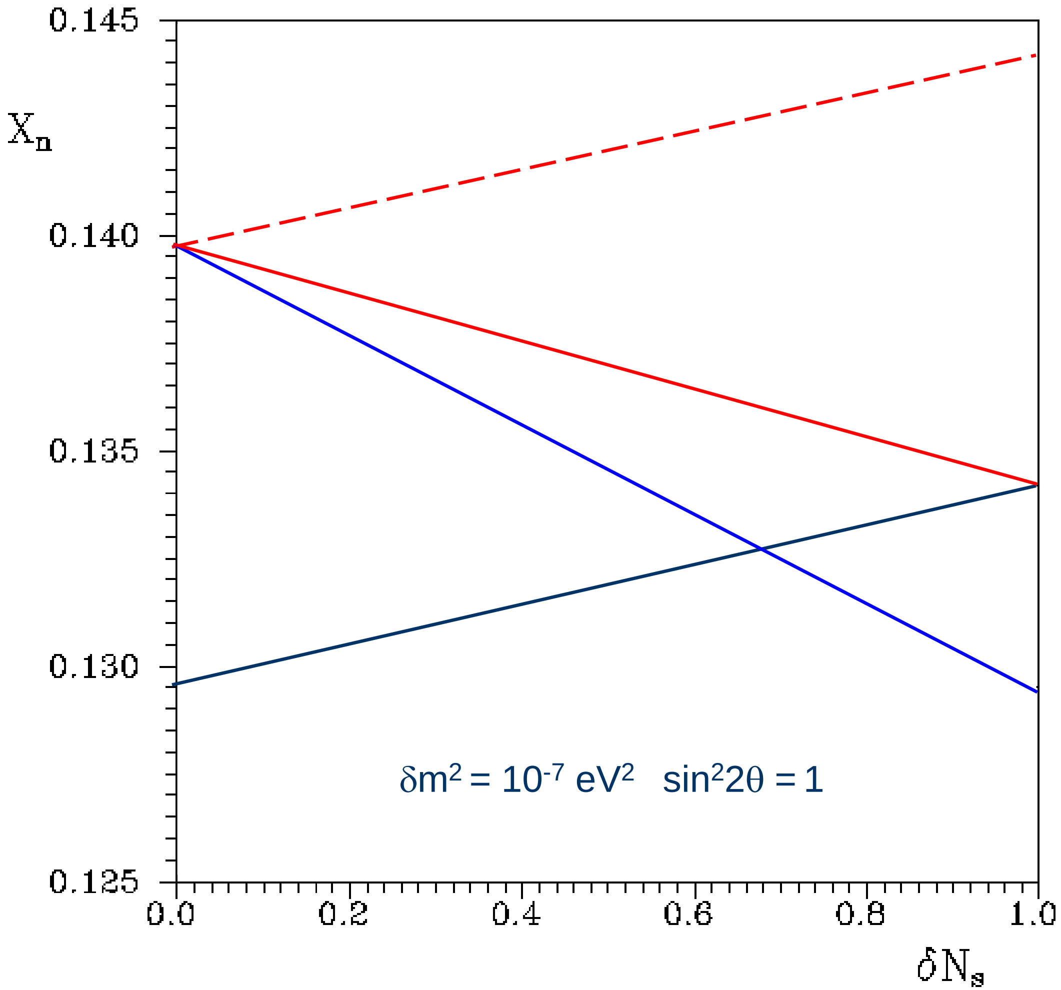
❖ In BBN with $\nu_e \leftrightarrow \nu_s$ the energy spectrum distribution and the number densities of electron neutrino may strongly differ from the SCM case. This influences the kinetics of nucleons before and during BBN and changes the produced abundances of the light elements.

