International conference on Physics
in Memoriam acad. prof. Matey Mateev

11 April 2011, Sofia

From Mateev's baryogenesis ideas to cosmological constraints on ν

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Outline

Mateev’s baryogenesis idea
BBN and CMB baryometers
BBN probe of nonequilibrium neutrino
BBN and lepton asymmetry
Leptogenesis by neutrino oscillations

Mateev's Baryogenesis Ideas

Cosmology in the 80ies was not the precision science it is today.

Observational milestones:

BBN abundances, Hubble expansion, CMB isotropy measurements and T_{cmb}, LSS

$$\beta = (n_b - n_{\bar{b}}) / n_\gamma \sim 10^{-10} - 10^{-9}$$

Saharov's baryogenesis conditions: BV, CPV, nonequilibrium β

Mateev's idea:

Using CPV of Kadyshevski&Mateev QFT model – calculate BA and constrain L

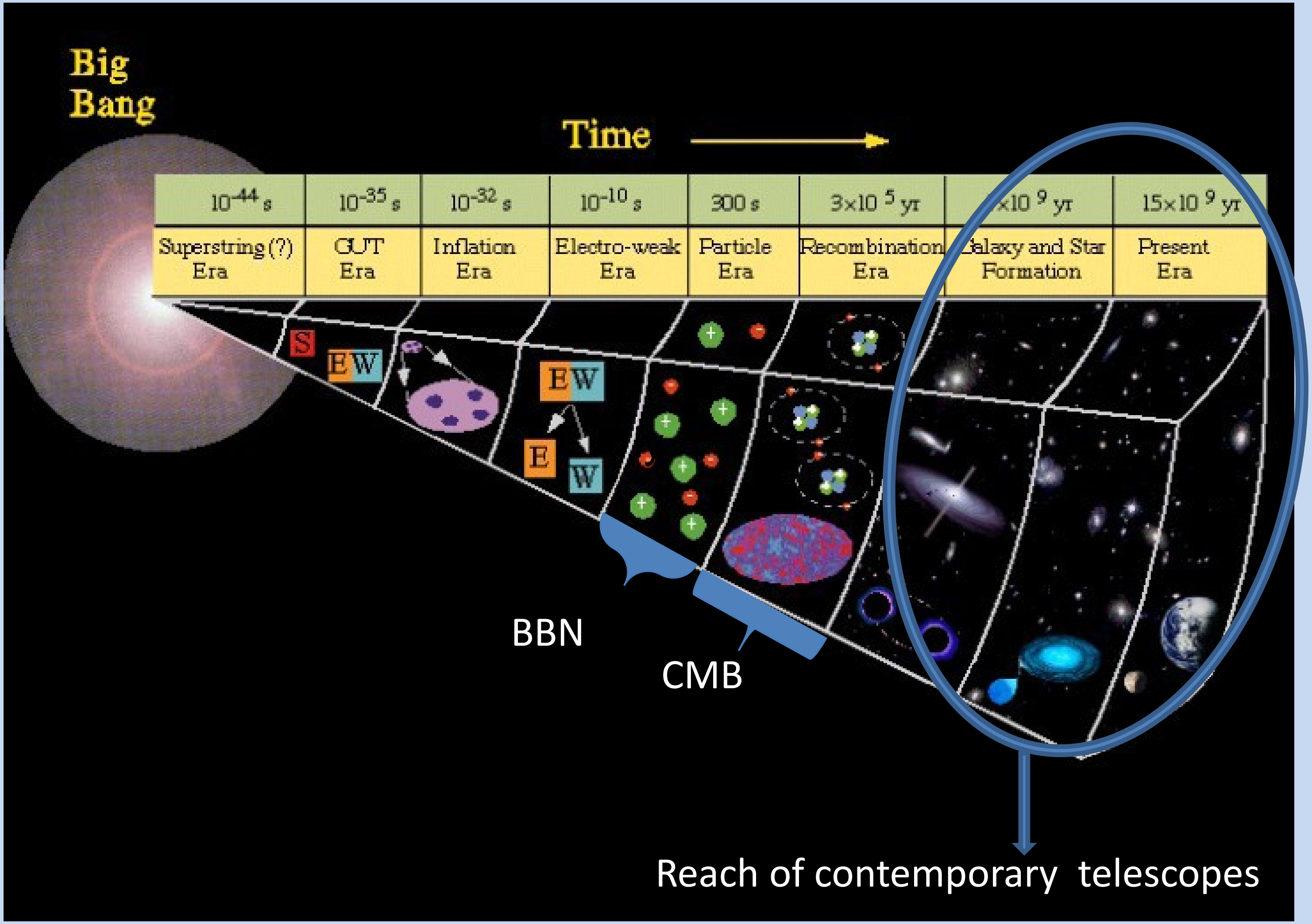
(fundamental length of KM model)

M. D. Mateev – an open-minded scientist with a wide physical interests and knowledge

first work on physical cosmology and astroparticle physics in Bulgaria

Kirilova D., **Mateev M.**, *Baryon-Antibaryon Asymmetry of the Universe and the Fundamental Length*, Theoretical physics and high energy physics, Sofia: Bulg. Acad. Sci., p.55-62, 1988.

Cosmology now – a precision science

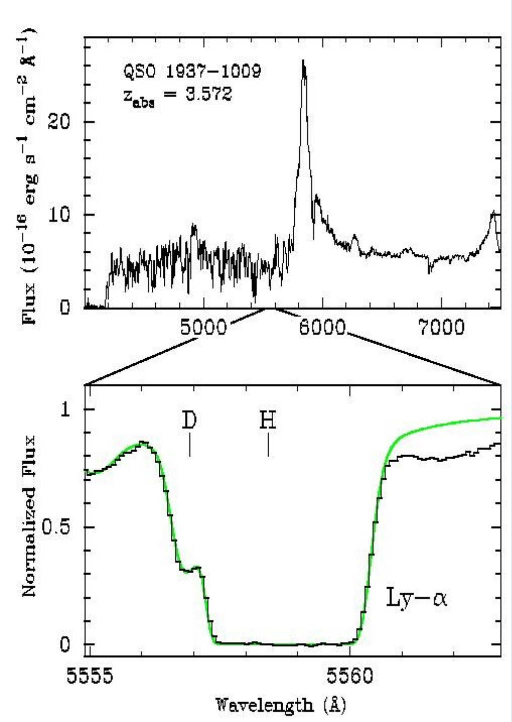


Contemporary Baryon Density Data

$$\beta = (n_b - n_{\bar{b}}) / n_\gamma \sim \eta = n_b / n_\gamma \sim 6.10^{-10}$$

