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He-4 from BBN and Cosmic Neutrino

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BBN and Neutrino

Big Bang Nucleosynthesis milestone of Big Bang cosmology

- Theoretically well established
- Precise data on nuclear processes rates from lab expts at low E (10 KeV – MeV)
- Observational data on D, He, Li
- Baryon fraction measured by CMB

BBN precision probe for early Universe and for new physics at BBN energies.

- BBN is sensitive baryometer, speedometer and leptometer.
- BBN probes any non-standard physics at BBN epoch.
- He-4 - most sensitive radiometer and leptometer at RD stage

BBN and CNB formation are nearby epochs, hence we expect considerable influence on primordial He-4 and neutrino

Neutrino experimental data firmly established physics BSMs

- Neutrino oscillations expt challenged SMs assumptions:
- m=0, N_{eff}=3, L=0, equilibrium FD distribution

Effects of BSM neutrino characteristics on He-4 and

cosmological constraints on them

Outline

He-4 in SBBN

Primordial He-4 as a test for BSM neutrino

- effective number of relativistic particles
- neutrino oscillations
  - in presence of L
  - in presence of ν_s
- L asymmetry

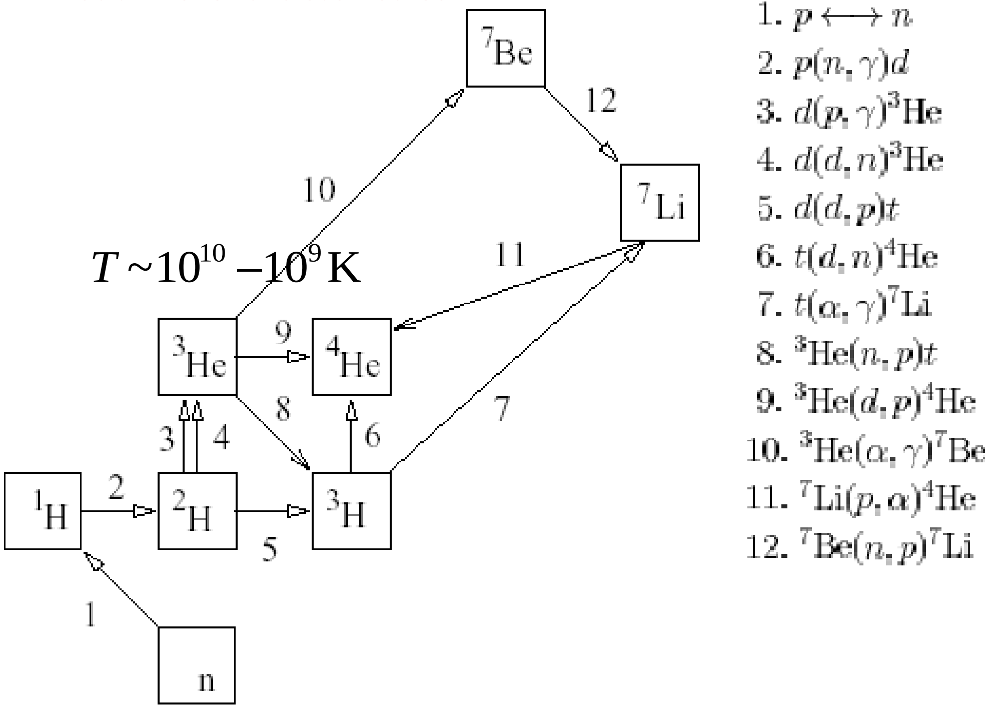
He-4 in standard BBN

BBN predicts the abundances of D, He-3, He-4, Li-7
produced during the early hot stage, 1 s – 20 m
1 - 0.1 MeV, of the Universe evolution.

The primordially produced abundances depend on:

- ✓ baryon-to-photon ratio η
- ✓ relativistic energy density
- ✓ n lifetime (880.1+-1.1 s)
- ✓ neutrino characteristics

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



1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3$He
4. $d(d,n)^3$He
5. $d(d,p)t$
6. $t(d,n)^4$He
7. $t(\alpha,\gamma)^7$Li
8. ^{3}He$(n,p)t$
9. ^{3}He$(d,p)^4$He
10. ^{3}He$(\alpha,\gamma)^7$Be
11. ^{7}Li$(p,\alpha)^4$He
12. ^{7}Be$(n,p)^7$Li

