Recent Developments in
Astronuclear and Astroparticle Physics

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On Big Bang Nucleosynthesis, Neutrino Oscillations and Lepton Asymmetry

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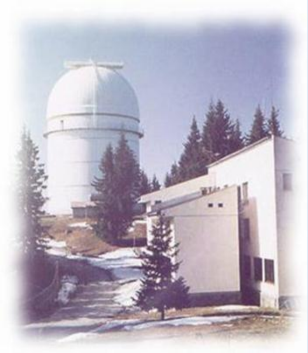


Outline

Relic Neutrinos

- CNB formation, characteristics
- Neutrino oscillations and CNB

BBN the Best Early Universe and SMP Test

- BBN and neutrino oscillations
- BBN and L
  - L comological effects and BBN limits
  - Leptogenesis by neutrino oscillations
  - BBN with neutrino oscillations and L

Relic Neutrino

Decoupling. Characteristics expected.

CNB Formation

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi\, G_{\rm N}\, \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}\,,$$

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_{\rm N}}{3}\,(\rho + 3p)\,,$$

T>1 MeV

$T_\nu = T_e = T_\gamma$

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

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

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

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

At RD stage neutrinos are important component, influence considerably H, n-p kinetics, etc.

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

T ~1 MeV

As the Universe cools the rate of interaction decrease and could no longer keep neutrino in equilibrium.

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

$T_{dec}(\nu_e) \sim 2$ MeV

$T_{dec}(\nu_{\mu,\tau}) \sim 3$ MeV

$T \sim m_e$, $e^+ e^- \to \gamma\gamma$

$T_\nu = (4/11)^{1/3}\, T_{cmb}$

$f_\nu(p,T) = \frac{1}{e^{p/T_\nu} + 1}$

$N_\nu = 3.046$ not 3 because of partial heating and oscillations account. Dolgov, Hansen & Semikoz, 1997 Mangano et al,;

$N_\nu = 2.984 \pm 0.008$ (LEP)

$T_0 \sim 2.7$ K RELIC NEUTRINO BACKGROUND

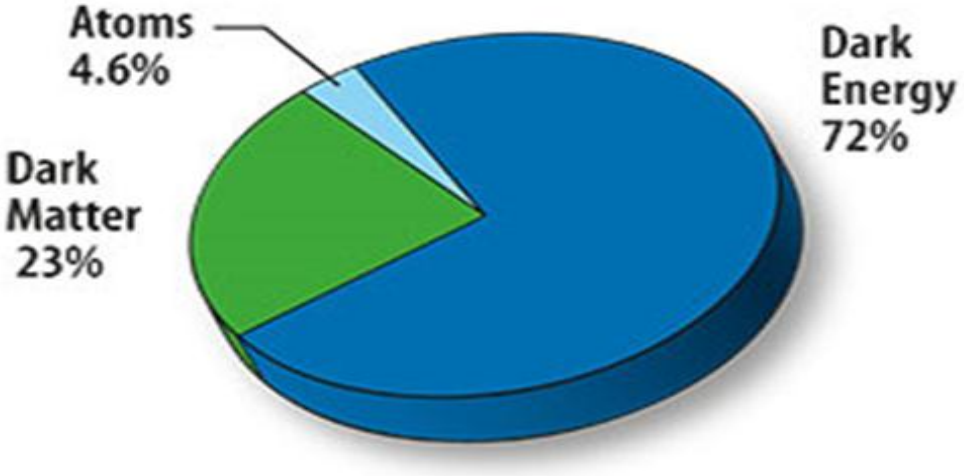
$T_{\nu\,0} \sim 1.9$ K.

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

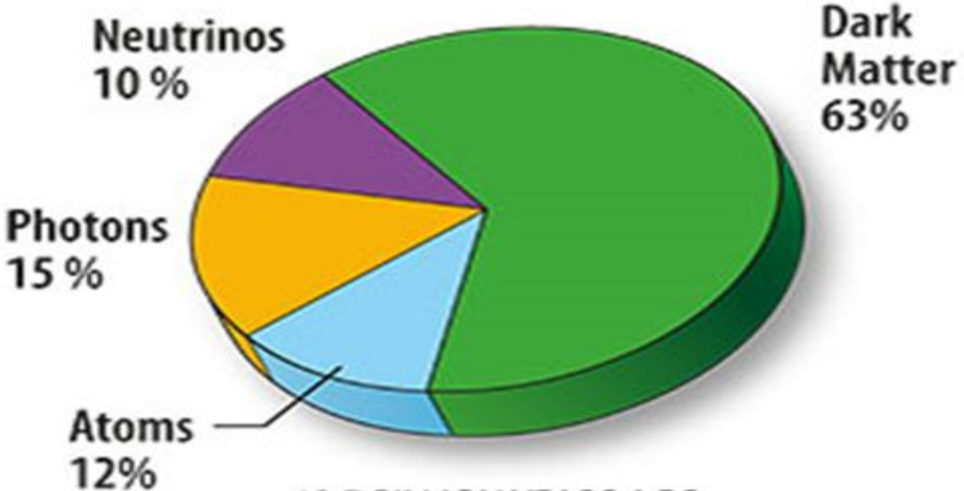
$n_\nu = 112\ \mathrm{cm}^{-3}$ $n_{cmb} = 411\ \mathrm{cm}^{-3}$

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

Neutrinos from CNB are expected to be the most numerous particles after CMB photons.



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

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 relic neutrinos today.

$$n_\nu = 339.3 \text{ cm}^{-3} \qquad \Omega_\nu = \frac{3m_0}{93.14h^2 \text{ eV}} \qquad 0.001 < \Omega_\nu < 0.02$$

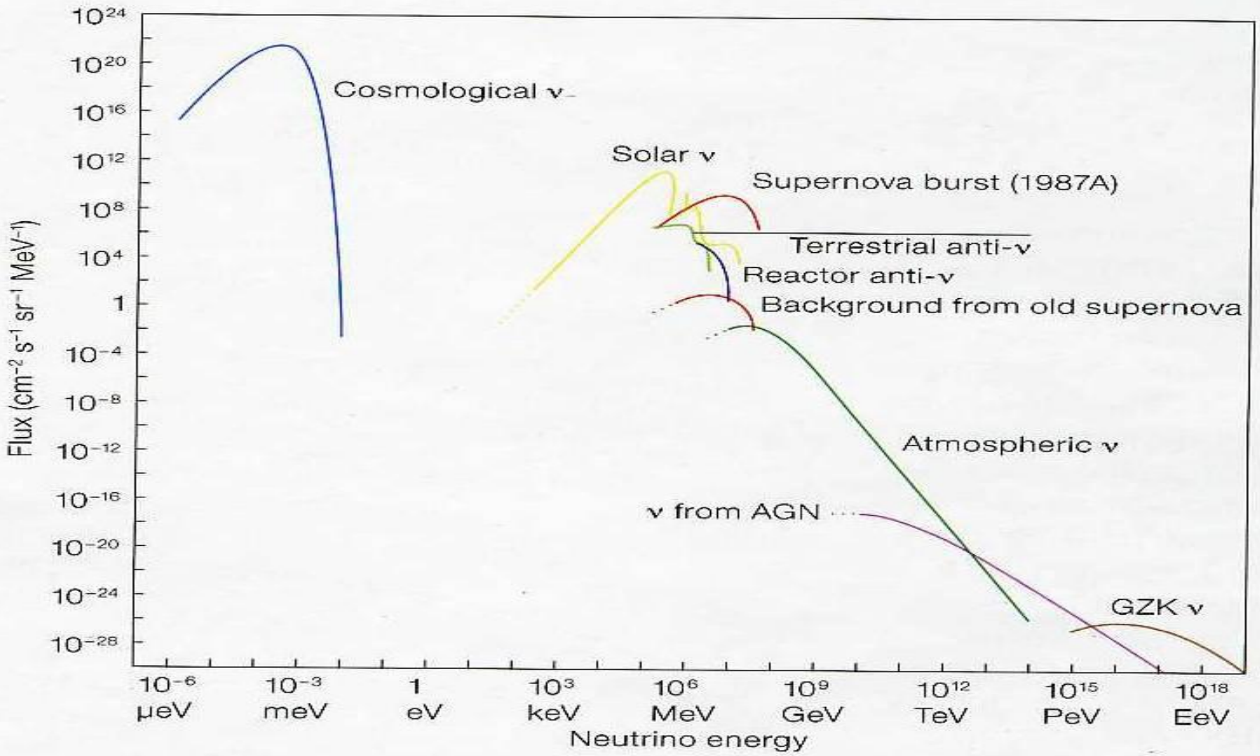


Figure 2: The 'grand unified' neutrino spectrum.