b is measured precisely by different independent means - BBN and CMB

DASI, BOOMERANG, MAXIMA, WMAP



measuring abundances of light elements

WMAP 7-year Cosmological Interpretation 13

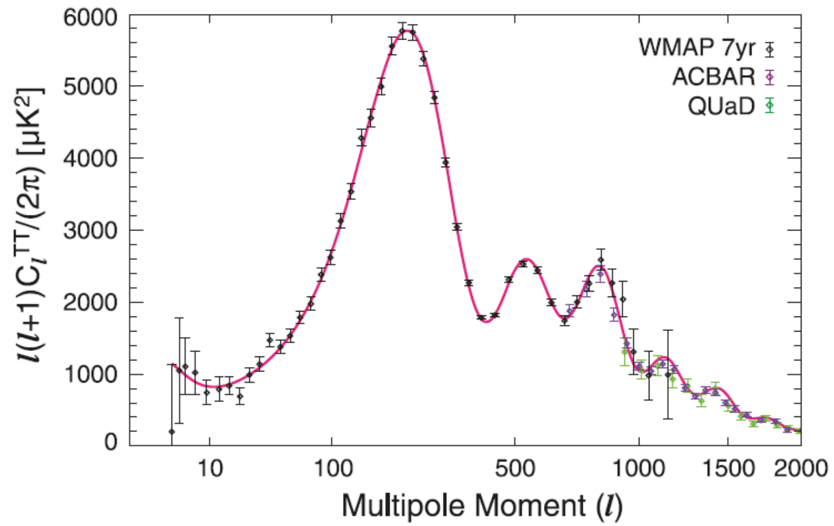


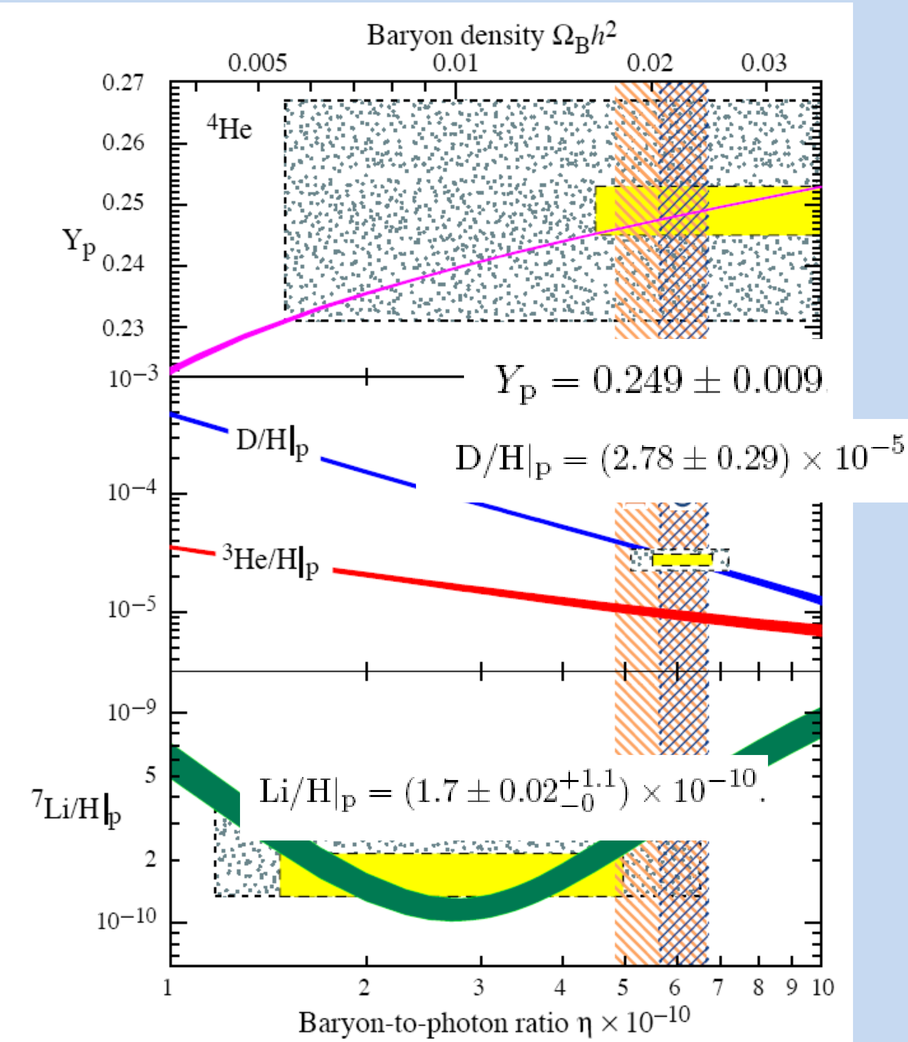
FIG. 7.— The *WMAP* 7-year temperature power spectrum (Larson et al. 2010), along with the temperature power spectra from the ACBAR (Reichardt et al. 2009) and QUaD (Brown et al. 2009) experiments. We show the ACBAR and QUaD data only at $l \geq 690$, where the errors in the *WMAP* power spectrum are dominated by noise. We do not use the power spectrum at $l > 2000$ because of a potential contribution from the SZ effect and point sources. The solid line shows the best-fitting 6-parameter flat ΛCDM model to the *WMAP* data alone (see the 3rd column of Table 1 for the maximum likelihood parameters).

from CMB anisotropy measurements

BBN baryometers

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

BBN - the most early and precision probe for physical conditions in the early Universe.



Зависимост на D, ^{3}He, ^{4}He, ^{7}Li от η. Наблюдателните данни обозначени на графиката в жълто, означават 2σ статист. грешка, по-големите карета показват 2σ статист. плюс системат. грешка. Вертикалните ленти указват значенията на барионната плътност, измерена от КМФ и КН.

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

The primordially produced abundances of these elements are functions of only one parameter – the baryon-to-photon ratio **η**.

$$\eta = n_b / n_\gamma$$

$$4.7 \leq \eta_{10} \leq 6.5 \ (95\% \ \mathrm{CL})$$

$$0.017 \leq \Omega_B h^2 \leq 0.024 \ (95\% \ \mathrm{CL})$$

D measured in highredshift, low-metallicity quasar absorption systems

He in clouds of ionized hydrogen (H II regions), the most meta poor of which are in dwarf galaxies.

Pop II (metal-poor) stars in the spheroid of our Galaxy, with metallicities going down to at 10^{-4}-10^{-5} of the Solar value.

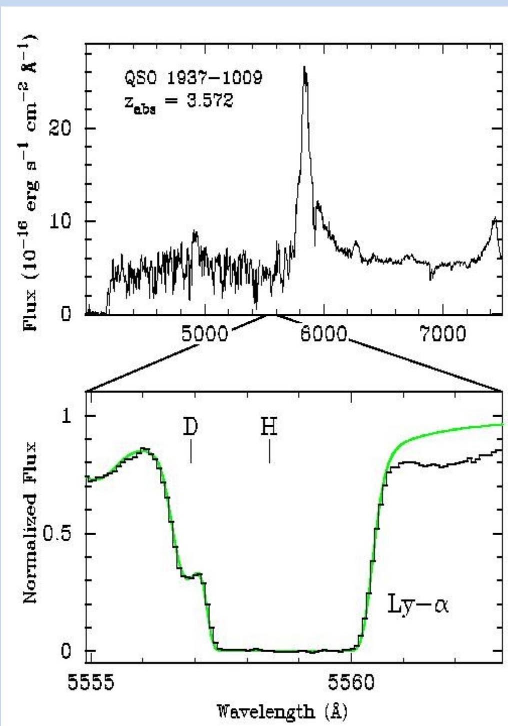
D – the most sensitive baryometer.

Contemporary Baryon Asymmetry Data

$$\beta = (n_b - n_{\bar{b}}) / n_\gamma \sim \eta = n_b / n_\gamma \sim 6.10^{-10}$$

□ is measured precisely by different independent means - BBN and CMB

D measured in high z, low-Z quasar absorption systems



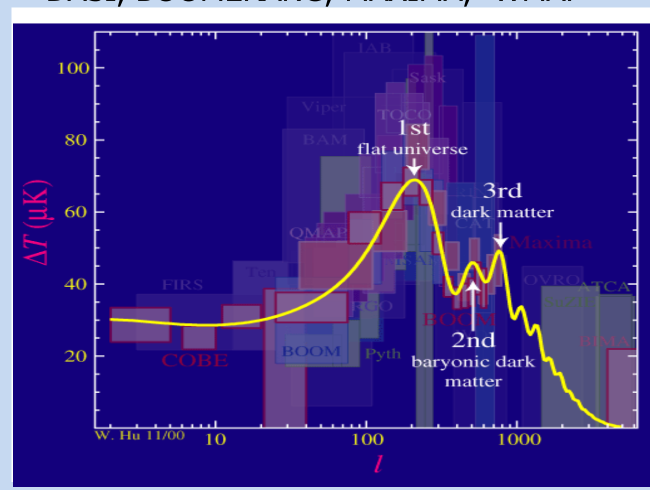
D/H=(2.87±0.2) 10^{-5}

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

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

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

DASI, BOOMERANG, MAXIMA, WMAP



$$\eta = (6.11 \pm 0.19)\times 10^{-10}$$

$$\Omega_b h^2 = 0.0223 \pm 0.0007$$

$$\Omega_b h^2 = 0.0226 \pm 0.0005$$ WMAP7

WMAP: baryons make up 4.6% of the universe (to within 0.1%)

Most of the baryons are dark (MACHOS). Baryons are negligible component:
~ 0.05 of the total density, bigger than the luminous matter (0.005), considerably less than the gravitating matter (0.3).

Where is the antimatter?

Standard cosmological model predicts equal quantities of matter and antimatter at the early stage of Universe evolution.

Now baryons are 8 orders of magnitude more than the expected from matter-antimatter symmetric early Universe. The local Universe is asymmetric.

Why the baryon-photon ratio is so BIG? Is the baryon asymmetry GLOBAL?

To explain the presence of considerable quantities of matter in the local Universe:
Models of baryogenesis? Separation of matter from antimatter?

Dolgov 99, DK , Nucl.phys.2000, DK, Chizhov, MNRAS 2000, DK, Valchanov, Panayotova 2000

Search of antimatter: BESS, MASS, CAPRICE, AMS, AMS 2 (2009), PAMELA, PEBS(2010), ..
CR data: indicate that there is not significant quantity of antimatter objects within a radius 1 Mpc.
no evidence for primary antimatter (anti p, anti nuclei) within 1 Mpc.