The interplay b/n effects

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

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

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



total effect decreases

kinetic effect decreases

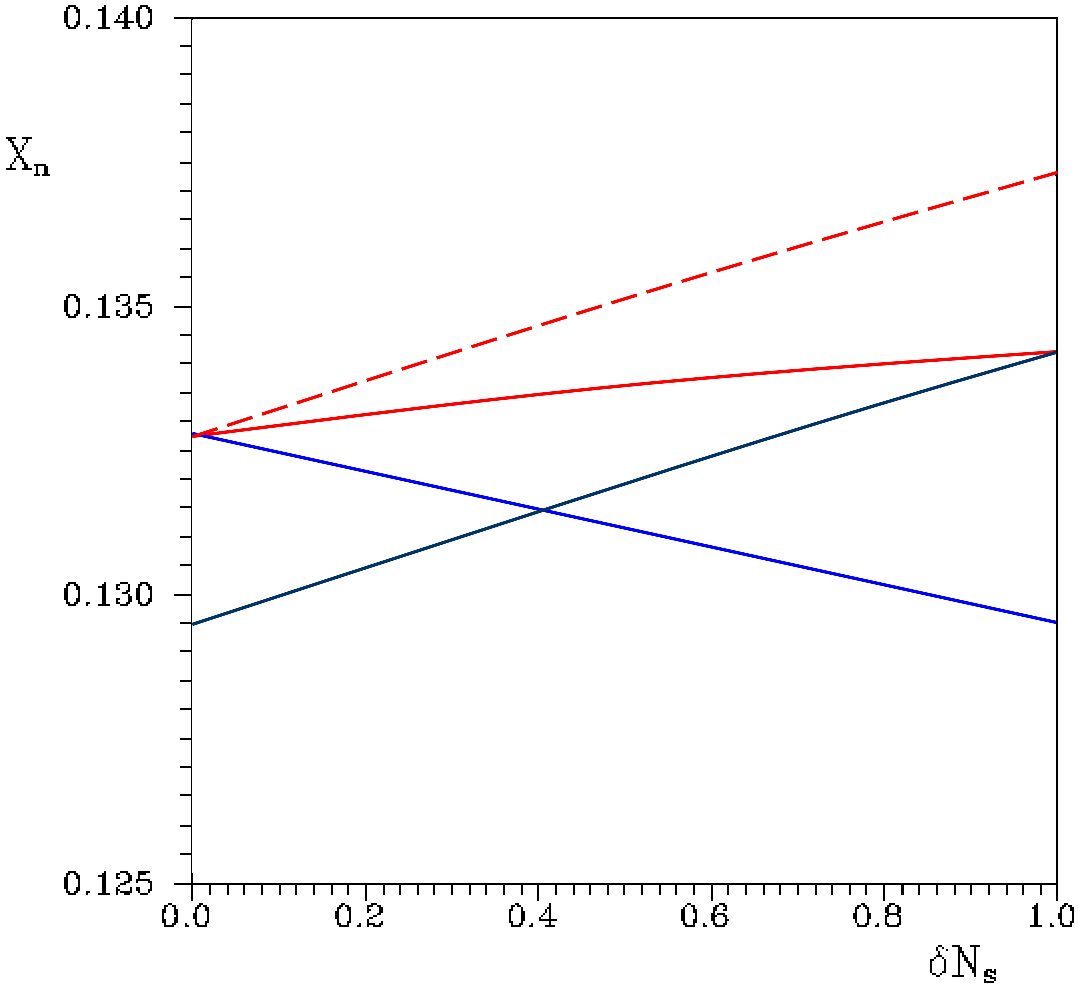
dynamic effect increases

The role of additional light ν_s

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