Figure from ASPERA roadmap

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*).

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

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

Effective number of relativistic neutrino species

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

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

Neutrinos Oscillations

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

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

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

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

- ✓ non-zero neutrino mass and mixing
- ✓ Distribution n(E) of neutrino may differ from the equilibrium FD form

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

$$N_e < N_{eq}$$

- ✓ L may become considerable

  in resonant active-sterile oscillations

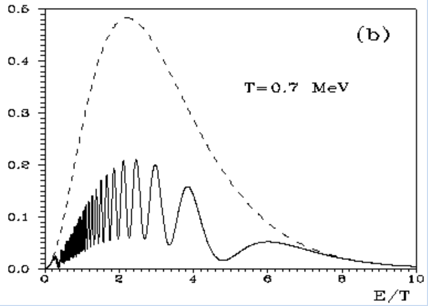
$\delta m^2 \neq 0$ ⟹ at least 2 neutrino with $m_\nu \neq 0$

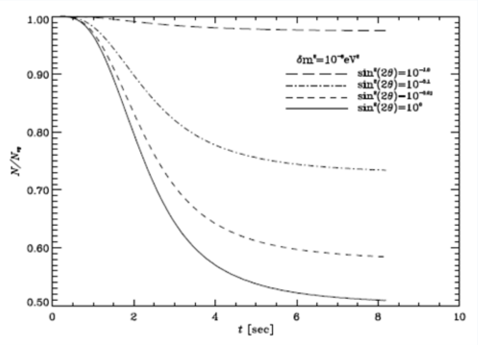
$$\Omega_\nu = \frac{3m_0}{93.14h^2\ \text{eV}} \qquad \boxed{0.001 < \Omega_\nu}$$

Flavor neutrino should not play an important role for DM (because it is HDM) and the formation of structure.

$$\boxed{0.001 < \Omega_\nu < 0.02}$$

Eventual sterile neutrino may be a good DM representative (CDM, WDM).





Propagation of neutrino in early Universe

- The thermal background of the early Universe influences the propagation of ν.

Differences in the interactions with the particles from the plasma lead to different average potentials for different neutrino types V_f f= e, μ, τ

Notzold&Raffelt 88

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

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

$V_f = Q\dots$ $+L\dots\dots\dots$ for antineutrino

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

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

In the adiabatic case the effect of the medium can be hidden in matter oscillation parameters: $\sin^2\theta_m = \sin^2\theta/[\sin^2\theta + ((Q/M^2_W \pm L)T^3/\delta m^2 - \cos 2\theta)^2]$

In general the medium suppresses oscillations.

When $(Q/M^2_W \pm L)T^3 = \cos 2\theta \delta m^2$ mixing in matter becomes maximal independent of mixing in vacuum - enhanced oscillation transfer.

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

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*

Kirilova&Chizhov 96; Foot&Volkas 96 *-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*

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

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

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.

Neutrinos in the Universe:

Effect the energy density
expansion rate
of the Universe

Constraints on number
of neutrino species

Matter/radiation equality shift

Constraints on neutrino masses
and number densities < 0.6 eV

DM candidate

Effect BBN kinetics

Spectrum distortion
asymmetry constraints

Constraints on
oscillation parameters
Constraints on
sterile neutrino population

Effect on CMB and LSS

Feel total energy density
stored in neutrinos

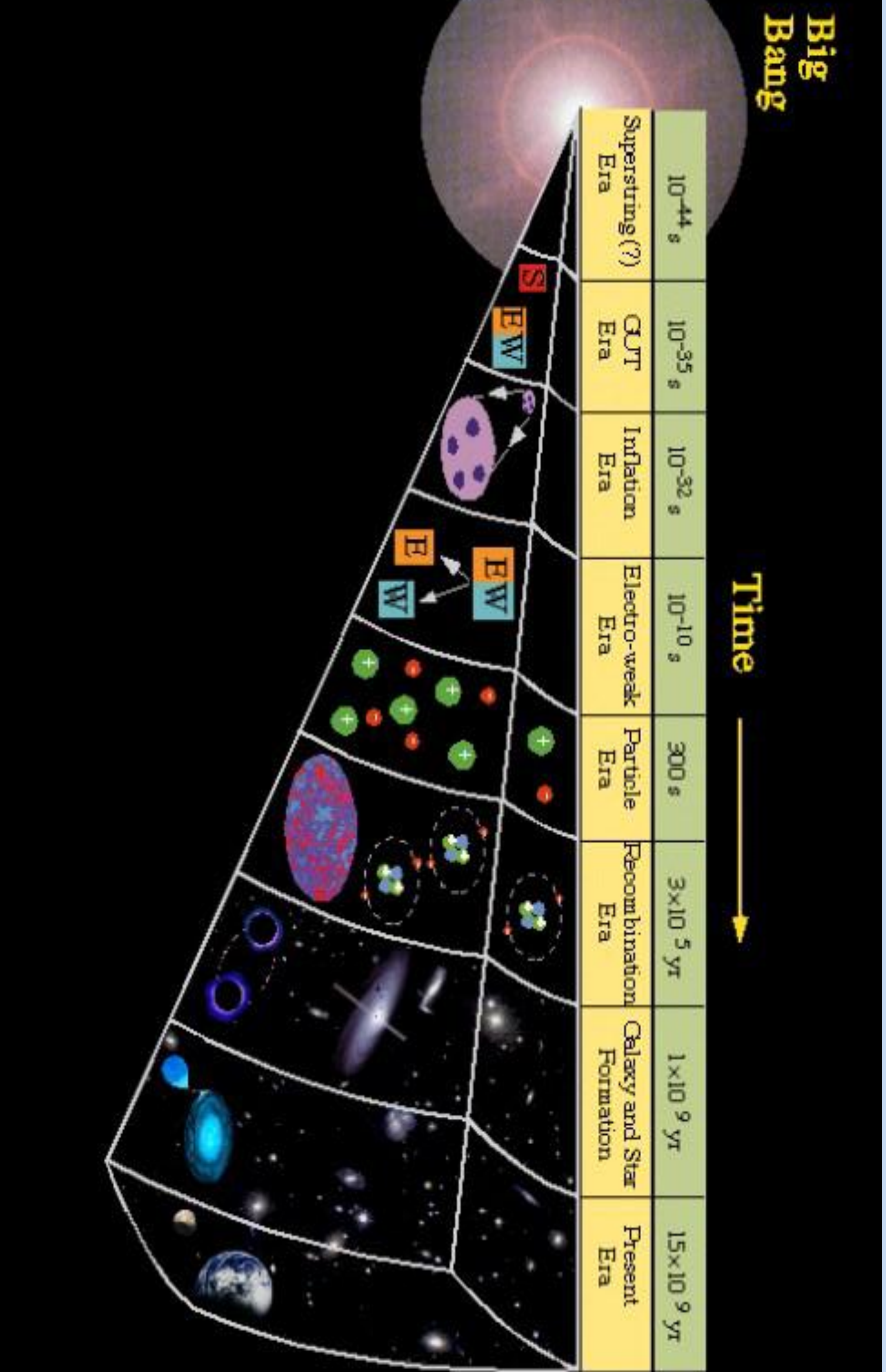
Constraints on neutrino masses
Constraints on lepton asymmetry