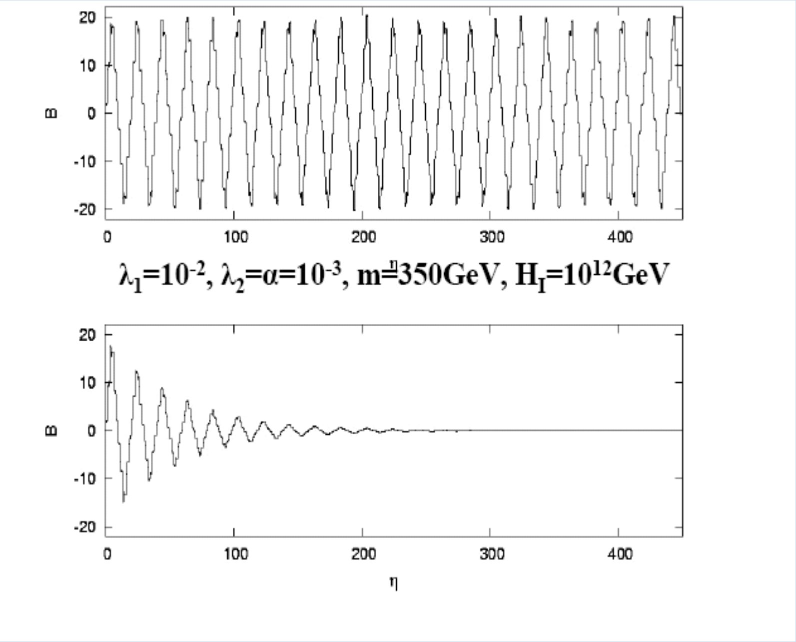
GR flux: exclude significant amounts of antimatter up to the distance of galaxy cluster scales ~ 10-20 Mpc.

At bigger distances > 10-20 Mpc, presence of antimatter is not excluded.
Small quantities of antimatter are possible even in our Galaxy:
antistars, anti globular cluster.

Steigman 79, Stecker 85

Scalar Condensate Baryogenesis

Dolgov A.,DK.,
On the Temperature of the Boson Condensate Evaporation and the Baryon Asymmetry of the Universe in the Affleck -Dine Scenario *Sov. J. Nucl. Phys.1989;*
-Production of particles by a variable scalar field
-Sov. J. Nucl. Phys., 1990.
-Baryon Charge Condensate and Baryogenesis,
-J. Moscow Phys. Soc. , 1991.



Particle creation processes play
an essential role for baryogenesis and reheating.

Chizhov M., DK.,
Generation of 128 Mpc Periodicity of the Universe in the Scalar Field Condensate Baryogenesis Scenario,
A& ApTr, 1996
Non-GUT Baryogenesis and Large Scale Structure of the Universe, *MNRAS, 2000.*
DK, Baryogenesis Model Suggesting Antigalaxies, *A& ApTr, 1998;* Baryogenesis Model predicting antimatter *Nucl. Phys. Proc. Suppl., 2003.*

DK, M.Panayotova, T.Valchanov,
Vast antimatter regions and SUSY-condensate baryogenesis, in *"Matter-Antimatter Asymmetry" 2002*

DK, M. Panayotova, The Account of Particle Creation Processes in the Scalar Condensate Baryogenesis model, *Bulg.J.Phys., 2007*

The models allow natural production of
large antimatter domains in the Universe.

Neutrino oscillations

Evidence for neutrino mixing and oscillations were obtained at the greatest neutrino experiments. Solar neutrino problem, atmospheric neutrino anomaly and the positive results of terrestrial experiments were resolved by the phenomenon of neutrino oscillations.

Recent analysis of global neutrino data within 3flavour framework: SKI+SKII+SKIII, MINOS, Kamland

Schwetz, Tortola, Valle, arXiv: 1103.0734; Mention 1101.2755

$$\delta m^2_{12} \sim (7.6 \pm 0.2)10^{-5} eV^2, \sin^2 \theta_{12} < 0.3$$

$$\delta m^2_{31} \sim (2.4 \pm 0.1)10^{-3} eV^2, \; 0.007 < \sin^2 2\theta_{13} < 0.03$$

$$\sin \theta_{23} \sim 0.5 \pm 0.06$$

Recent analysis 3+1 and 3+2 : Hint of oscillations with 2 □$_s$ with sub-eV mass
Reactor experiments+LSND+MiniBooNe+Gallium expt

Kopp, Maltoni,Schwetz, arXiv: 1103.4570

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

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Neutrino oscillations effect early Universe processes. Does cosmology allow 2 light □$_s$?
CMB, galaxy clustering and and SNIa data allow 3+2 models. *Giusarma et al. ,arXiv: 1102.4774*
BBN favour non-zero □$_s$ but BBN He and D data excludes 3+2 models.

BBN and nonequilibrium neutrino

- **Active-sterile oscillations** considerable cosmological influence
- ✓ Dynamical effect: Excite additional light particles into equilibrium δN_s

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

Fast $\nu_a \leftrightarrow \nu_s$ effective before ν_a decoupling - effect CMB and BBN through increasing □ and H

He-4 mass fraction is a strong function of the effective number of light stable particles at BBN epoch $\delta Y_d \sim 0.013\, \delta N_s$ (the best speedometer).

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

- ✓ Distort the neutrino energy spectrum from the equilibrium FD form

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

DK 88, DK&Chizhov 96

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

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

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

BBN is a sensitive probe both to additional species and to distortions in the energy distribution of neutrinos.

BBN stringent limits on oscillation parameters.

DK&Chizhov 98,2000, Dolgov&Villante 03, DK&panayotova, 2006, DK07

Oscillations –medium influence

- Medium suppresses the oscillations amplitude
- Medium may enhance them
- Negligible spectrum distortion ?

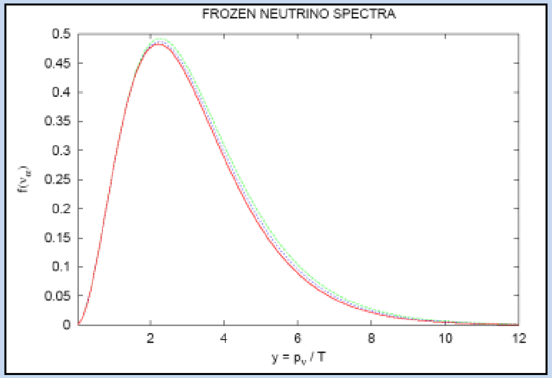
(work with particle densities and T shift; one momentum approximations.)

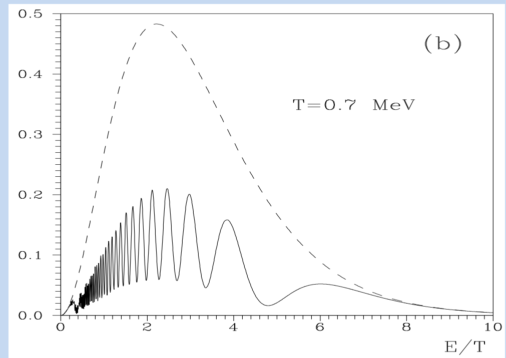
-Fast oscillations equilize pre-existing asymmetries

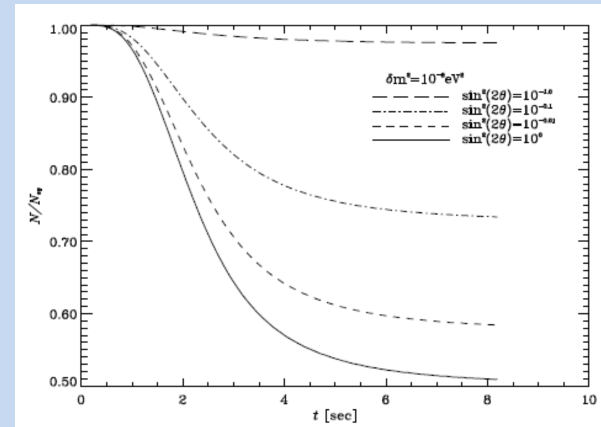
- Oscillations cause great spectrum distortion, asymmetry growth

Persists, and is often the leading effect , hence it should be precisely described!

- Active-sterile oscillations proceeding after decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$
  major effect - distortion of neutrino energy spectrum and depletion of electron neutrino.







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

$N_e < N_{eq}$

2 neutrino mixing: Sterile state is filled for the sake of ν_e

4 neutrino mixing: ν_e is partially re-filled for the sake of muon and tau neutrino

$\delta N_{k,4} < \delta N_{k,2}$ Flavor mixing decreases the depletion and spectrum distortion

Precise description of neutrino momenta distribution is needed: 1000 bins used to describe it in non-resonant case, and up to 10 000 in the resonant case.

Energy spectrum distortion caused by oscillations depends on the level of initial population of ν_s.