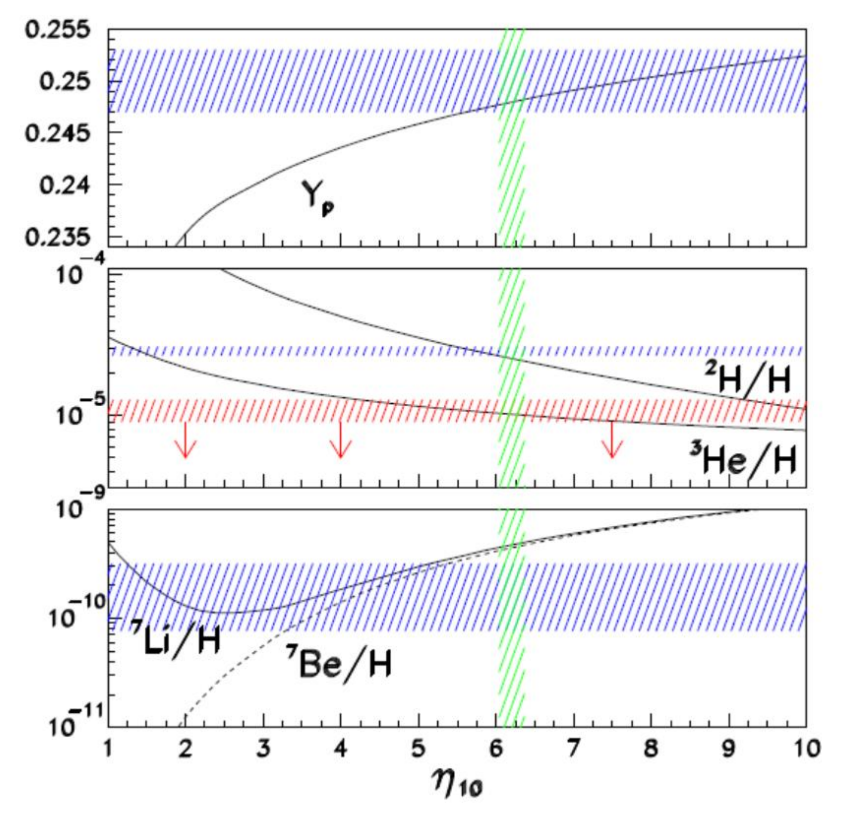
1.Weak interactions freeze out

2. D forms

3. Nuclear chain (>400 reactions)

run BBN code (PArthENoPE) to get Y_p, X_D Li-7, Li-6, Be, B, CNO

Observational data verse calculated abundances of primordially produced elements.



Observational data (2σ error). Vertical band give η_{CMB}

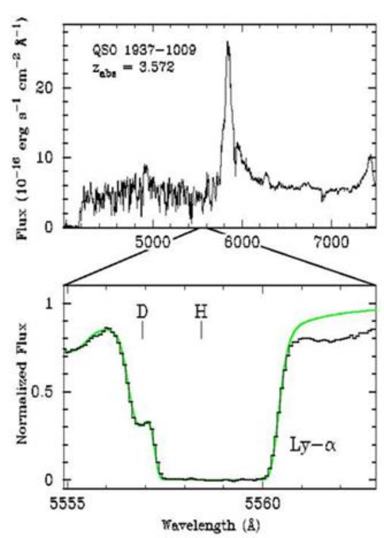
Main problem: Primordial abundances are not observed directly (chemical evolution after BBN).

Observations in systems least contaminated by stellar evolution
Account for galactic chemical evolution

(424 reactions code) *Coc et al, 2014*

D abundance

D measurements towards QSA in high redshift z, low metalicity Z (0.1-0.001 of the Solar Z) H-rich clouds absorbing light from background QSA.



- ➢ Improved precision during last years

  Cooke et al, 2014

D/H=(2.53±0.04) 10^{-5}

❖ Among light elements D is the best baryometer.

$$\eta = (5.7 \pm 0.3) \times 10^{-10}$$

$$\Omega_b h^2 = 0.021 \pm 0.001$$

$$\Omega_b h^2 = 3.65 \times 10^7 \eta, \quad \Omega_b = \frac{\rho_b}{\rho_c}, \quad \rho_c = \frac{3H^2}{8\pi G_N}$$

❖ Baryon density is measured with very high precision by BBN.

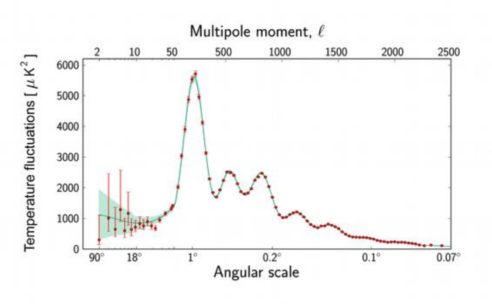
$5.7 \times 10^{-10} < \eta_{BBN} < 6.7 \times 10^{-10}$ 95% CL

$$0.021 < \Omega_b h^2 < 0.025$$

❖ CMB anisotropy measurements at ~380 000 y are consistent with BBN D measurements

$\eta_{CMB} = 6.047 \times 10^{-10}$ ±0.074 95% CL

$$\Omega_b h^2 = 0.02207 \pm 0.00027$$



Baryon density is ~ 0.05 of the total density → not enough to close the Universe.

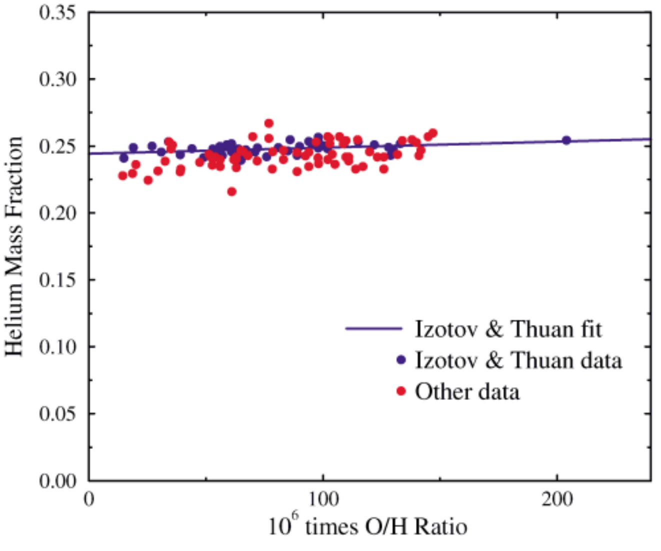
much bigger than the luminous matter (0.005) → most of the baryons are optically dark.

considerably less than the gravitating matter (0.3) → nonbaryonic DM needed

Hubble ST + CMB + clusters

The Abundance of Primordial He-4

- *Observations* in systems least contaminated by stellar evolution: in clouds of ionized H (H II regions), the most metal-poor blue compact galaxies
- *Account* for galactic chemical evolution - extrapolated towards zero metalicity
- Small statystical error but large systematics (interstellar reddening, clouds T, e density)



$Y_p=0{,}2421\pm 0{,}0021$	*Izotov, Thuan 2000*
$Y_p=0{,}2429\pm 0{,}009$	*Izotov, Thuan 2004*
$Y_p=0{,}245\pm 0{,}013$	*Olive, Skillman 2004*
$Y_p=0{,}252\pm 0{,}001$	*Izotov et al 2007*
$Y_p=0{,}2565\pm 0{,}001 \pm 0{,}005$(syst)	*Izotov, Thuan 2010* *93 Sp of 86 low Z HII*
$Y_p=0{,}2561\pm 0{,}0108$	*Aver et al. 2010*
$Y_p=0{,}2465\pm 0{,}0097$	*Aver et al. 2013*
$Y_p=0{,}254\pm 0{,}00016\pm 0{,}003$	*Izotov et al 2013 (111 HII)*