not sensitive to different species
or spectrum distortions

baryogenesis through
leptogenesis

BBN and Neutrino

UNIVERSE HISTORY



Processes	cosmic time	T
GUT	10^{-35} s	10^{15} GeV
Inflation		
BA generation		
EW symmetry breaking	10^{-10} s	100 GeV
QCD	10^{-5} s	0.3 GeV
CNB formation	1 s	3 - 1 MeV
BBN	1 s – 3 m	1 - 0.1 MeV
CMB formation	300 000 y	0.3 eV
Galaxy formation	~10^{9} y	
Today	13.7 10^{9} y	0.0003 eV ~ 3K

BBN - a milestone of Big Bang cosmology

$$H_0, q_0, \Omega_i(\Omega_0, \Omega_\Lambda, \Omega_M, \Omega_B, \Omega_\gamma, \Omega_\nu, \ldots), t_0, T_0, P(k), C_l$$

- Homogeneity and isotropy and structures in the Universe
- The expansion of the Universe
- The abundances of the light elements

The light elements abundances provide evidence for a hotter and denser early Universe, when these elements have been fused from protons and neutrons. Point to non-baryonic DM.

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

- The cosmic microwave background radiation

Effects of CNB on BBN, CMB, LSS – indirect detection of the CNB and indication about RD stage

Primordial Nucleosynthesis

George Gamow

1904 – 1968

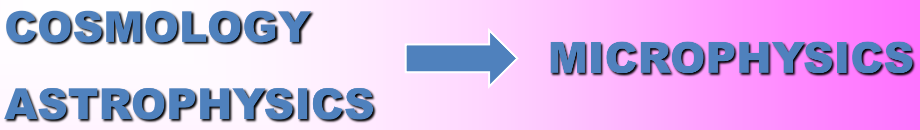
In 1946–1948 develops BBN theory.

Theoretically well established

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

Precise data on D, He, Li

Baryon fraction measured by CMB



COSMOLOGY

ASTROPHYSICS

MICROPHYSICS

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

The Abundances of Light Elements

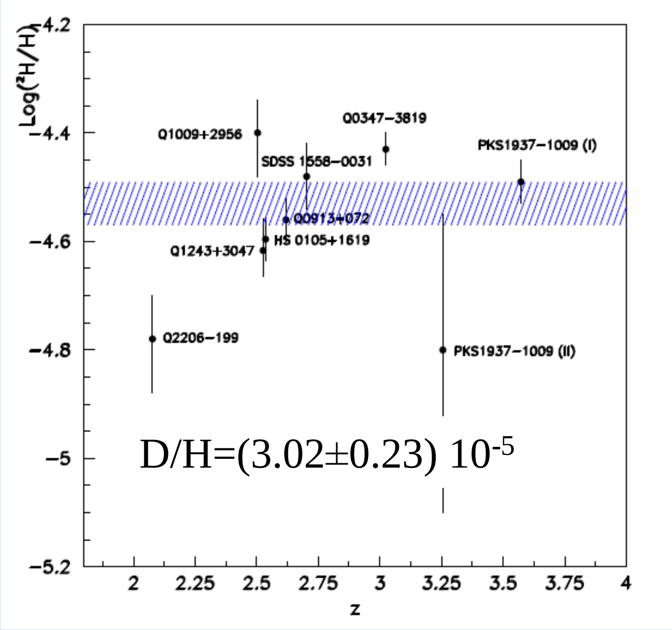
Main problem: Primordial abundances are not observed directly (chemical evolution after BBN).

Observations

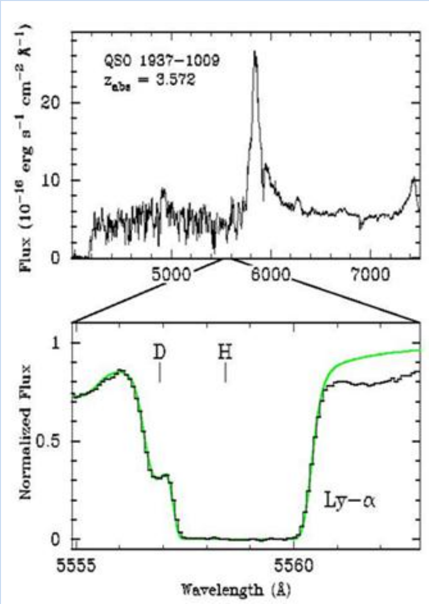
in systems least contaminated by stellar evolution.

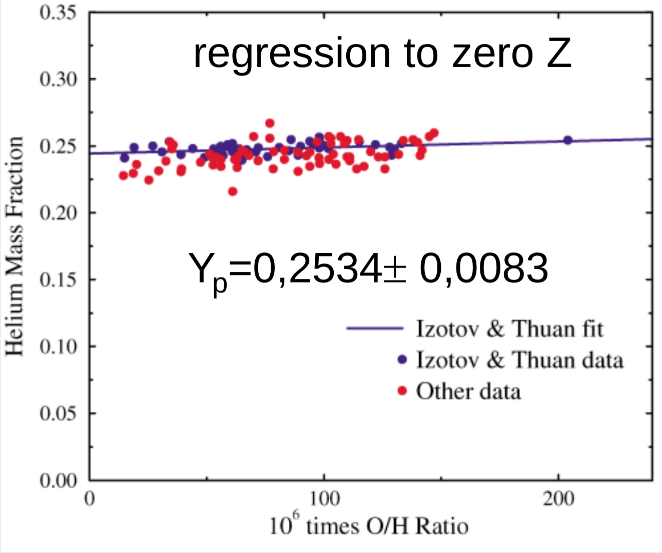
- D is measured in high z low-Z H-rich clouds absorbing light from background QSA.
- He in clouds of ionized H (H II regions), the most metal-poor blue compact galaxies.

Iocco et al. PR472, 1 (2009), Olive et al. 2012



D/H=(3.02±0.23) 10^{-5}





regression to zero Z

Y_p=0,2534± 0,0083

Account

for galactic chemical 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.