The interplay b/n effects

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

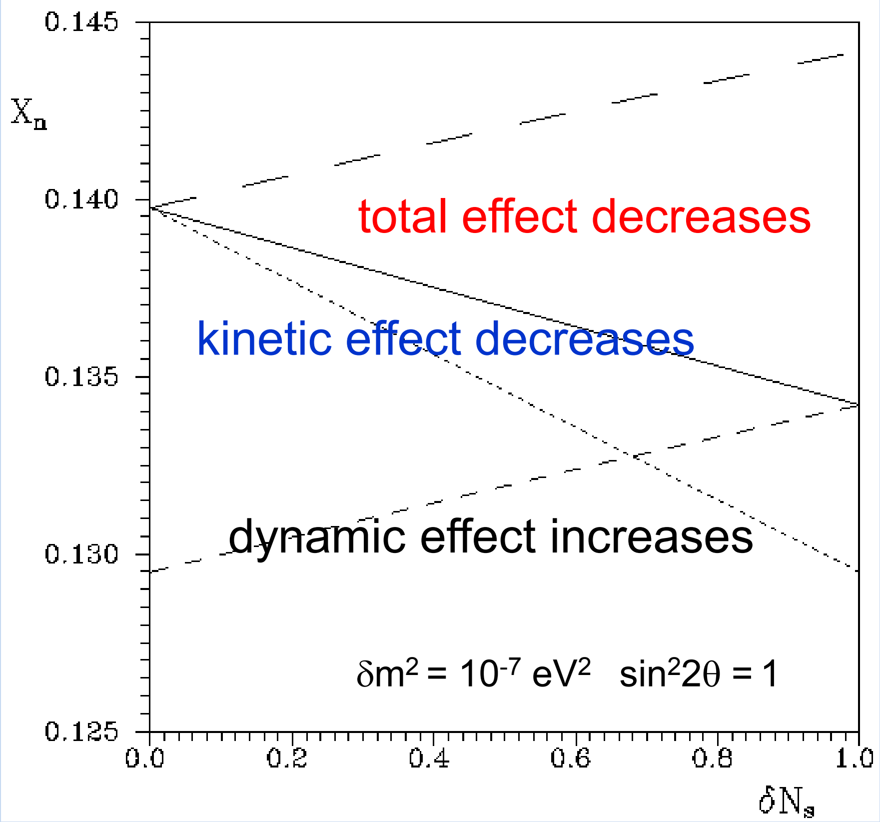
$\delta N_{k,0} > 1$ $\delta N = \delta N_{k,0} - \delta N_{k,0}\, \delta N_s + \delta N_s$

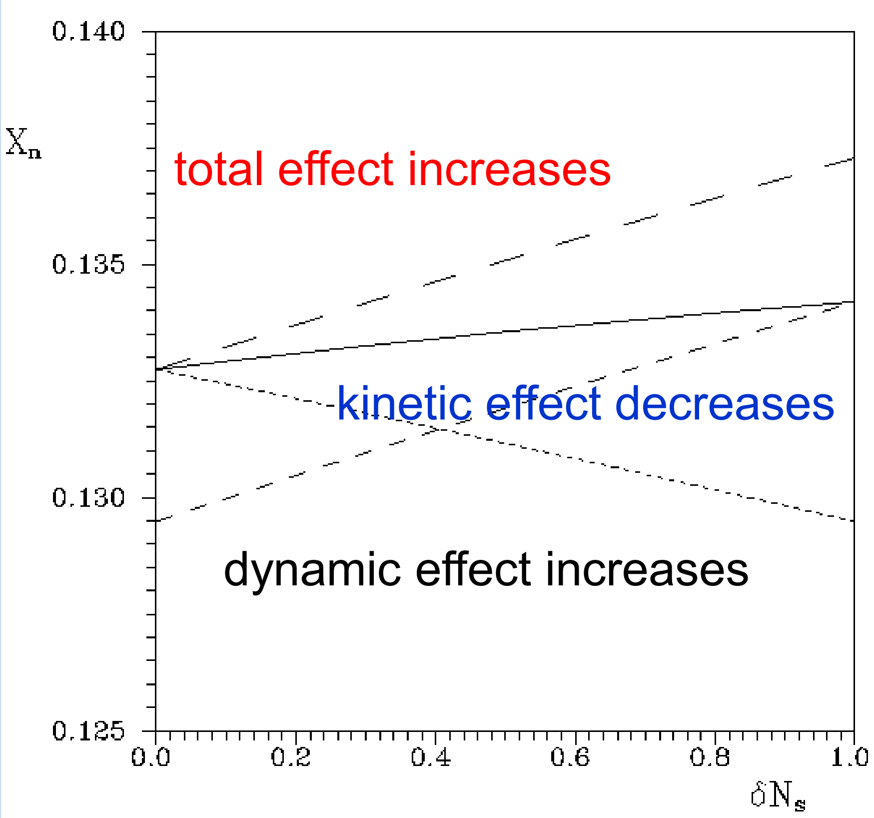
$\delta N_{k,0}\, \delta N_s > \delta N_s$

$\delta N_{k,0} < 1$ $\delta N = \delta N_{k,0} - \delta N_{k,0}\, \delta N_s + \delta N_s$

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

DK, IJMPD04,07

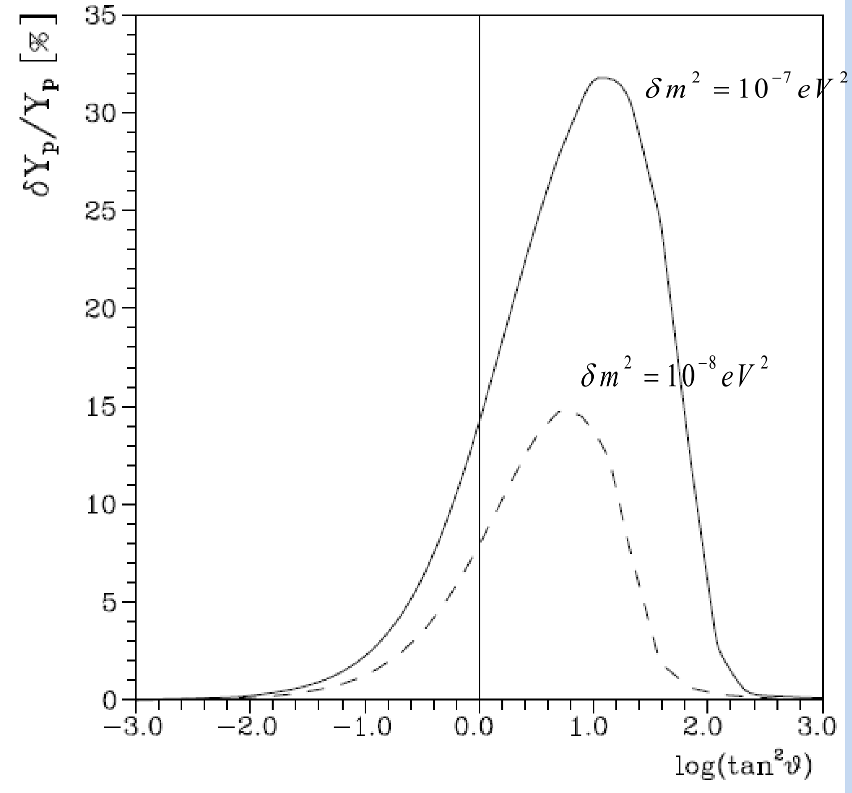




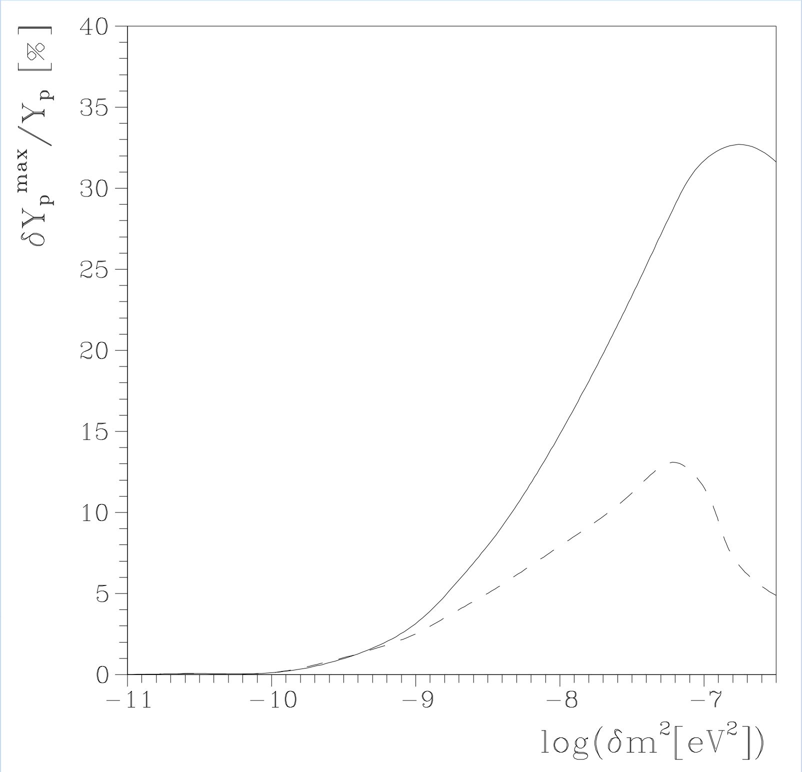
The kinetic effects of oscillations depend on the initial population of the neutrino.