$Y_p=0{,}266\pm 0{,}021$ from Planck (consistent with HII determination)

He-4 most abundant (25%), precisely measured (3%), simple post-BBN evolution.
Good agreement b/n observational determinations and BBN predictions → prefered element for cosmological tests and constraints on BSM physics

He production

- T > 1 MeV

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

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

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

$$\frac{n}{p} \sim e^{-\frac{\Delta m}{T}}$$

$\Delta m = 1.293 MeV$

- T < 1 MeV

$$\Gamma \sim G_F^2 T^5 \qquad H \sim \sqrt{g_{eff}}\, G T^2$$

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

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

- T < 80 KeV

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

$\tau_n = 880 s$

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

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

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

Primordial He-4 Y_p, predicted by BBN, is calculated with great precision.
Assuming CMB measured baryon density: : 0.2461-0.2466 (424 reactions code) *Cok et al, 2014*

He-4 and BSM Neutrino

^{4}He – powerful test for BSM neutrino physics

❖ BBN produced He-4 – the most precise radiometer: provides stringent bounds on excess radiation due to its dependence on $H \sim \sqrt{g_{eff} G T^2}$:

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

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

❖ BBN produced He-4 is sensitive to neutrino characteristics (n, N, sp, L..)

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

- Number of generations (types of relativistic neutrino)
- Neutrino Oscillations
- Lepton Asymmetry
- **Neutrino decays**

He-4 speedometer

BBN constrains the effective number of relativistic species

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

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

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*

$Y_p = 0,2565 \pm 0.001(\text{stat}) \pm 0,005(\text{syst})$ *Izotov&Thuan, 2010* *93 Sp of 86 low Z HII*

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

4

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

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.

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

Ade et al 2013 $N_{\rm eff} = 3.36^{+0.34}_{-0.34}$ (CMB for η)

Cooke et al. 2013 $N_{\rm eff} = 3.28^{+0.28}_{-0.28}$

Coc et al. 2014: $2.67 < N_{\rm eff} < 3.77$ (Planck for η)

Planck Collaboration $N_{\rm eff} = 3.36^{+0.34}_{-0.32}$

Main Oscillations Effects on He-4

$\nu_a \leftrightarrow \nu_s$

Dynamical effect:

Production of additional neutrino species enhances the energy density increase $H \sim \sqrt{g_{eff}} G T^2$ $\rightarrow$ ^{4}He overproduction *Dolgov, 1981*

1 additional $\nu \rightarrow \delta Y_p / Y_p = 5\,\%$

Kinetic effect:

ν_e energy spectrum distortion due to $\Gamma_{osc} \sim \frac{\delta m^2}{E}$

ν_e depletion, neutrino-antineutrino asymmetry change, deviation from FD distribution

decrease $\Gamma \sim G_F^2 E_\nu^2 N_\nu$, n/p freezes earlier $\rightarrow$ ^{4}He overproduction *D.K.,1988; Barbieri,Dolgov, 1990; DK M.Chizhov,1996*

Fast $\nu_a \leftrightarrow \nu_s$ effective before ν_a decoupling increase δN_s

Nonequilibrium $\nu_e \leftrightarrow \nu_s$ effective after ν_a decoupling and $\delta N_s<1$ cause distortion of ν_e distribution

neutrino-antineutrino asymmetry growth for $|\delta m^2| \sin^4 2\theta \leq 10^{-9.5} eV^2$

He-4 produced in BBN with late $\nu_e \leftrightarrow \nu_s$

- Evolution of nucleons in the presence of late $\nu_e \leftrightarrow \nu_s$ $\delta m^2 \sin^4 2\theta \le 10^{-7}$

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

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

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

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

- Interplay b/n dynamical and kinetic effect of oscillations on He-4 was explored.

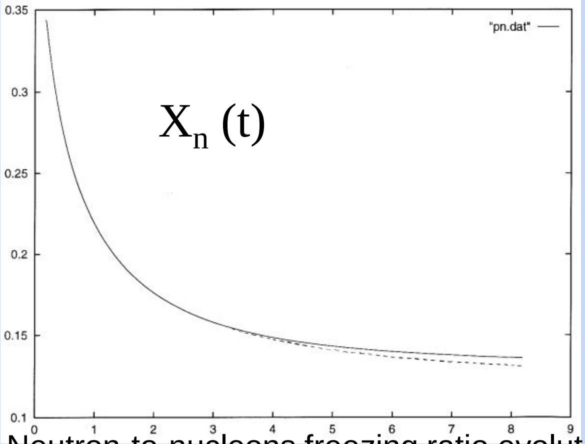
$\delta N = \delta N_{k,0} - \delta N_{k,0}\, \delta N_s + \delta N_s$ $\delta Y_p \sim 0.013\, \delta N$ *D.K. IJMPD 2004*

- Dependences of He-4 production on oscillation parameters, L and population of inert neutrino $Y_p(\delta m^2, \theta, L, \delta N_s)$ were numerically calculated.

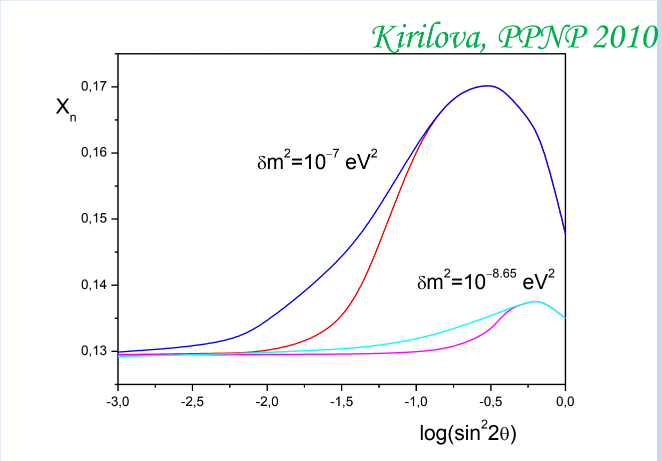
D.K, Chizhov, NPB 98, 2000; D.K, ApPhys 2003; JCAP 2012

- Maximum He-4 overproduction was found.