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:

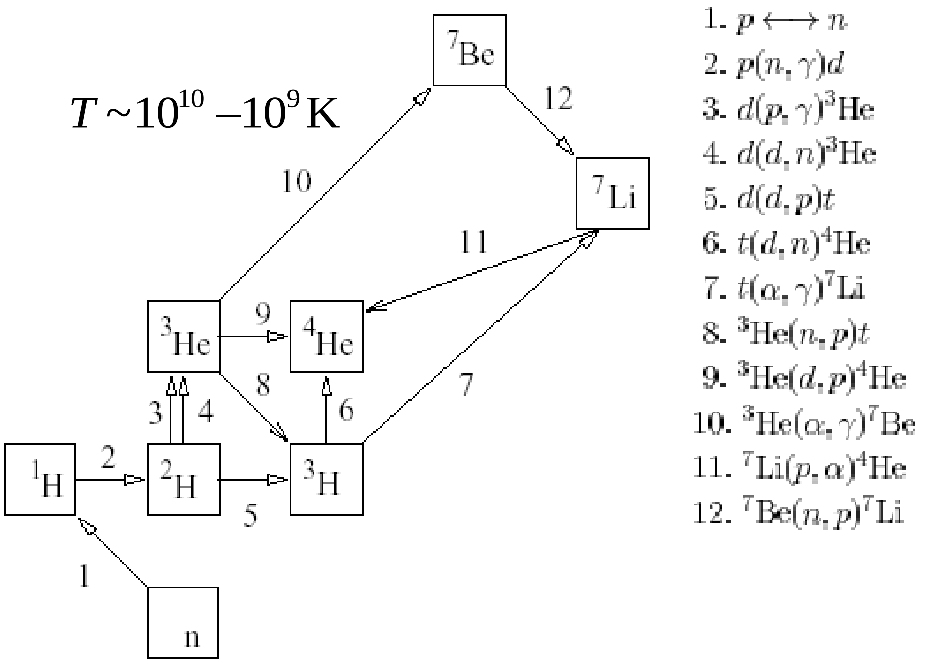
✓ baryon-to-photon ratio (CMB measured now),

✓ relativistic energy density (effective number of nu)

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

$$\rho_\nu + \rho_X(?) \equiv N_\nu \; \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

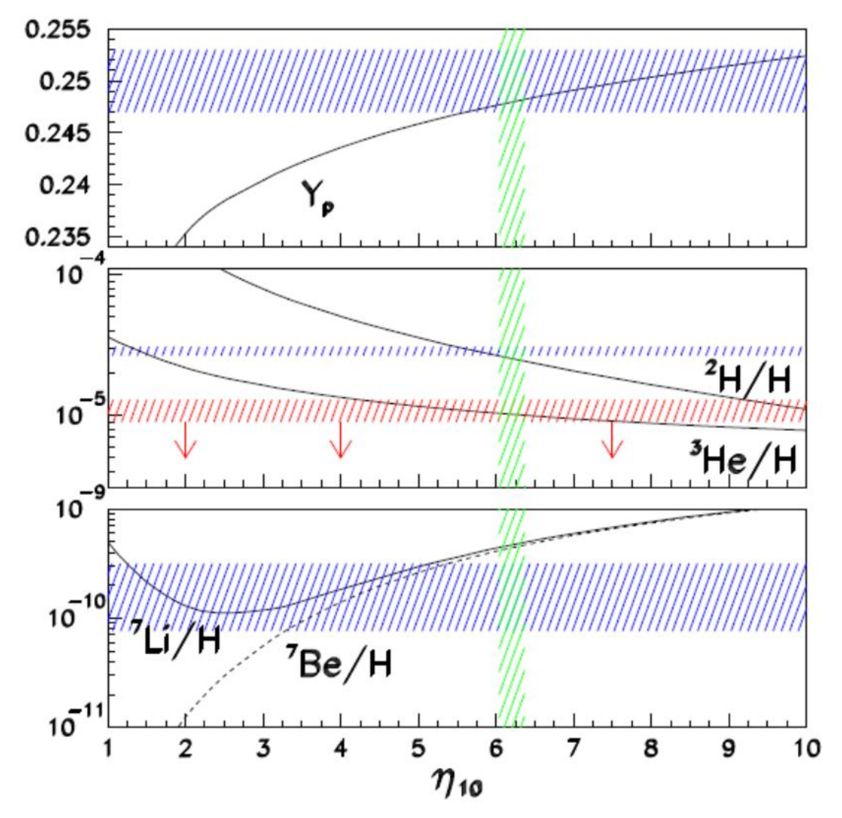
✓ n lifetime: 885.7±0.8; 878.5±0.8s *(Serebrov et al. 2005)*



$T \sim 10^{10} – 10^{9}\,\mathrm{K}$

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

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



Observational data (2σ error). Vertical band give baryon density measured by CMB.

BBN is most sensitive baryometer, speedometer and leptometer. BBN probes neutrino properties, non-standard physics, early Universe

BBN predictions are in agreement with observational data for $\Omega_B \sim 0.05$.

BBN – Universe Baryometer at z=10^9

❖ The baryon density is measured with very high precision. Among light elements D is the best baryometer.

$5.1 \times 10^{-10} < \eta_{BBN} < 6.5 \times 10^{-10}$ 95%

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

$$0.019 < \Omega_b h^2 = 0.024$$

BBN + D measurements
Towards quasars with big z
and low Z

$\eta_D = 6 \pm 0.3 \times 10^{-10}$ at 95% CL

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

$$\Omega_b h^2 = 0.021^{+0.002}_{-0.002}$$

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

❖ CMB measures baryons
at ~380 000 y:

$\eta_{WMAP} = 6.16 \pm 0.16 \times 10^{-10}$ at 68% CL

DASI, BOOMERANG, MAXIMA, WMAP7

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

Baryon density is ~ 0.05 of the total density, i.e. much bigger than the luminous matter (0.005), but considerably less than the gravitating matter (0.3).
Where are the dark baryons?

- ✓ Baryon density is ~ 0.05 of the total density → baryons cannot close the Universe

Our nucleonic matter building the planets, the stars... is a negligible fraction <5% !

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

- ✓ considerably less than the gravitating matter (0.3) → There exists nonbaryonic DM.

Why baryonic matter is such a small fraction?

What is the nonbaryonic matter?

Where are the hidden baryons?

Where are the antibaryons?

Combined Results of Hubble ST + WMAP + clusters point to the existence of DM > baryon density.
What is nonbaryonic matter?

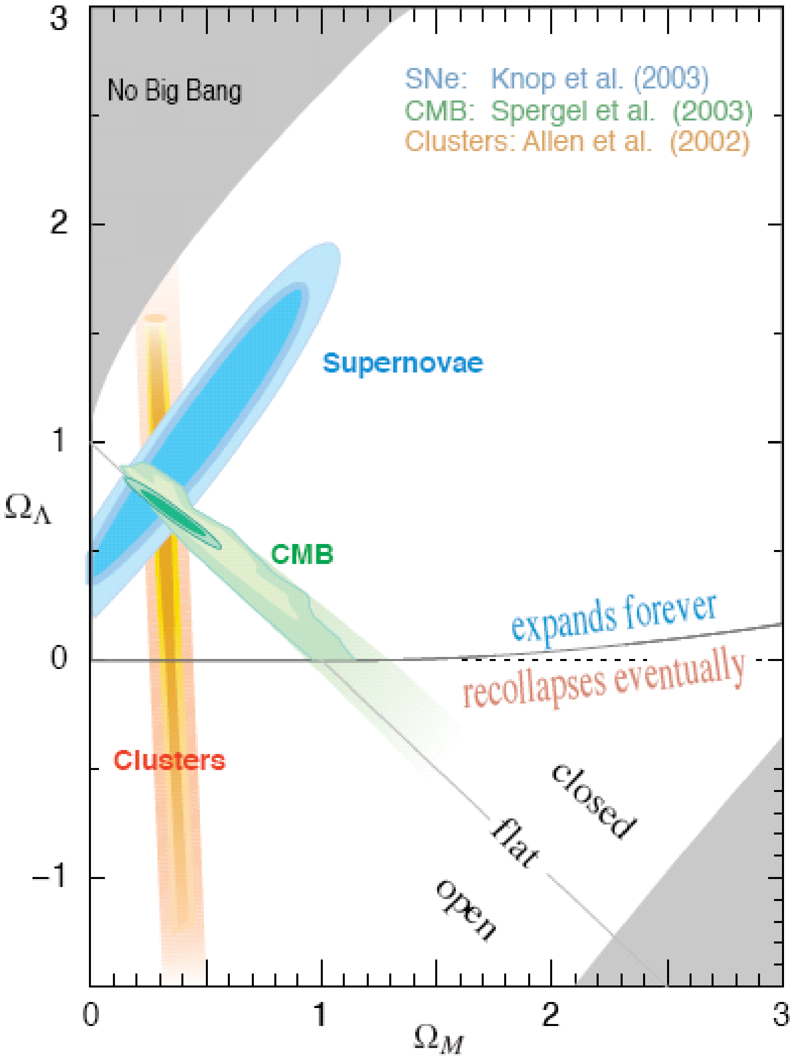


Figure 21.1: This shows the preferred region in the Ω_m–Ω_Λ plane from the compilation of supernovae data in Ref. 18, and also the complementary results coming from some other observations. [Courtesy of the Supernova Cosmology

Baryon Asymmetry of the Universe

SBBN predicts equal quantities at the hot stage and now the relic density should be:

$$\beta \sim 10^{-18}$$

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

Why baryon density is so big? Where is the antimatter?