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

Dependence of max overproduction on mixing



Max overproduction on mass difference

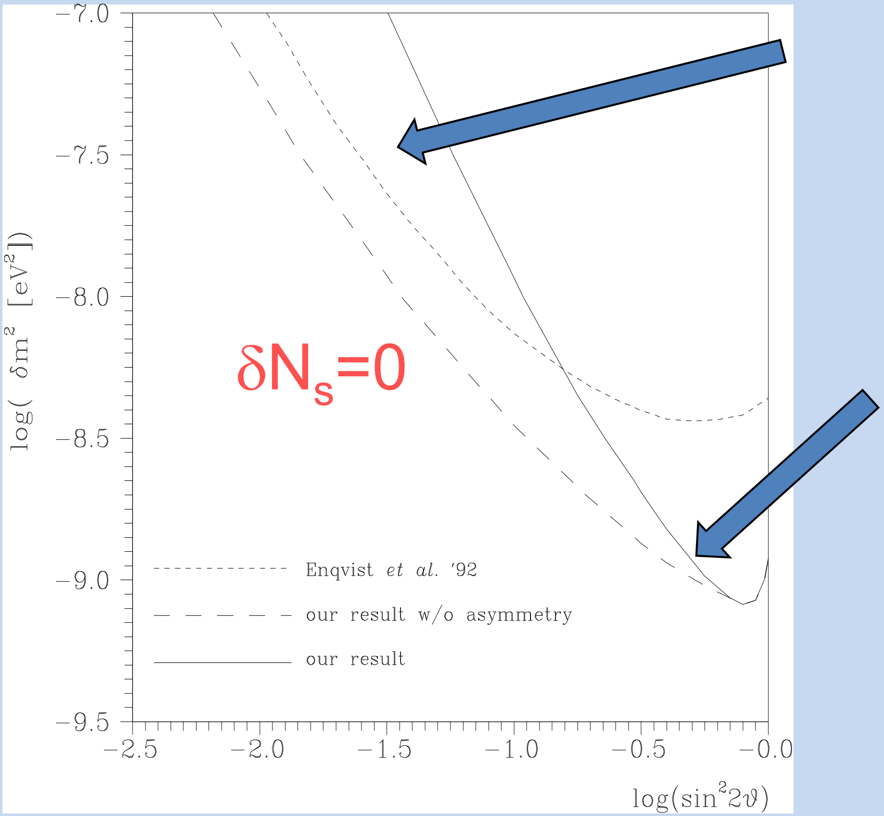


DK, Astrop.Phys.,2003

For BBN with $n_e \leftrightarrow n_s$ 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.

BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ allows to constrain ν oscillation parameters for He-4 uncertainty up to32% (14%) in resonant (non-resonant) case.

Distortion reflected on BBN constraints



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

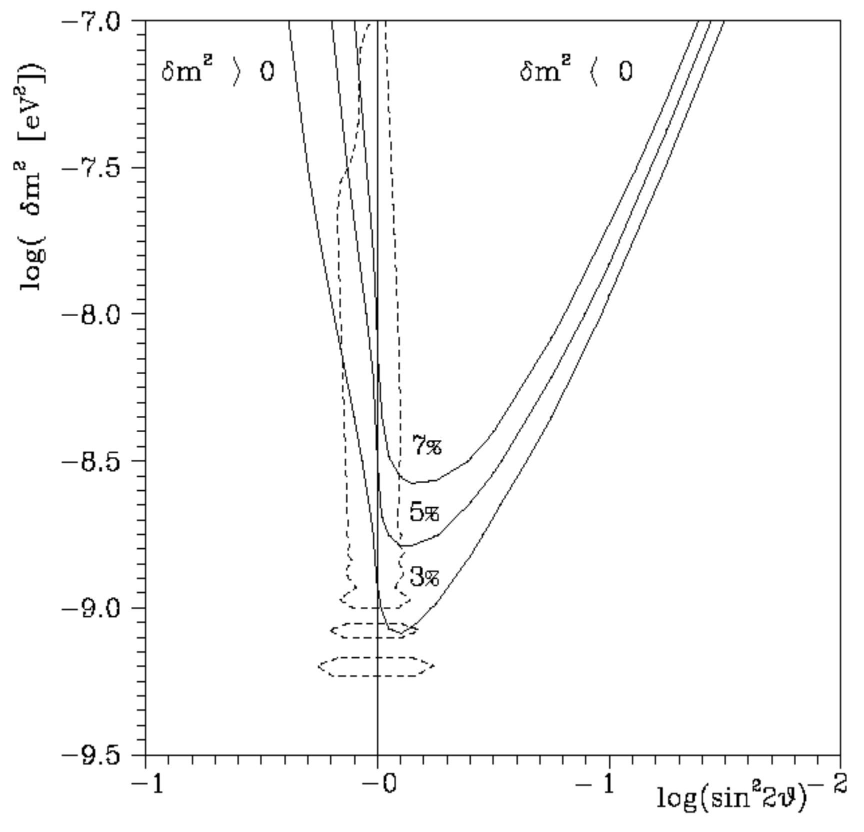
- The spectrum distortion leads to a decrease of the weak rates, to an increase of the n/p freezing T and He overproduction. Correspondingly the account of spectrum distortion leads to strengthening of BBN constraints at large mixings.

BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillation parameters

He-4 is the preferred element:

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

  $Y_p = 0{,}2482 \pm 0{,}0007$
- ✓ has a simple post-BBN chemical evolution
- ✓ best speedometer and leptometer
- ✓ sensitive to neutrino characteristics (n, N, sp,LA..)



Fit to BBN constraints ($\delta Y_p/Y_p$=3%) at smaller δm^2 (re-population of active neutrino slow, spectrum distortion considerable) :

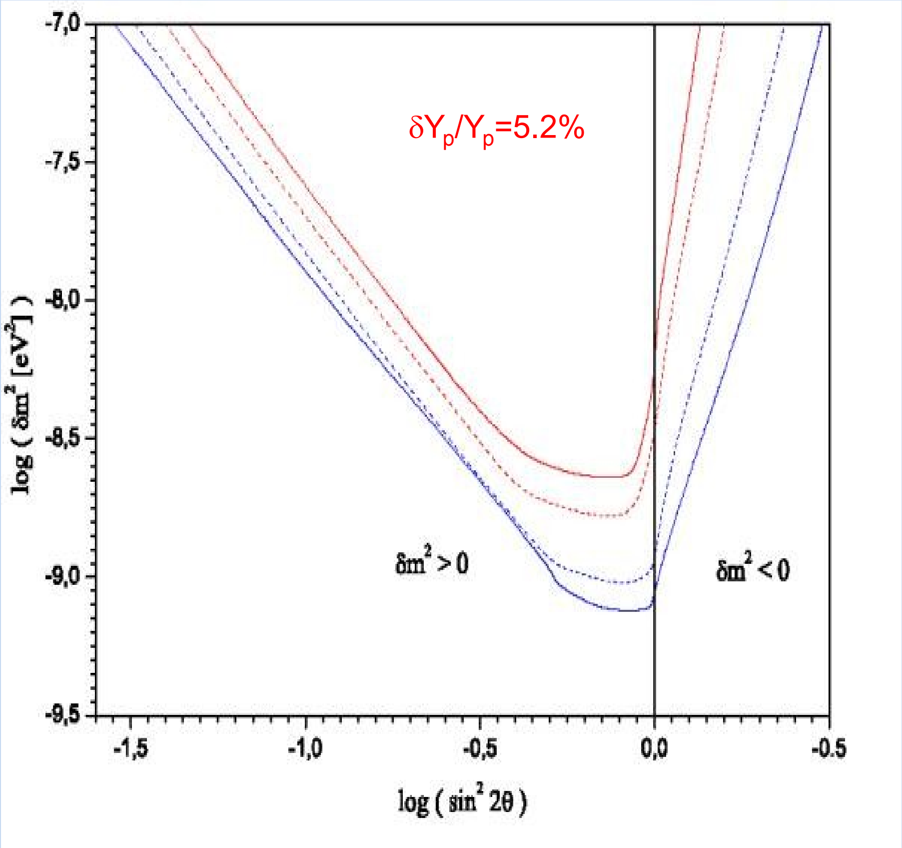
$$\delta m^2 \left(\sin^2 2\theta\right)^4 \leq 1.5\times 10^{-9}\, eV^2 \quad \delta m^2 > 0$$

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

DK, Chizhov NPB2000,2001

BBN constraints relaxed or strengthened?

Additional ν_s population may strengthen or relax BBN constraints.



DK&Panayotova JCAP 2006;DK IJMPD 07

Y_p=0,2565 ± 0.001(stat)± 0,005(syst)

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

✓Y_{th}=0,2482± 0,0007

Due to interplay b/n the effects of non-zero initial population of ν_s 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.

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

3+2 Neutrino oscillations

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Schwetz, Tortola, Valle, arXiv: 1103.0734; Mention 1101.2755

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BBN and Lepton Asymmetry

Lepton asymmetry of the Universe

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

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

$$\xi = \mu / T$$

may be orders of magnitude bigger than the baryon one, $\beta = (n_b - n_{\bar{b}}) / n_\gamma \sim 6.10^{-10}$

Though usually assumed L~□, big LA may reside in the neutrino sector (universal charge neutrality implies L_e=□).