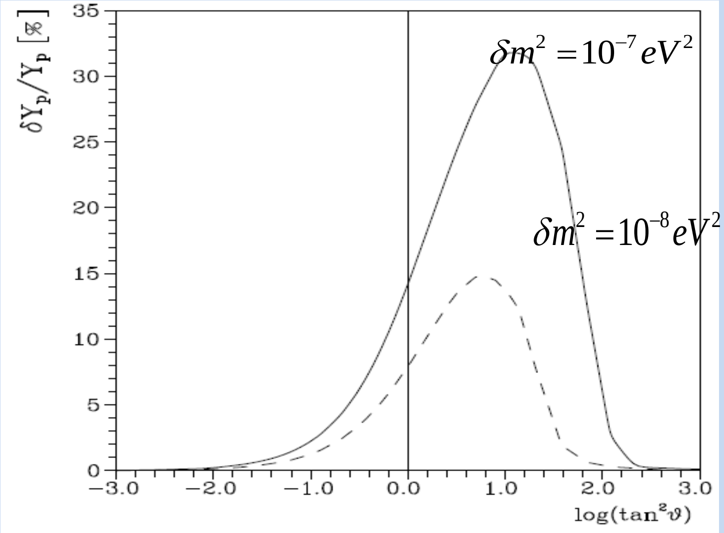
He-4 from BBN with late $\nu_e \leftrightarrow \nu_s$



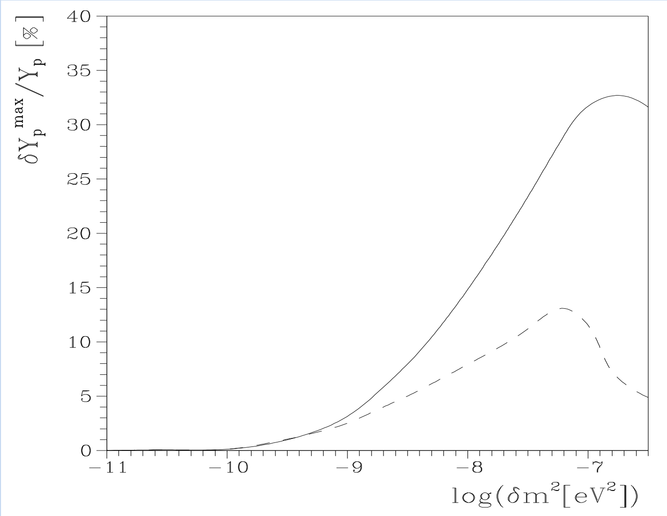
Neutron-to-nucleons freezing ratio evolution in case of L growth (solid line) and in case asymmetry growth is neglected


Kirilova, PPNP 2010

Maximum He-4 overproduction in BBN with oscillations



Dependence of maximum overproduction on the mixing

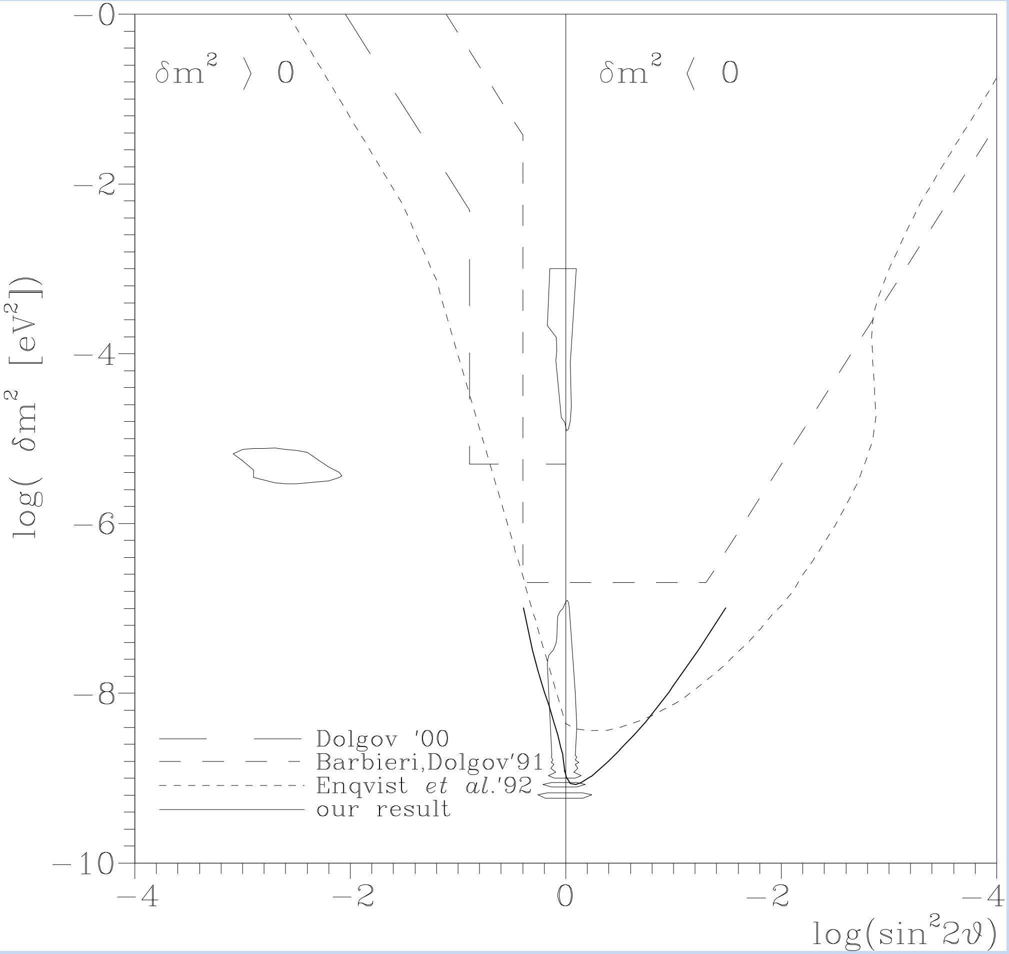


Dependence of maximum overproduction on mass

- He-4 decreases at small mixing due to L growth.
- BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ constrains ν oscillation for He-4 uncertainty up to 32%