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

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



total effect increases

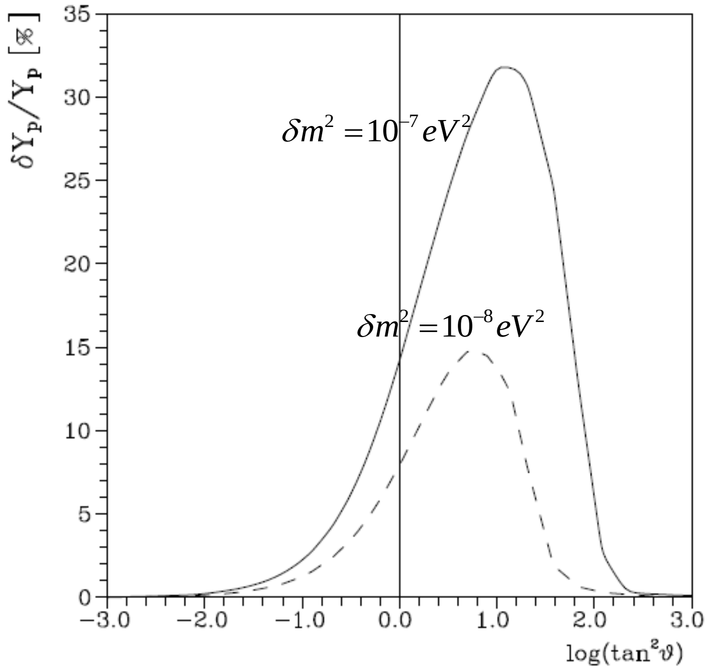
kinetic effect decreases

dynamic effect increases

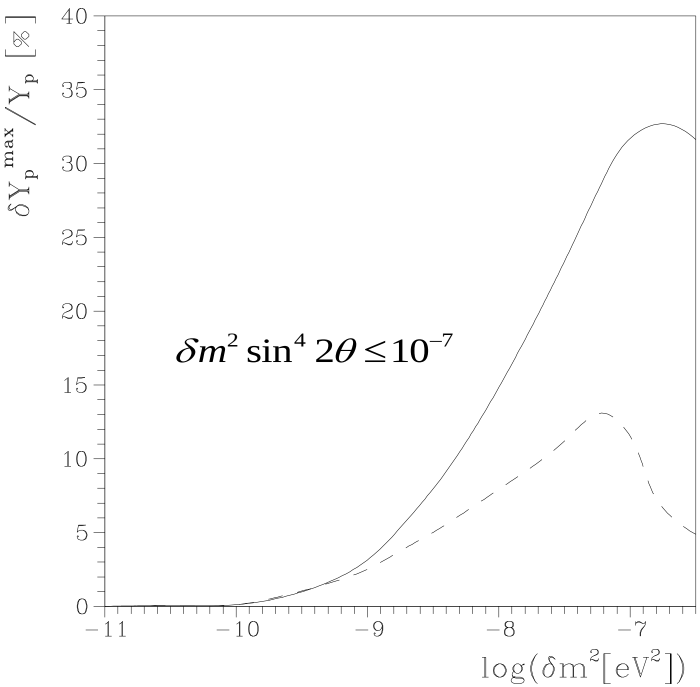
Maximum He-4

- For BBN with $\nu_e \leftrightarrow \nu_s$ 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.