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

CNB has not been detected yet, hence LA may be 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

LSS, etc.

Lepton Asymmetry Effects

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

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

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

leading to faster expansion H=(8/3□G□)$^{1/2}$, 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

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

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

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

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 □ 10^{-7} effects neutrino evolution, its number density, spectrum distribution, oscillations pattern and hence n/p kinetics and BBN

DK&ChizhovNPB98,2000;DK PNPP, 2010

- LA changes the decoupling T of neutrino

Lepton Asymmetry Constraints

- At present BBN provides the most stringent constraint on L $|\xi_{\nu_{\mu,\tau}}| < 1.5$ $|\xi_{\nu}| < 0.1$ in case of combined variation of chemical potentials

In case of neutrino oscillations degeneracies equilibrate due to oscillations before BBN

Dolgov et al., NPB, 2002 $|\xi_{\nu}| < 0.1$ *Serpico&Raffelt,2005* $-0.04 < \xi_{\nu} < 0.07$

Serpico, Pinto&Raffelt θ_{13} role $\xi_{\nu_e} \neq \xi_{\nu_\mu} = \xi_{\nu_\tau}$: $\xi_{\nu} < 2.3$ $L < 5$

Simha&Steigman, JCAP, 2008 $\xi_{\nu_e} = \xi_{\nu_\mu} \neq \xi_{\nu_\tau}$: $\xi_{\nu\tau} < 4$ $L < 7.6$

$\xi_{\nu_e} = \xi_{\nu_\mu} = \xi_{\nu_\tau}$: $|\xi_{\nu}| < 0.1$ $L \sim 0.07 \mp$

- CMB and LSS provide much looser bounds

Asymmetry - Oscillations Interplay
Lepton Asymmetry Generation

- Oscillations in a medium are capable to suppress pre-existing asymmetry
  Barbieri&Dolgov ,90.91; Enqvist et al.,1992
- Asymmetry is capable to suppress oscillations
  Foot&Volkas, 95; DK&Chizhov , NPB 98
- LA can enhance neutrino oscillations
  DK&Chizhov , NPB 98
- LA may be generated by MSW resonant neutrino oscillations in the early Universe in active sterile oscillations

LA generation possibility in MSW resonant neutrino oscillations in the early Universe in active sterile oscillations was first found

$\delta m^2 > 10^{-5} eV^2$ in collisions dominated oscillations *Foot&Volkas 96*

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

L-T=M

-L-T=M

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

Interplay between small LA and neutrino oscillations in the early Universe and their effect on BBN for the specific case:

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

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

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

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

LA effect in density and direct effect in n-p kinetics – negligible

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

- Different cases of LA were studied:

  initially present and dynamically generated by oscillations.

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

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

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

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

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

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

$\boldsymbol{H}_0$ *is free neutrino Hamiltonian*

$Q \sim E_\nu T \qquad L \sim 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} \qquad L_{\nu_e} \sim \int d^3 p \left(\rho_{LL} - \bar{\rho}_{LL} \right) / N_\gamma$ $\qquad g_{eff} = 10.75 + \frac{7}{4} \delta N_s \qquad \delta N_s = N_\nu - 3$

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

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

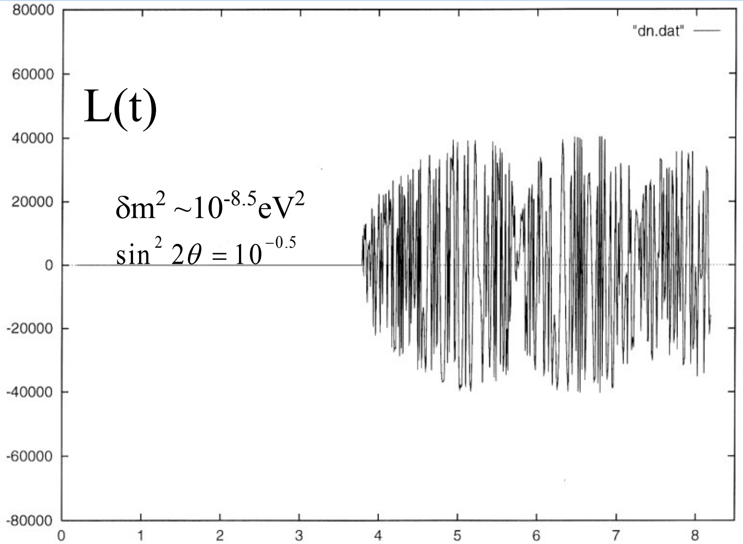
Oscillations generated LA and BBN

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

The region of parameter space for which large generation of LA is possible:

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

Generation of LA up to 5 orders of magnitude larger than □ is possible, i.e. L□10^{-5}



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

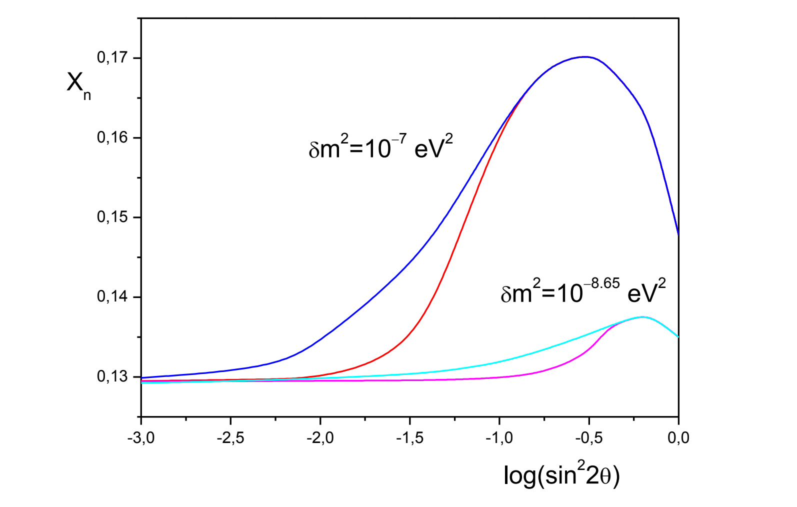
$$\frac{\partial n_p}{\partial t} = Hp_n \frac{\partial n_n}{\partial p_n} + \int d\Omega(e^-, p, \nu) \left| A(e^- p \to \nu n) \right|^2 (n_{e^-} n_p - n_n \rho_{LL})$$

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

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

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

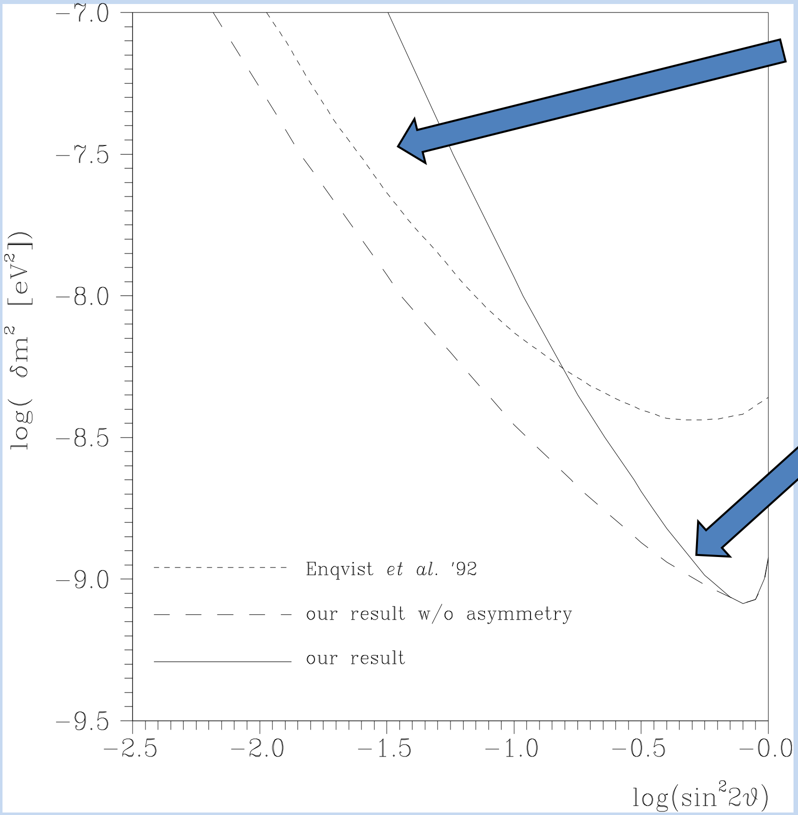
X_n and correspondingly the primordially produced He-4 decreases at small mixing parameters values due to asymmetry growth.



DK, PNPP,2010; 2011

Effect of oscillations generated LA 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.