Cosmological constraints on neutrino oscillations

$\delta Y_p/Y_p=3\%$, initially empty inert state $\delta N_s=0$



Fits to BBN constraints

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

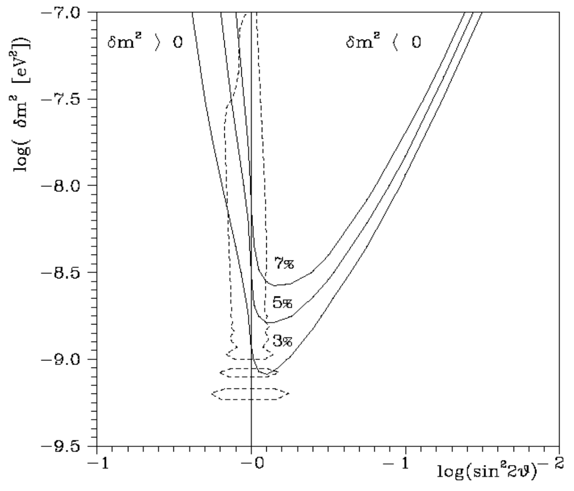
$$\delta m^2_{es}\sin^4 2\theta_{es} \le 3.16\times10^{-5} eV^2 \ln^2(1-\Delta N_\nu)$$

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

$$\delta m^2 \sin^4 2\theta \le 10^{-7}$$ DK,Chizhov NPB 2001

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

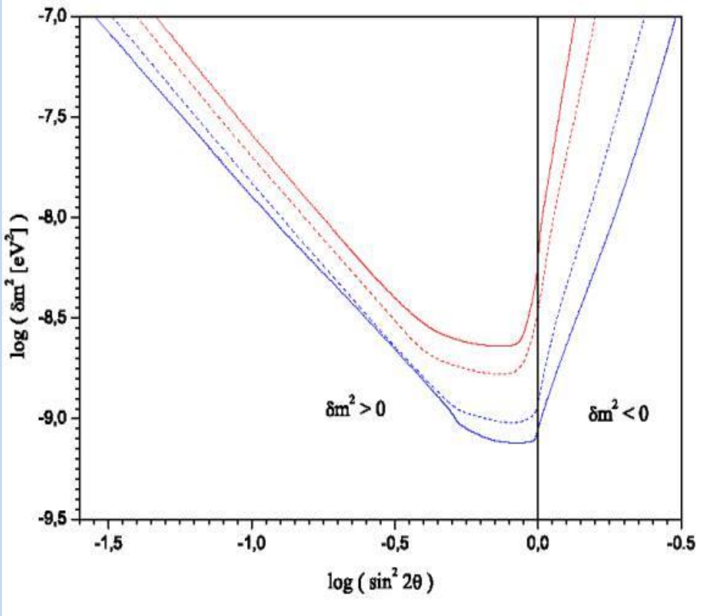
$$\delta m^2 < 8.2\times10^{-10} eV^2 \qquad \text{large } \theta,\ \delta m^2 < 0$$



- ✓ BBN constraints are 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.
- ✓ Exclude electron-sterile solution to LSND

BBN constraints on $\nu_e \leftrightarrow \nu_s$ and non-zero δN_s

DK&Panayotova JCAP2006;DK IJMPD 07



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

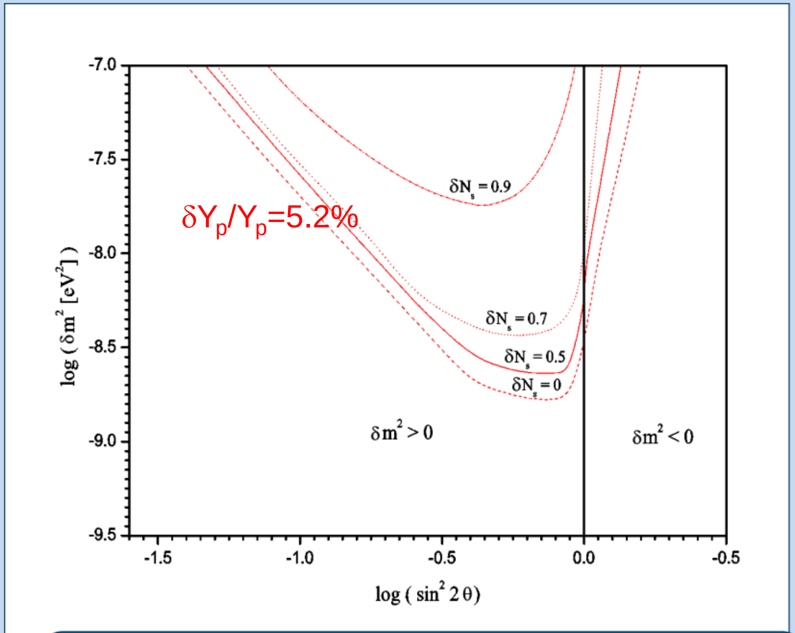
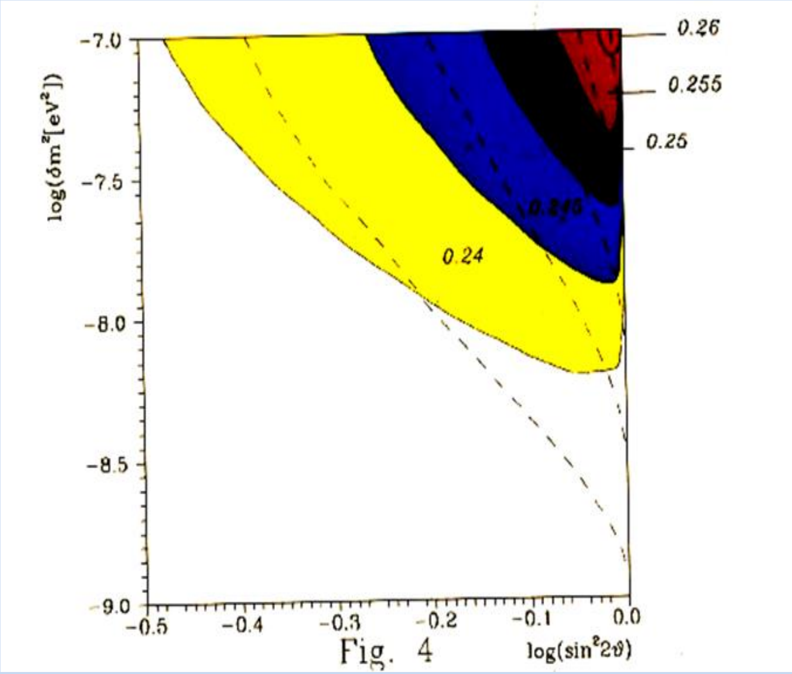