Is the asymmetry local or global?

How and when the asymmetry was produced?

Saharov's baryogenesis conditions: BV, CPV, nonequilibrium

baryogenesis models (GUT, SUSSY, BTL, SCB..) *Dolgov 99,2011; Dolgov, DK 89*

If the symmetry is local what were the separation mechanisms?

DK, Chizhov MNRAS 2000, DKirilova, NPB2002

Missions searching for traces of antimatter: anti p, anti-nuclei, annihilation radiation:

PAMELA, BESS, AMS, AMS 2, PEBS(2010), etc

- CR data from search of anti p, positrons and antinuclei indicate that there is no significant quantity of antimatter objects within a radius 1 Mpc.
- Gama ray: no significant amounts of antimatter up to galaxy cluster scales ~ 10 -20 Mpc

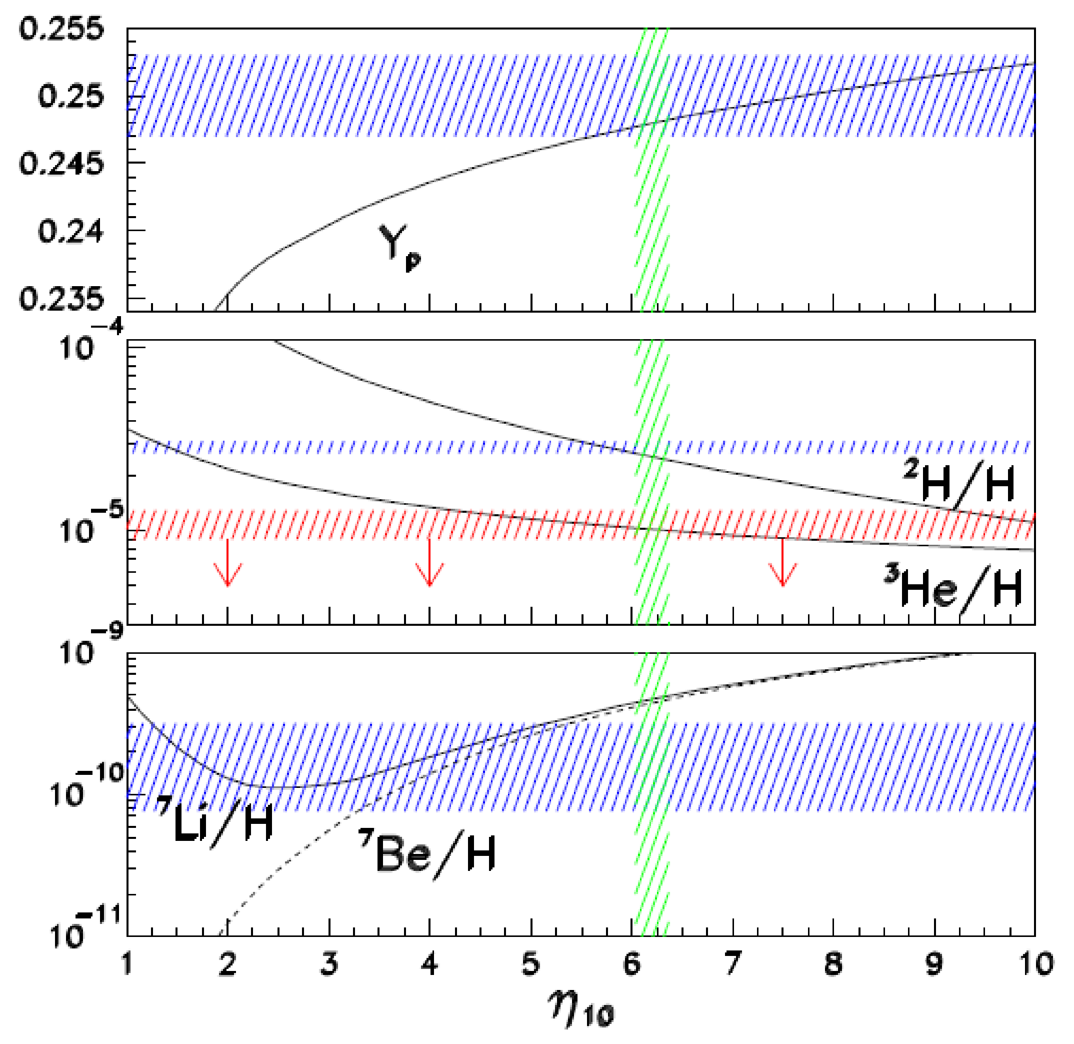
Steigman 79, Stecker 85

Locally, up to ~10-20 Mpc, the Universe is made of matter.

Both theory and observations allow astronomically significant quantities antimatter.

BBN - Best Speedometer at RD Stage

BBN Speedometer



$2.8 \leq N_\nu \leq 3.6$ (95% CL)

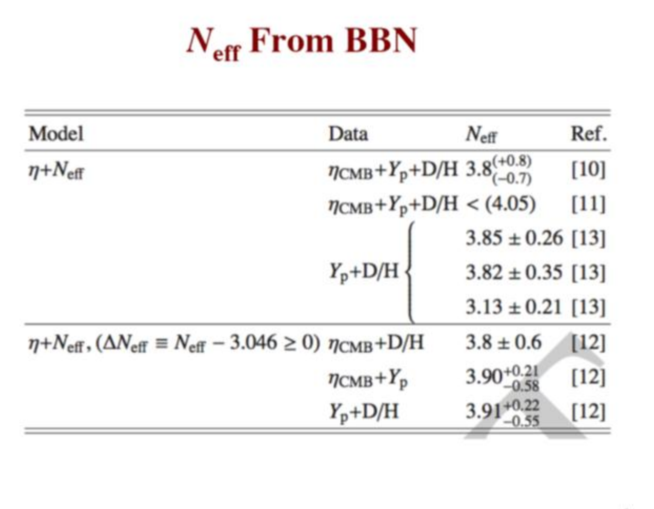
Iocco et al, 2009

Using Y from IT10:

$Y_p = 0{,}2565 \pm 0.001(\text{stat}) \pm 0{,}005(\text{syst})$

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

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



N_{eff} From BBN

Model	Data		N_{eff}	Ref.
$\eta + N_{\text{eff}}$	$\eta_{\text{CMB}} + Y_p + D/H$		$3.8^{(+0.8)}_{(-0.7)}$	[10]
	$\eta_{\text{CMB}} + Y_p + D/H$		$< (4.05)$	[11]
	$Y_p + D/H$	$\left\{ \right.$	3.85 ± 0.26	[13]
			3.82 ± 0.35	[13]
			3.13 ± 0.21	[13]
$\eta + N_{\text{eff}}, (\Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 \geq 0)$	$\eta_{\text{CMB}} + D/H$		3.8 ± 0.6	[12]
	$\eta_{\text{CMB}} + Y_p$		$3.90^{+0.21}_{-0.58}$	[12]
	$Y_p + D/H$		$3.91^{+0.22}_{-0.55}$	[12]