Initial LA and BBN with oscillations

L >10^{-7} may considerably influence BBN:

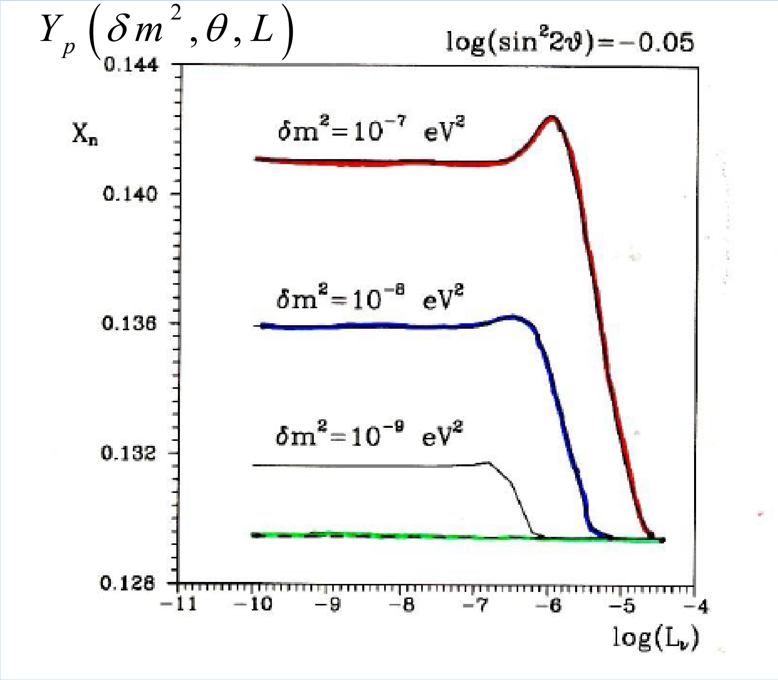
L ~10^{-7} enhances oscillations, while

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

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

Small 10^{-7} <L<<0.01, not effecting directly BBN kinetics, influence *indirectly* BBN via oscillations.

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



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

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

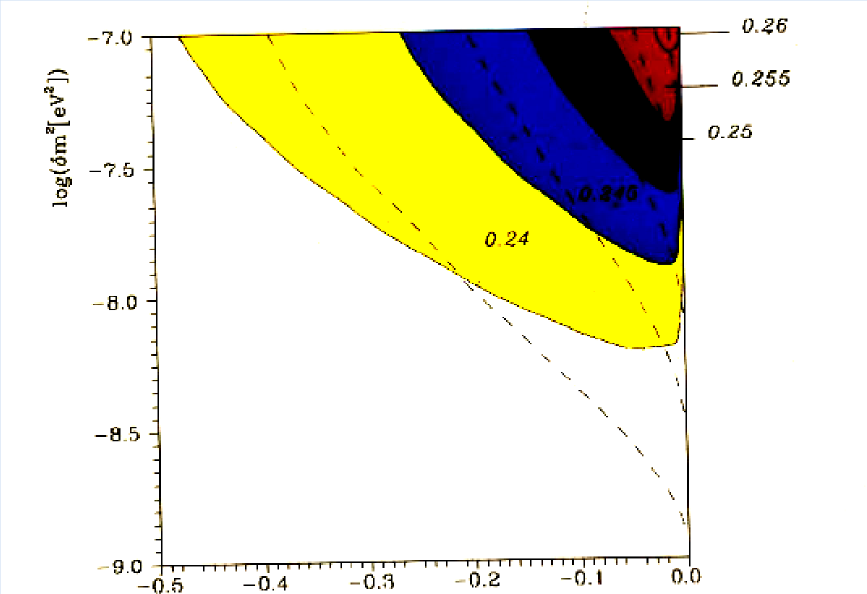


Fig. 4

In the last case, instead, the following approximate bound holds:

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

BBN Summary

Spectrum distortion plays a major role in the influence of neutrino oscillations on BBN.

For oscillations after neutrino decoupling it leads up to 6 times higher helium overproduction than the dynamical effect of an additional neutrino state.
Distortion decreases with the increase of the initial population of the sterile neutrino, the kinetic effect decreases correspondingly.
Helium may be both overproduced or underproduced with the increase of the initial population of ν_s depending which effect dominates (dynamical or kinetic).
Additional partially filled sterile state may lead to strengthening as well as to relaxation of the BBN constraints.

BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ oscillations allows to put constraints on ν oscillation parameters for He-4 uncertainty up to 32%(14%) in resonant (non-resonant) case, provided ν_s was not in equilibrium, which corresponds to N<9.

At large mixing BBN constraints strengthen by orders of magnitude when distortion effect of oscillations is accounted for, at small mixings they are relaxed due to oscillations generated asymmetry in the resonant case.

Flavor mixing account will lead to a decrease of the spectrum distortion effect and relaxation of the constraints.

LA Summary

- Effective lepton asymmetry generation mechanism in active-sterile Mikheyev-Smirnov-Wolfenstein oscillations exists, able to produce LA by orders of magnitude bigger than BA.
- Small lepton asymmetry LA << 0.01, either relic or generated by active-sterile neutrino oscillations, may have considerable cosmological influence. In particular LA as small as 10^{-7} may be felt by BBN through neutrino oscillations.
- Lepton asymmetry is able to enhance, suppress or inhibit oscillations.
- LA provides relaxation or enhancement of BBN constraints on oscillations.

  It relaxes BBN bounds at large mixing and strengthens them at small mixings.

  Large enough LA alleviates BBN constraints on oscillation parameters.

  Dynamically generated asymmetry relaxes BBN constraints at small mixing angles.

  2+3 oscillations models may be allowed by BBN with L.

✓ The indications of additional relativistic density - additional light particles, LA , etc. ..

$N_{BBN}=3.8+0.8-0.7$ $N_{CMB}=4.34+0.9-0.9$ $N_{SDS}=4.8+1.9-1.8$

might point to LA, additional sterile neutrino states

Conclusions

The problem of BA of the Universe is still fascinating. Though baryon density is measured with a high accuracy today, the exact baryogenesis mechanism is not known. The possibility for astronomically large antimatter objects is experimentally and theoretically studied.

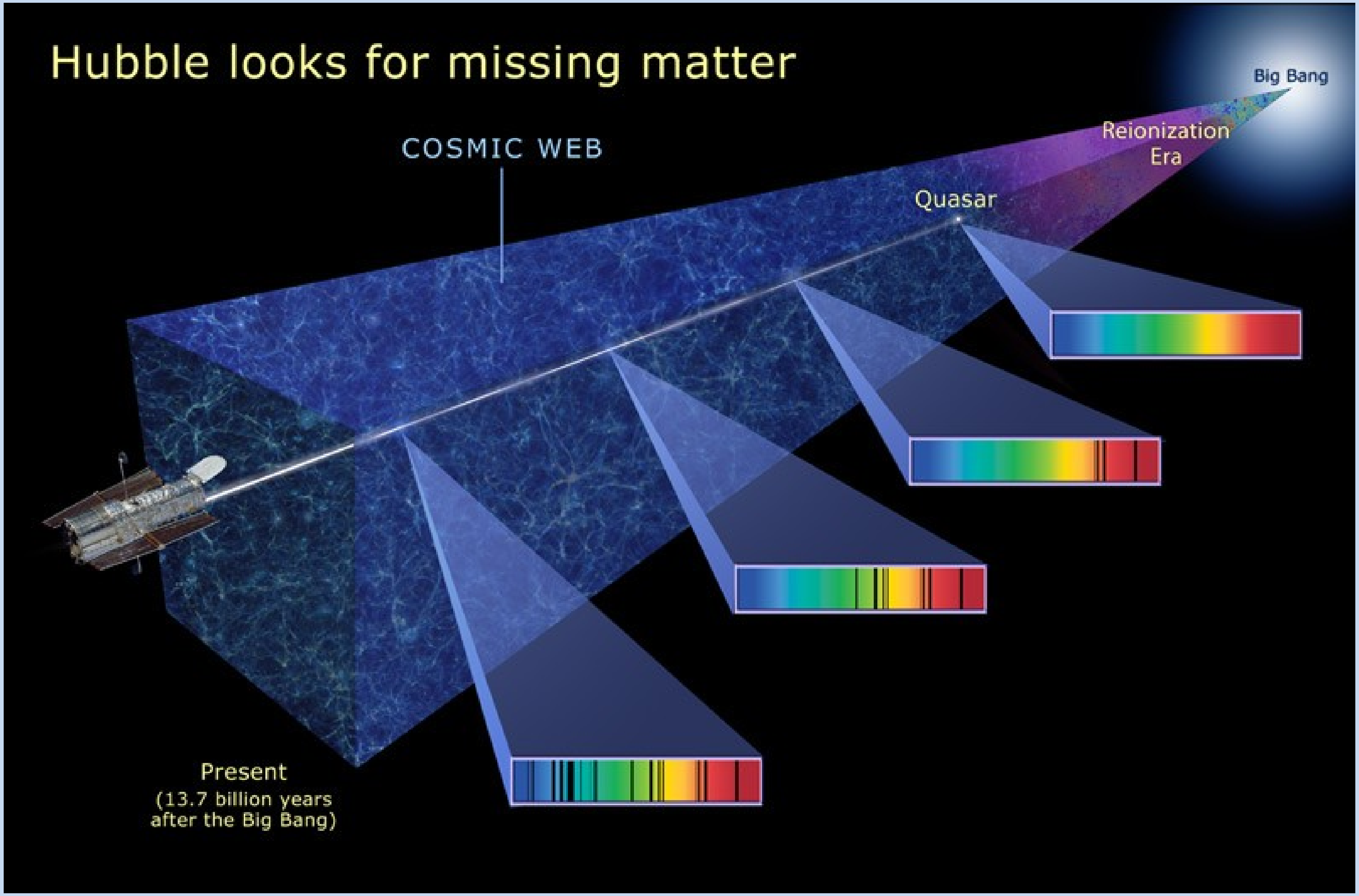
Besides being very accurate baryometer, BBN depends strongly on the expansion rate and on the lepton asymmetry of the Universe - it is the best speedometer and leptometer. Hence, It is the most sensitive cosmological probe of number of neutrino species, of distortions in the energy distribution of neutrinos, lepton asymmetry, neutrino mass differences and mixings, etc. It provides constraints on many neutrino characteristics.