DK, Astrop.Phys.,2003

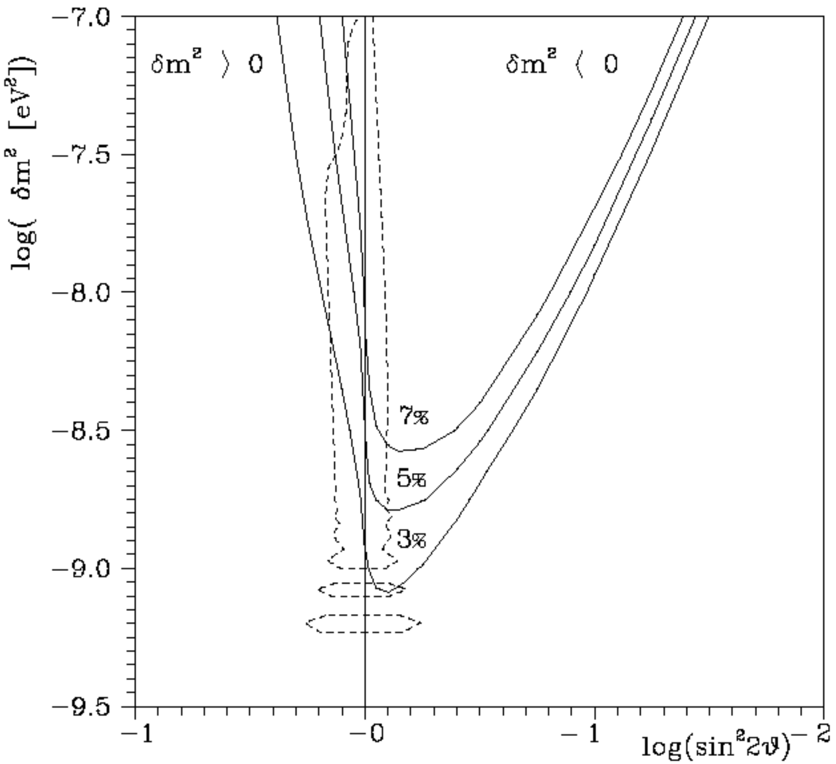


Dependence of maximum overproduction on the mixing



Maximal overproduction dependence on mass difference

BBN constraints on neutrino oscillation parameters



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

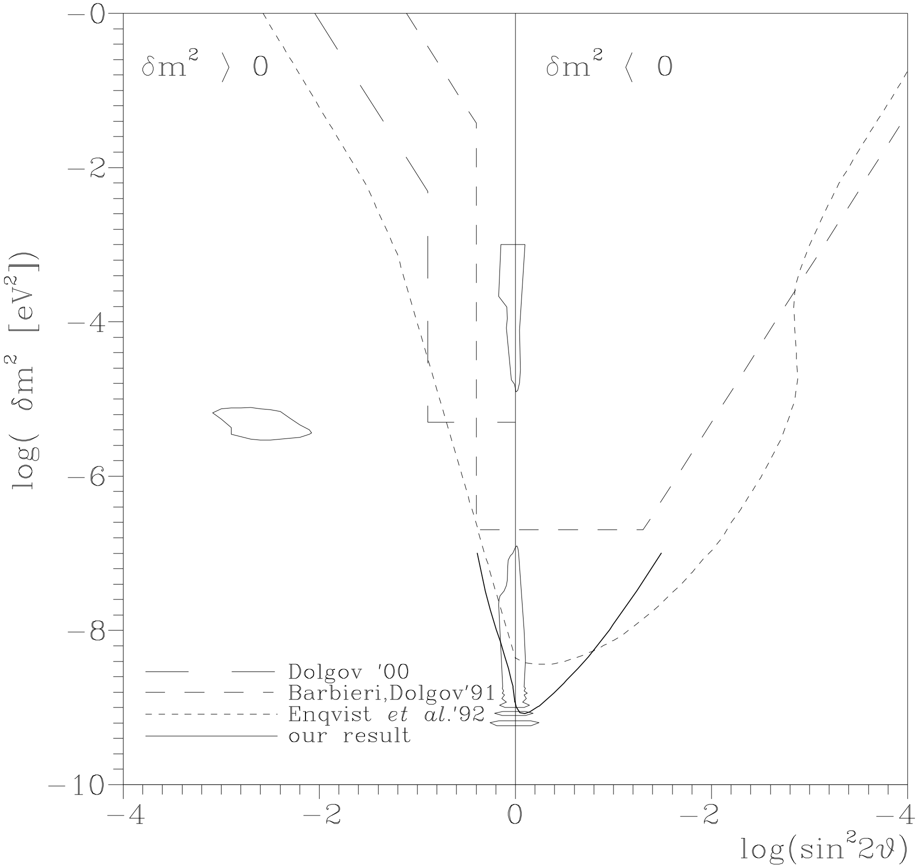
$$\delta m^2 < 8.2\times10^{-10} eV^2 \quad \text{large } \theta, \ \delta m^2 < 0$$

.