Fig.1 - The resonant ($\delta m^2>0$) and non-resonant ($\delta m^2<0$) iso-helium contours for $\delta Y_p/Y_p=5.2\%$ and $\delta N_s=0$ – dashed contour, $\delta N_s=0.5$ – solid contour, $\delta N_s=0.7$ – dotted contour and $\delta N_s=0.9$ – dotted-dashed contour are presented .

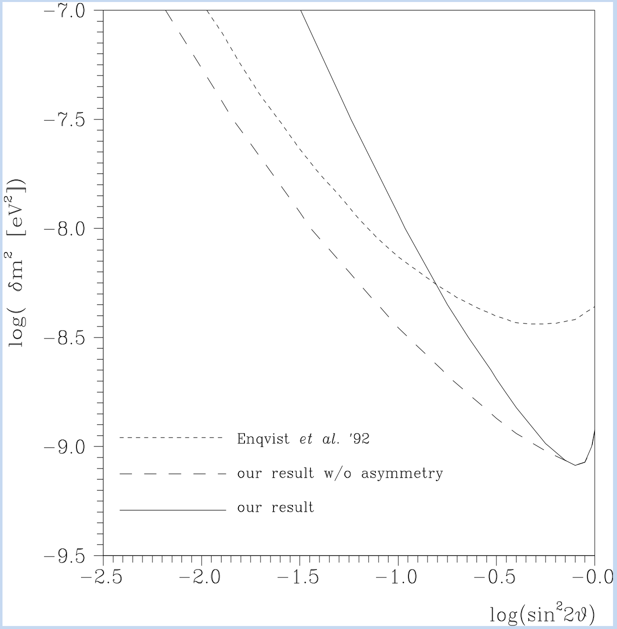
Kinetic effect dominates, hence He-4 overproduction decreases with δN_s increase.

Additional ν_s population may strengthen or relax BBN constraints depending on the interplay b/n dynamical and kinetic effect on He-4.

He-4 constraints on oscillations parameters changed by L



$\delta N^{in}_s=0$



Kirilova&ChizhovNPB2000

- ❖ Relic L may relax He-4 constraints on neutrino mass differences at large mixing and strengthen them at small mixing. Large enough L $\delta m^2(eV^2) < L^{3/2}$ may suppress oscillations. *Kirilova JCAP 2012*

- ❖ Generated neutrino-antineutrino asymmetry by resonant oscillations leads to relaxation of the He-4 constraints on neutrino mass differences at small mixings.

He-4 and L

$$L=(n_l-n_{\bar{l}})/n_\gamma \qquad L\sim\sum_i L_{\nu_i}$$

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

- Non-zero L increases the radiation energy density ΔN_{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

Simha&Steigman, 2008: $Y_p\sim(0.2482\pm0.0006)+0.0016\eta_{10}+0.013\Delta N_{eff}-0.3\xi_{\nu_e}$

- Indirect kinetic - $0.01>L\geq 10^{-8}$ effects n/p kinetics and BBN through neutrino oscillations *DK&ChizhovNPB98; DK JCAP,2012.*

❖ Primordially produced He-4 provides the most stringent constraint on L

- ➢ Accounting for flavor neutrino oscillations and ν decoupling

Neutrino degeneracies equilibrate due to oscillations before BBN

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

$$|L|<0.1$$

$$\sin^2\theta_{13}>0.03$$

Castorini et al. 2012 -0.071<L<0.054 *; Steigman, 2012* ξ=0.038 ±0.026 from He-4

Mangano et al., 2013 |L|<0.2 big θ_{13}

- ➢ Constraints on L from He-4 in case of BBN with electron-sterile oscillations tiny L may be constrained $L\sim10^{-8}$