Active-sterile oscillations may considerably distort neutrino spectrum and produce neutrino-antineutrino asymmetry.

BBN constraints on neutrino oscillation parameters depend nontrivially on the lepton asymmetry.

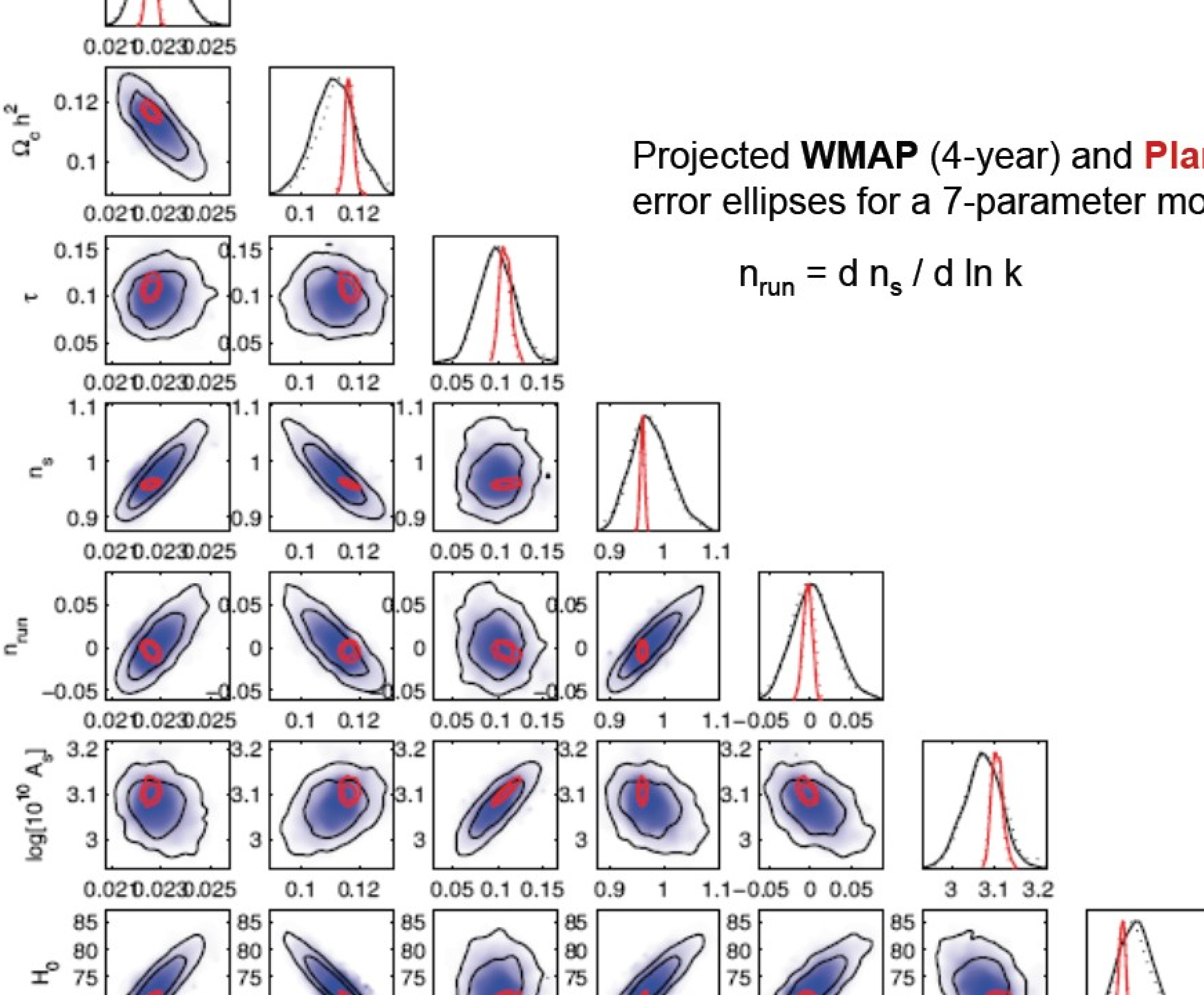

Благодаря за вниманието!
Thanks for the attention!

Half of the dark baryons are in the intergalactic space



В спектрите получени от светлината от далечни квазари са намерени абсорбционни спектрални линии на барионното вещество, което поглъща на определена честоти. По този начин получаваме картина на структурата на междугалактичното пространство.

Наблюдения на космичния телескоп Hubble Space Telescope с далечния ултравиолетов спектроскоп (Far Ultraviolet Spectroscopic Explorer) в посока на далечни 28 квазари представящи най-детайлните наблюдения на междугалактичната среда до 4 млрд ly .



Projected **WMAP** (4-year) and **Planc** error ellipses for a 7-parameter mode

$$n_{run} = d\, n_s \,/\, d \ln k$$

Уточняване на характеристиките на РНФ

	$T^{\gamma}_{fin} / T^{\gamma}_{0}$	$\delta\rho_{\nu e}$(%)	$\delta\rho_{\nu\mu}$(%)	$\delta\rho_{\nu\tau}$(%)	N_{eff}
Мигновенно излизане от ТДР	1.40102	0	0	0	3
СМ	1.3978	0.94	0.43	0.43	3.046
+3ν смесване (θ_{13}=0)	1.3978	0.73	0.52	0.52	3.046

ΔN_{eff} ~ 3 (WMAP)

ΔN_{eff} ~ 0.2 (Planck)

Dolgov, Hansen & Semikoz, NPB 503 (1997) 426
Mangano et al, PLB 534 (2002) 8; NPB 729 (2005) 221

Bowen et al MNRAS 2002

Неутринната енергийна плътност днес (3 еднакви маси)

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{3m_0}{94.12 h^2 \ \text{eV}^2} \quad \Rightarrow \quad \Omega_\nu = \frac{3m_0}{93.14 h^2 \ \text{eV}^2}$$

Плътност на частиците

$$n_\nu = 335.7 \ \text{cm}^{-3} \quad \Rightarrow \quad n_\nu = 339.3 \ \text{cm}^{-3}$$

Реликтовото неутрино днес е най-многобройната ча**с**тица след КМФ фотони.

WMAP 7

January 26, 2010

- Детектиран първичен He , пред-звезден произход (+ACBAR +QUaD експерименти)
- Потвърждение на инфлационни предсказания – флуктуациите на големи мащаби са по- интензивни от тези на малки
- Независими (КМФ+ H baryon acoustic oscillations) указания за природата на ТЕ – най-добро съотвествие с Λ; плоска геометрия с точност 1%. (без данни от свръхнови)
- $\omega = -1.1 \pm 0.14$; при -1 геометрията е плоска с точност -0.77% +0.31%
- WMAP + H + LSS ограничения върху броя на типовете неутрино :

  $N_\nu < 4.34 \pm 0.87$. (стандартния модел : 3.04)
- Детектирани са Т флуктуации (намаляване на Т по направление на купа) на КМФ от горещ газ в галактиките, в резултат на взаимодействие на КМФ с газа.
- Наблюдаваната поляризация около студени или топли зони следва предсказаното теоретично поведение от СКМ.

Why explore LA ?

- ✓ Knowledge about LA helps to determine the cosmological parameters

- ✓ There exist cosmological evidence about the presence of additional relativistic density - additional light particles, LA , etc. ..

  N_{BBN}=3.8+0.8-0.7 N_{CMB}=4.34+0.9-0.9 N_{SDS}=4.8+1.9-1.8

- ✓ Combined neutrino oscillations data (including MiniBoone and LSND) require 1 or 2 additional sterile neutrino. Active-sterile oscillations may generate LA.

- ✓ LA provides relaxation or enhancement of BBN constraints on oscillations.