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

BBN Constraints v/s Previous Existing

BBN with 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, i.e. kinetic equilibrium constraints for non-resonant case

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

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

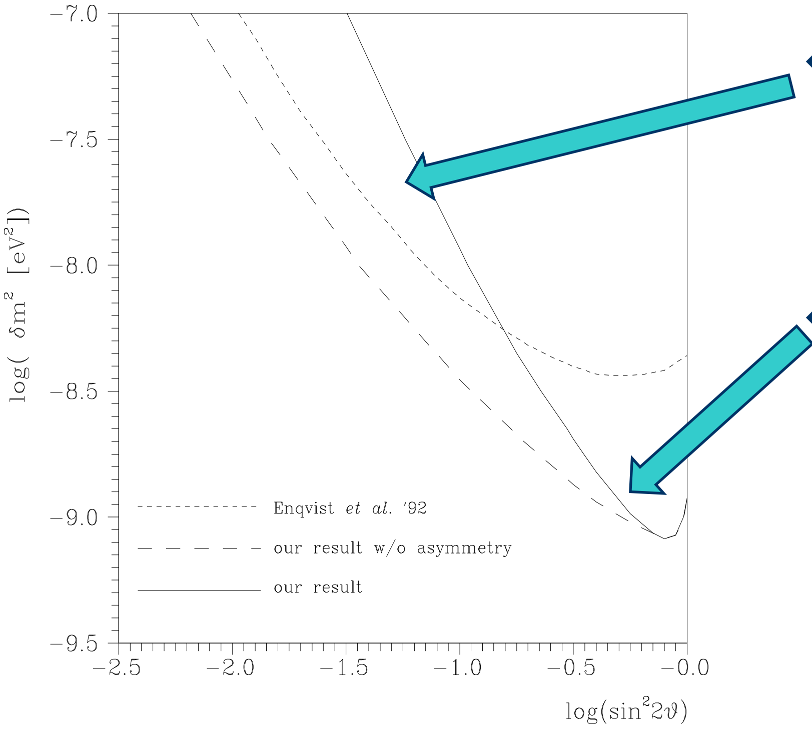
DK.,Chizhov 1996, 2001 – distortion of neutrino spectrum and asymmetry growth account

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

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

Effects of asymmetry and distortion of spectrum

$\delta N_s=0$

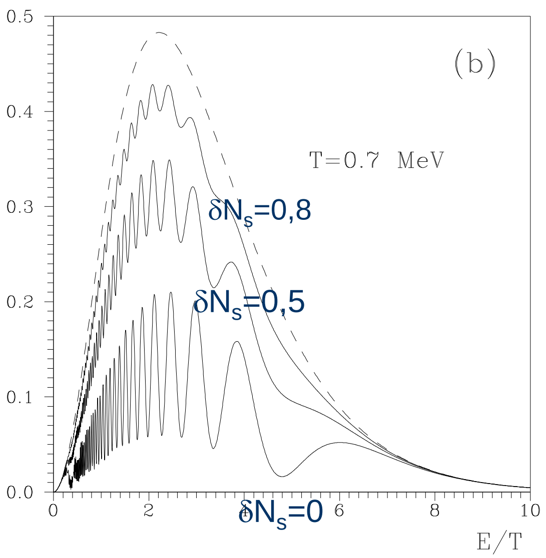


- ❖ The asymmetry relaxes the constraints at small mixing angles.
- ❖ The spectrum distortion strengthens the constraints at large mixing angles.

BBN constraints change in case proper account for spectrum distortion and asymmetry growth due to oscillations is provided.

Role of the initial population of inert neutrino

2 type of effects: dynamical – increasing H(g)
suppressing kinetic effect



The kinetic effects of oscillations depend on the initial population of the neutrino.