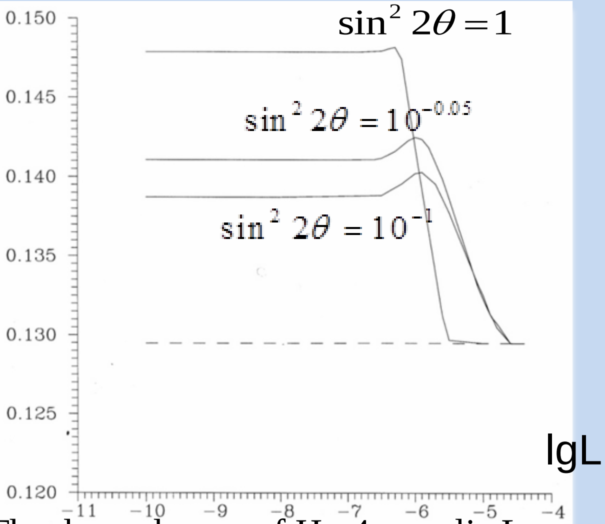
DK, JCAP 2012;Hyperfine Int. 2013

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

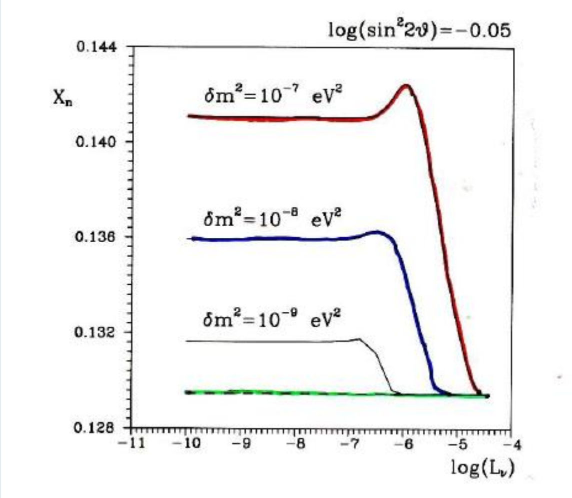
He-4 in BBN with late neutrino oscillations and relic L>10^{-10}

Kirilova JCAP 2012

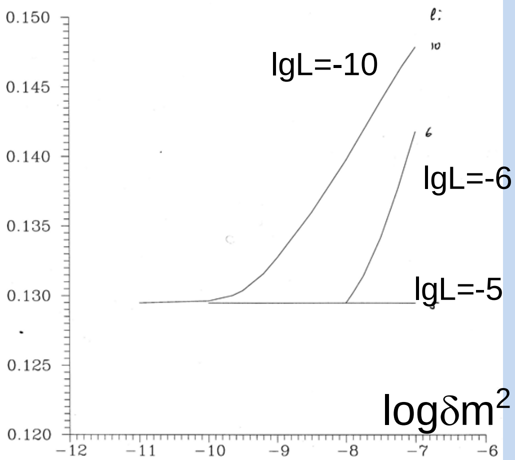
$$Y_p\left(\delta m^2, \theta, L\right)$$



The dependences of He-4 on relic L (for different mixing) .



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



The dependences of He-4 on δm^2 (for different L) .

- ✓ Small L change primordial production of He by enhancing or suppressing oscillations.
- ✓ L is able to strengthen, relax and eliminate He-4 cosmological constraints on ν oscillations. Then approximate bound holds: $\delta m^2 (eV^2) < L^{3/2}$
- ✓ $L < (\delta m^2)^{2/3}$

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

DK, CEJP 2014

Conclusions

Primordial He-4 is one of the most precise probes of physics at the RD stage and the most reliable cosmological test of physics beyond SM.

He-4 is very sensitive to radiation density, neutrino spectrum distortion and L It is the most sensitive cosmological probe of the number of neutrino species, of distortions in the energy distribution of neutrinos, lepton asymmetry, neutrino mixing parameters, non-standard interactions, etc.

He-4 is overproduced in BBN with neutrino oscillations effective after neutrino decoupling. BBN constraints strengthen by orders of magnitude when distortion effect of oscillations is accounted for. BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ constrains ν oscillation parameters for He-uncertainty up to 32%(14%) in resonant (non-resonant) case.

He constraints on neutrino oscillations depend nontrivially on the population of sterile neutrino and L.

Additional sterile state may lead to enhancement or reduction of the He overporoduction by oscillations, thus strengthen or relax cosmological constraints.

L is able to enhance, suppress or inhibit oscillations leading to changes of the cosmological constraints on oscillation parameters.

BBN constraints on L strengthen considerably in case of presence of $\nu_e \leftrightarrow \nu_s$ oscillations: He-4 produced in BBN with active-sterile oscillations may feel $L \geq 10^{-8}$.

Благодаря за вниманието!

Thanks for the attention!

Solving numerically BBN dynamics

1. Weak interactions freeze out at T ~1 MeV
2. Deuterium forms via $p\,n \to D\,\gamma$ at T ~ 0.1 MeV
3. Nuclear chain

$$\frac{\dot a}{a} = H = \sqrt{\frac{8\,\pi G_N}{3}\,\rho}$$

$$\frac{\dot n_B}{n_B} = -\,3\,H \quad ,$$

$$\dot\rho = -\,3\,H\,(\rho + P) \quad ,$$

$$\dot X_i = \sum_{j,k,l} N_i \left(\Gamma_{kl\to ij} \frac{X_k^{N_k}\, X_l^{N_l}}{N_k!\, N_l!} - \Gamma_{ij\to kl} \frac{X_i^{N_i}\, X_j^{N_j}}{N_i!\, N_j!} \right) \equiv \Gamma_i \quad ,$$

$$n_B \sum_j Z_j\, X_j = n_{e^-} - n_{e^+} \equiv L\left(\frac{m_e}{T}, \phi_e\right) \equiv T^3\, \hat L\left(\frac{m_e}{T}, \phi_e\right) \quad ,$$

$$\boxed{\left(\frac{\partial}{\partial t} - H\,|\mathrm{p}|\frac{\partial}{\partial|\mathrm{p}|}\right) f_{\nu_\alpha}(|\mathrm{p}|, t) = I_{\nu_\alpha}\left[f_{\nu_e}, f_{\bar\nu_e}, f_{\nu_x}, f_{\bar\nu_x}, f_{e^-}, f_{e^+}\right]} \,,$$

- **Run BBN code (PArthENoPE) to get** $Y_P(N_{\nu,}\eta)$, $X_D(N_{\nu,}\eta)$ *Miele et al. 2011*

$$^2\mathrm{H/H} = 2.87^{+0.22}_{-0.21} \times 10^{-5}, \qquad \mathrm{Y}_p = 0.247 \pm 0.002_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$$

Neutrino in SM

- massless
- Neutrino spectra have equilibrium Fermi-Dirac distribution, L=0

at T>1 MeV $\boxed{n_\nu^{eq} = \exp(-E/T)/(1+\exp(-E/T))}$ $T_\nu = T_e = T_\gamma$

at T~1 MeV neutrino decouple $\Gamma \sim G_F^2 E_\nu^2 N_\nu \leq H$

$T \sim m_e$, $e^+e^- \to \gamma\gamma$ photons were heated $T_\nu = (4/11)^{1/3}\, T_{cmb}$