^{4}He – the best speedometer

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

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

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

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

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

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

$$\Delta m = 1.293 MeV$$

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

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

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

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

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

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

$Y_T = (H(\rho(g)), \Gamma) = 0{,}2482 \pm 0{,}0007$

$Y_o = 0{,}256 \pm 0{,}01$

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

BBN constraints

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

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

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

Non-zero ΔN_{eff} will indicate any extra relativistic component:

$\Delta N_{\mathrm{eff}} < 1.6$

WMAP,ACBAR,CBI,BOOMERANG

like sterile neutrino, neutrino oscillations, lepton asymmetry, neutrino decays, nonstandard thermal history, etc

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

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

- **Constrains lepton asymmetry**

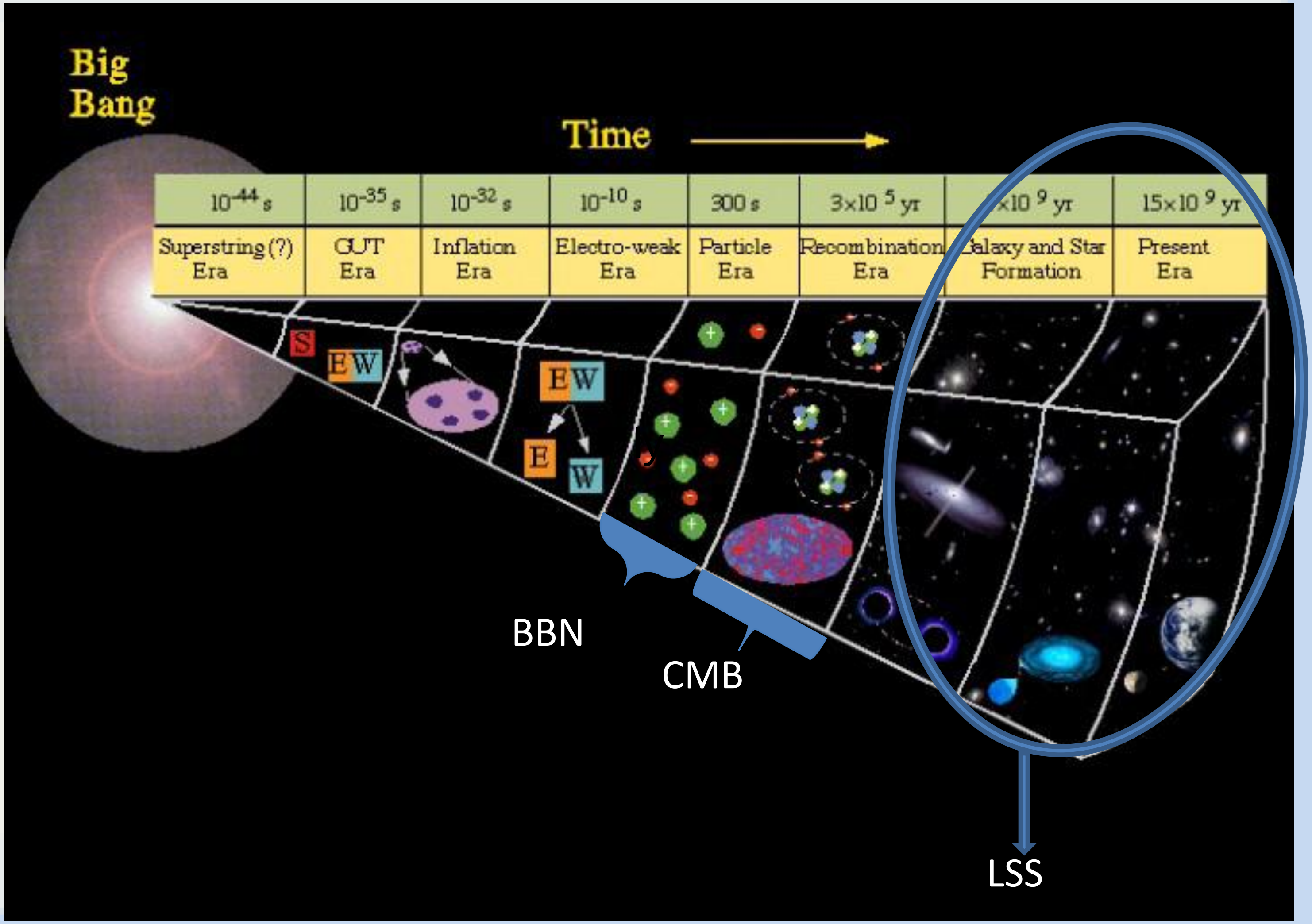
$$\Delta N_{\mathrm{eff}} = 15/7[([\mu/\mathrm{T})/\pi]^4 + 2[(\mu/\mathrm{T})/\pi]^2\}$$

- **Constrains sterile neutrino decoupling** $T_R > 130$ MeV, **production right handed bosons**

- **Constrains neutrino oscillations parameters**

……………………………………….

Observational data from different epochs predict excess radiation density



Excess radiation density

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

$\Delta N_{\rm eff}$ measures any relativistic component, including inert neutrino brought into equlibrium, oscillations, LA, decays, etc.

✓ Cosmological indications suggesting additional relativistic density:

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

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

A IT2010 68% CL 95% confidence

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

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

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

Excess radiation density

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

✓ Cosmological indications suggesting additional relativistic density:

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

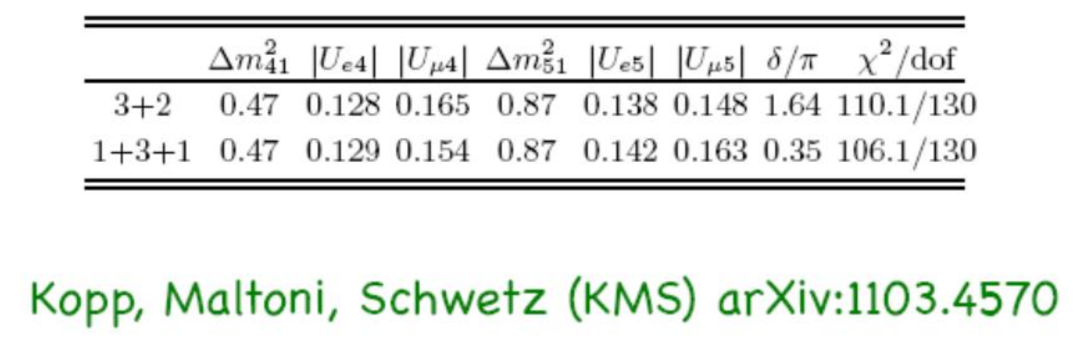
✓ Combined neutrino oscillations data (including MiniBoone and LSND):

require 1 or 2 additional light sterile neutrino (in eq. before BBN),

participating into oscillations with flavor neutrinos with higher mass differences values, than the ones required by solar and atmospheric neutrino oscillations experiments.