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

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

$\delta N_{k,0}\, \delta N_s > \delta N_s$ total effect decreases

$\delta N_{k,0}\, \delta N_s < \delta N_s$ Total effect increases

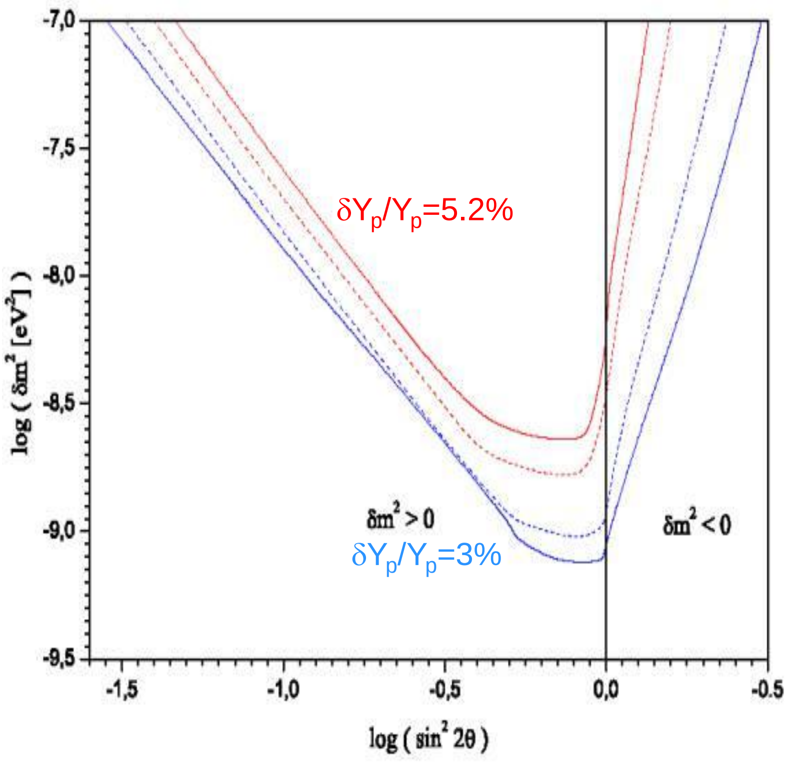
Energy spectrum distortion caused by oscillations depends on the level of initial population of $\nu_{s.}$
The kinetic effect decreases with δN_s, the dynamical one increases.

DK, IJMPD04,07; DKPanayotova, JCAP 2006

Role of the initial population of ν_s

BBN constraints relaxed or strengthened?

Additional ν_s population may strengthen or relax BBN constraints on oscillations. Thus, in case of oscillating neutrino, additional sterile population may either relax or strengthen BBN limit on N_{eff} depending on the strength of the kinetic effect of oscillation.



There exist an interplay b/n the effects of non-zero initial population of ν_s on BBN: in case the dynamical effect dominates, He-4 production is enhanced and BBN constraints strengthen, in case the kinetic effect dominates He-4 production decreases and BBN constraints relax.

The dotted blue (red) contour presents

$\delta Y_p/Y_p=3\%$ ($\delta Y_p/Y_p=5.2\%$) for $\delta N_s=0$,

the solid blue (red) contour presents

$\delta Y_p/Y_p=3\%$ ($\delta Y_p/Y_p=5.2\%$) for $\delta N_s=0{,}5$.