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

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

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

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

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

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

Effective number of relativistic neutrino species

$N_{eff} = 3.046$ $n_\nu = 339.3\ \mathrm{cm}^{-3}$

Neutrino oscillations found → neutrino non-zero mass and mixing, change in N_{eff} n(E) L

Sterile Neutrinos Status

Wellcomed by cosmology:

- may play subdominant role as DM component (eV, KeV)
- may play a role in LSS formation (when constituting few % of the DM it suppresses small scale power in the matter power spectrum and better fits the observational data from SDSS, cluster abundance, weak lensing, Lyman Alpha forest, CMB)
- plays major role in natural baryogenesis through leptogenesis
- The X ray photons from sterile neutrino decays may catalize the production of molecular H and speed up the star formation, causing earlier reionization – observational feature predicted
- CMB feels the increase in the density due to additional particles
- Sterile neutrino is constrained by BBN because it increases the expansion rate and hence dynamically influences He production, in case it is brought into equilibrium. Its decoupling temperature must be $T_R > 130$ MeV.

  $L=10^{-10}$
- In case of oscillations with active neutrino it exerts major effect on nucleons kinetics during pre-BBN and its mixing parameters are constrained by BBN+CMB
- Et cetera…..

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

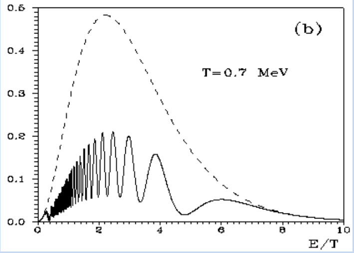
✓ non-zero neutrino mass and mixing

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

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

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

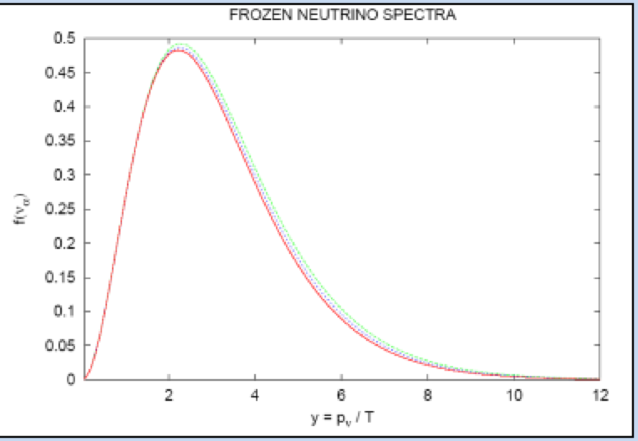
additional species may be brought into equillibrium

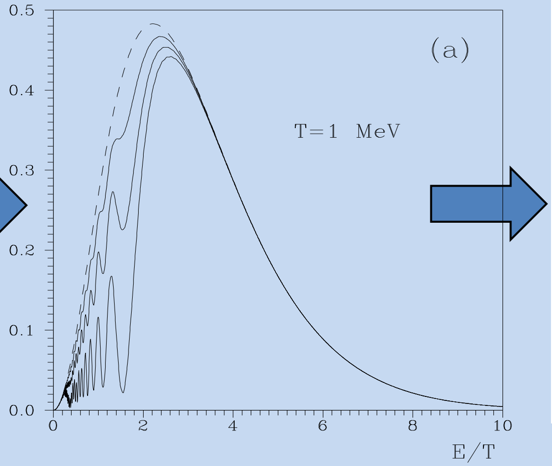
✓ sterile neutrino

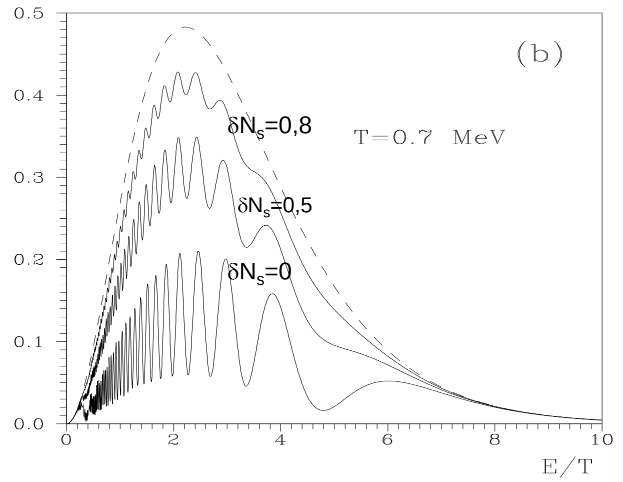
- Active-sterile oscillations proceeding after decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ may strongly distort neutrino distribution and deplete electron neutrino.

Kirilova 88, Kirilova&Chizhov PLB,97

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



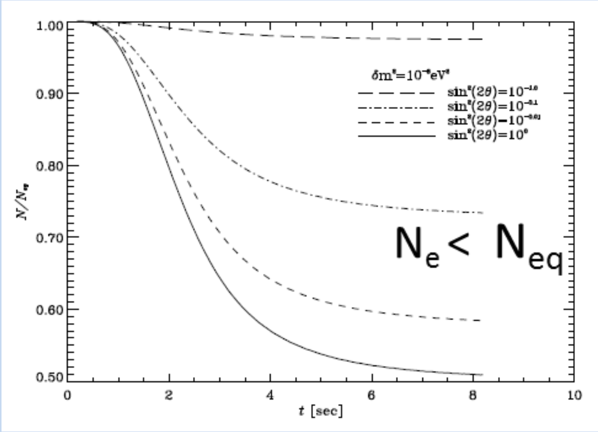




Kirilova,IJMPD,2004

The distortion due to active-sterile oscillations and the kinetic effect caused

δN_k depends on the degree of initial population of ν_s.



$N_e < N_{eq}$

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.

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.