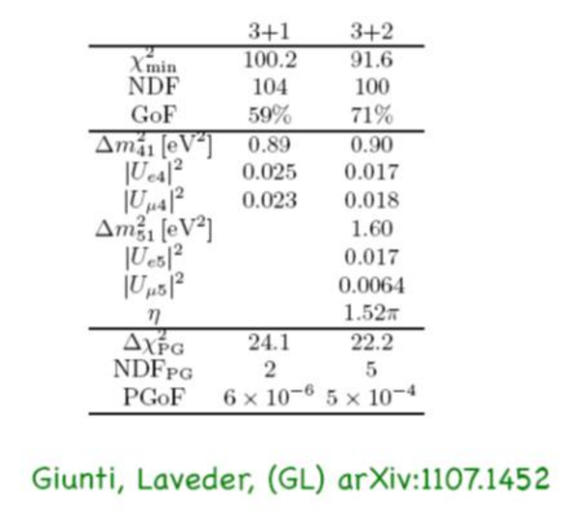
Neutrino oscillations indications

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



	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Kopp, Maltoni, Schwetz (KMS) arXiv:1103.4570



	3+1	3+2
χ^2_{min}	100.2	91.6
NDF	104	100
GoF	59%	71%
Δm^2_{41} [eV^2]	0.89	0.90
$\lvert U_{e4}\rvert^2$	0.025	0.017
$\lvert U_{\mu 4}\rvert^2$	0.023	0.018
Δm^2_{51} [eV^2]		1.60
$\lvert U_{e5}\rvert^2$		0.017
$\lvert U_{\mu 5}\rvert^2$		0.0064
η		1.52π
$\Delta\chi^2_{\mathrm{PG}}$	24.1	22.2
NDF$_{\mathrm{PG}}$	2	5
PGoF	6×10^{-6}	5×10^{-4}

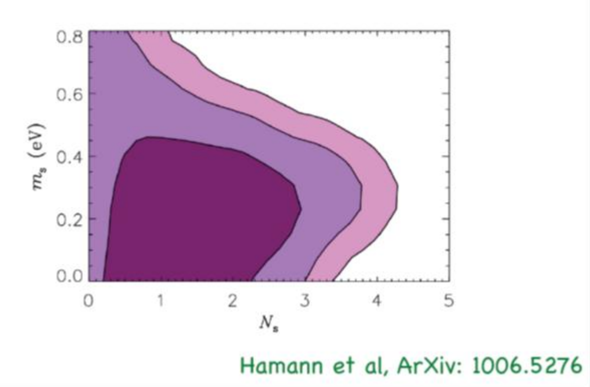
Giunti, Laveder, (GL) arXiv:1107.1452

$$\delta m^2{}_{41} \sim 0.5eV^2,$$
$$\delta m^2{}_{51} \sim 0.9eV^2$$

Neutrino oscillations effect early Universe processes. Does cosmology allow 2 light ν_s?

Does BBN favour non-zero ν_s ?

Excess radiation density



Hamann et al, ArXiv: 1006.5276

Giusarma et al. ,arXiv: 1102.4774

✓ Does cosmology allow these additional neutrinos? Were these inert neutrinos brought into equilibrium by oscillations? What other explanations of the excess density exist?

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

if neutrinos are in sub-eV range *Hamann et al. 2010;*

eV neutrinos are disfavored in SCM – too much HDM

Modified cosmological models: additional radiation

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

BBN current He and D data allow 1 new d.f. Modfied BBN may be necessary.

Krauss, Lunardini, Smith 2010 $-0.14< \xi_{\nu e} <0.12$ and dN fits IT and WMAP7

Excess radiation cannot be explained by degenerate BBN *Mangano et al. 2011*

BBN hardly allows two thermalized light inert states.

The additional relativistic density might point to L, additional sterile neutrino states, neutrino active-sterile oscillations, decaying particles during BBN, etc. *DK JCAP 2012*

BBN constraints

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

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

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

Non-zero ΔN_{eff} will indicate any extra relativistic component:

$\Delta N_{eff} < 1.6$

WMAP,ACBAR,CBI,BOOMERANG

like sterile neutrino, neutrino oscillations, lepton asymmetry, neutrino decays, nonstandard thermal history, etc

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

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

- **Constrains lepton asymmetry**

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

- **Constrains sterile neutrino decoupling** $T_R > 130$ MeV, **production right handed bosons**

- **Constrains neutrino oscillations parameters**

……………………………………………

Neutrino Oscillations Effects

- ❖ **Flavor Matter 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. DK 88, Barbieri, Dolgov 90, Kainulainen 91, Enqvist et al.,92

✓ **Distorting the neutrino energy spectrum from the equilibrium FD form**

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

DK 88, D.K&Chizhov,96

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

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

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

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

BBN stringent limits on oscillation parameters.

DK&Chizhov 98,2000, Dolgov&Villante 03, DK04,07;DK&Panayotova 06 ;Panayotova 2011, DK 2012

Effects of nonequilibrium $\nu_a \leftrightarrow \nu_s$

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

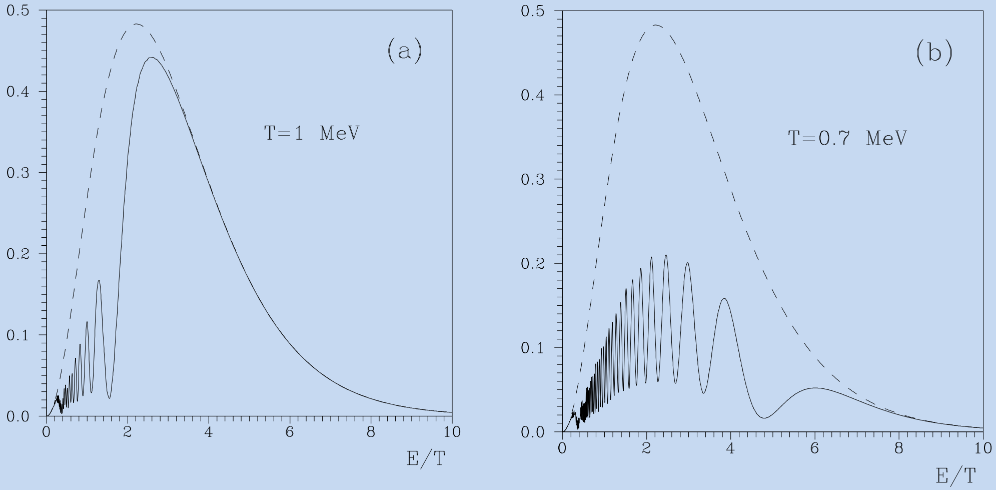
$\Rightarrow \nu_e$ depletion, $N_\nu \sim \int dEE^2 n_\nu(E)$ *D.K.,1988; Barbieri,Dolgov, 1990,91*

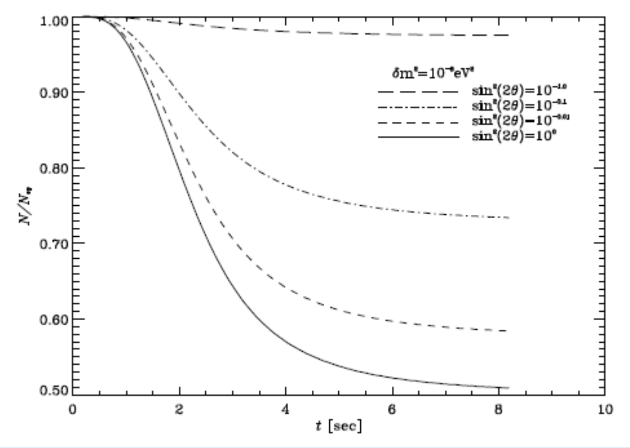
Enqvist et.al., 92; DK M.Chizhov, PLB ,1996,97

$\Rightarrow$ energy threshold effect $\Gamma \sim G_F^2 E_\nu^2 N_\nu$ $\Rightarrow$ pre-BBN kinetics