DK, Panayotova, 2006, ; DK, 2007

Relaxation of the constraints via L

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

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

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

✓Large enougth L may alleviate BBN constraints

DK, M.Chizhov, Nucl.Phys.B 98;CAPP00

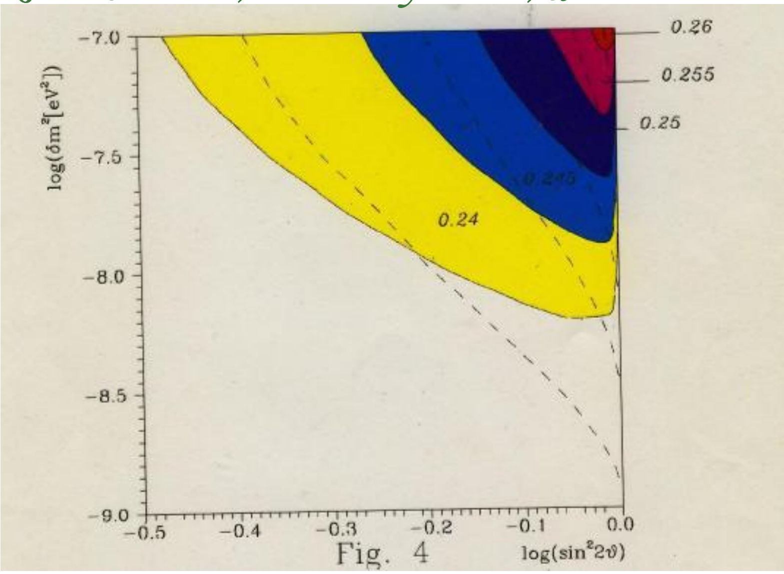
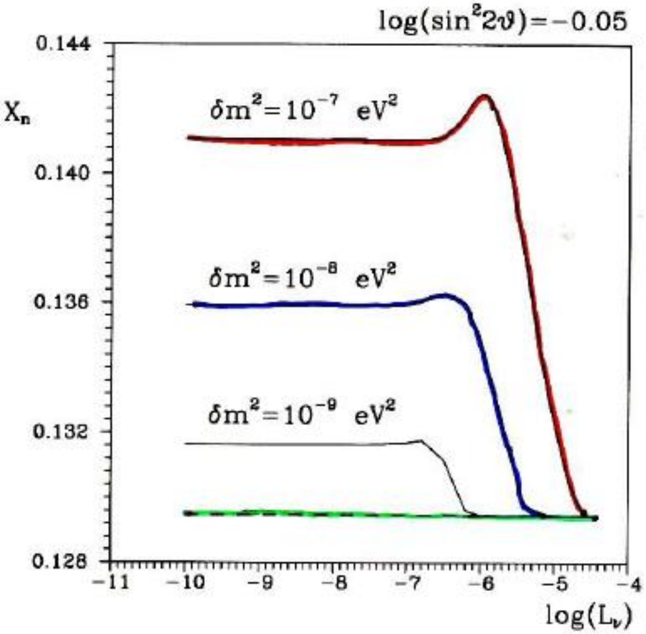


Fig. 4



Constrains from BBN. Summary

- For oscillations parameters favored by the atmospheric and solar neutrino data flavor equilibrium between active neutrino species is established before BBN epoch. No constraints.
- Fast active-sterile oscillations before decoupling of active neutrinos lead to additional species into equilibrium and speed Universe expantion. CBM and BBN constraints hold.

  Due to oscillations the sterile state is filled by the active neutrino, which is refilled by the plasma. Thus the net effect is total energy density increase in neutrino sector. CMB anisotropy spectrum feels energy density increase, hence constrains the fast active-sterile oscillations .

  CMB+LSS constraints (sensitive to the total energy density) exist $1<\delta N_s<5$.
- In case of the oscillations effective after active neutrino decoupling, the total energy density of neutrinos remains unchanged. Hence CMB and LSS constraints cannot be obtained with today's precision of CMB and LSS data.

❖ BBN consraints exist. BBN provides most stringent constraint on δm^2

- BBN is very sensitive to neutrino spectrum distortion and asymmetry.

  BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ allows He-4 overproduction up to 32% $\delta N_{k,0} \sim 6$ in resonant and 14% ($\delta N_{k,0} \sim 3$) for non-resonant case. BBN constraints on oscillations parameters in case of non-equilibrium oscillations do exist even when He-4 uncertainty is over 5%.

  Additional initial population of the sterile state not always leads to strengthening of constraints (as can be naively thought) it may also relax them.

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

  Large enough L may alleviate BBN constraints on oscillation parameters.
- BBN bound on N_{eff} are strengthened in case of neutrino oscillations.

CONCLUSIONS

- BBN is the most sensitive cosmological probe of number of neutrino species, of distortions in the energy distribution of neutrinos, lepton asymmetry, neutrino mass differences and mixings, etc. It provides constraints on many neutrino characteristics.
- BBN constraints on neutrino oscillations parameters depend nontrivially on the population of sterile neutrino and the lepton asymmetry.
- In case of active-sterile neutrino oscillations neutrinos of CNB may be expected to be considerably depleted and less energetic with an energy spectum strongly distorted from the equilibrium Fermi-Dirac form.


Благодаря за вниманието!
Thanks for the attention!