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

Dolgov et al., 2002





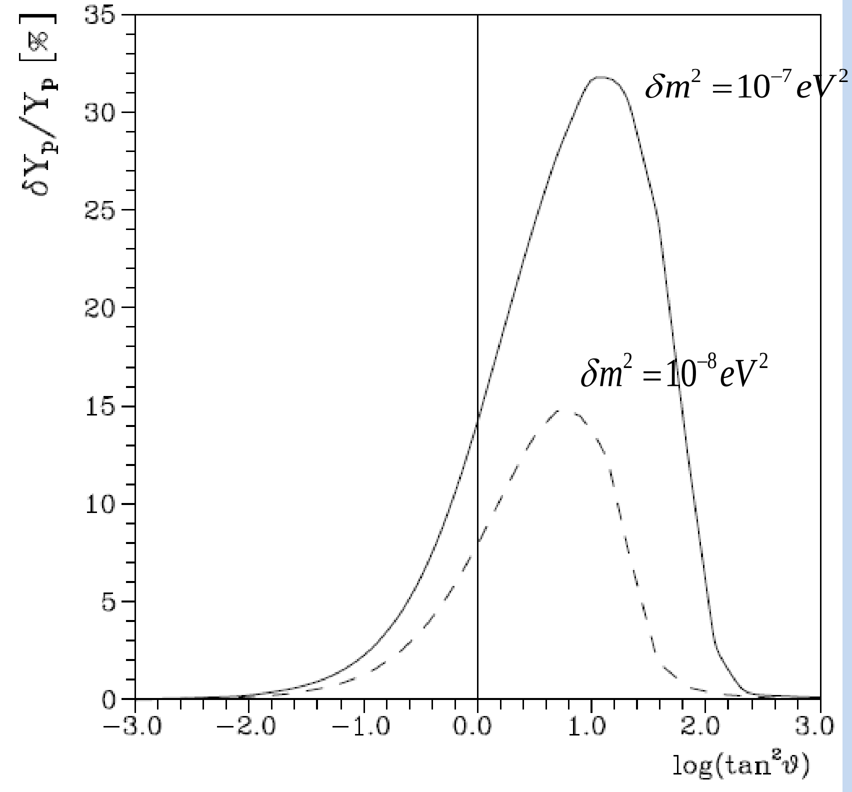
In case of oscillations effective after ν decoupling and provided that the sterile state is not in equilibrium ($\delta N_s<1$), kinetic effect on BBN dominate for wide range of oscillation parameters. In terms of effective number of neutrinos: $\delta N_{k,0} \leq 6$ res.osc., $\delta N_{k,0} \leq 3$ nonres.

DK , Astrop.Phys.,2003

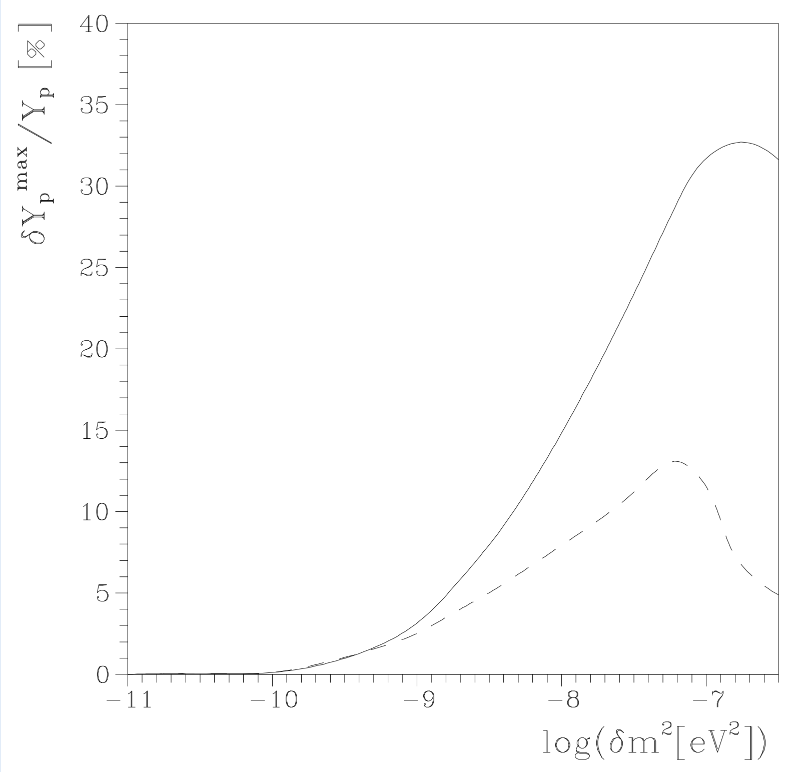
Kinetic effects and should be appropriately described.

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.

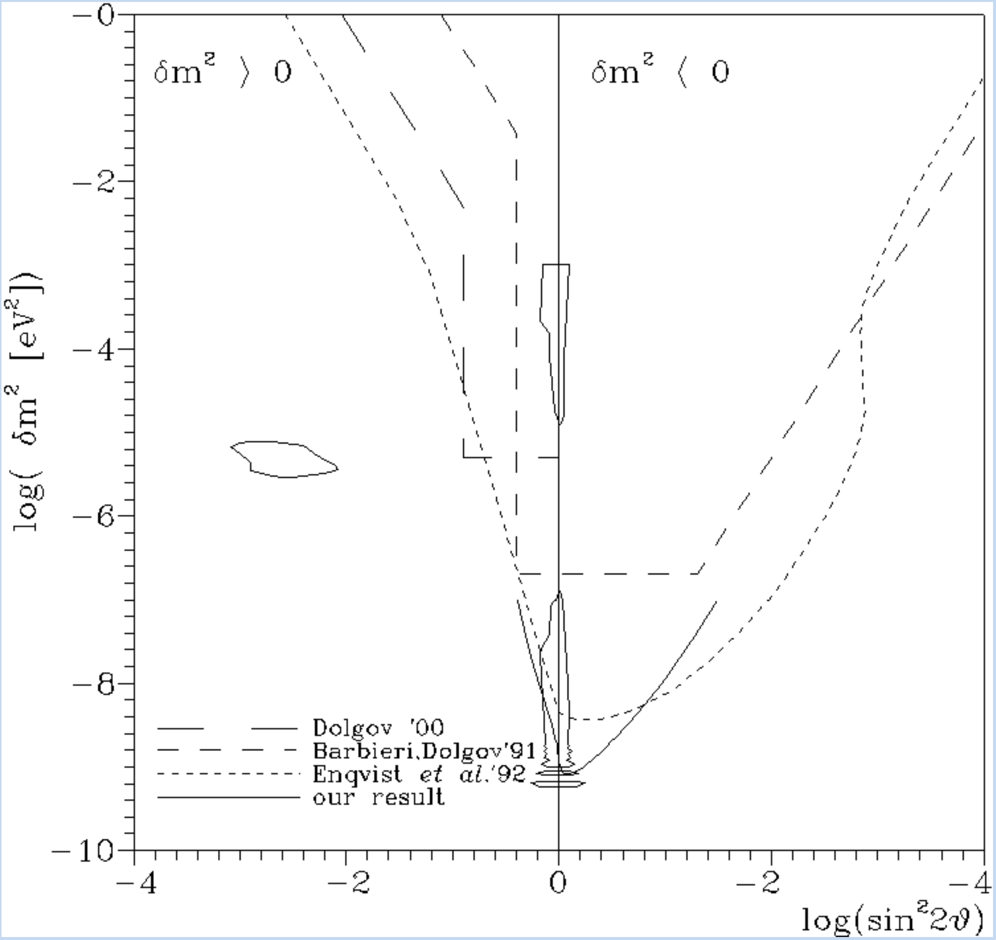
BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillation parameters

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 spedometer and leptometer
✓ sensitive to neutrino characteristics



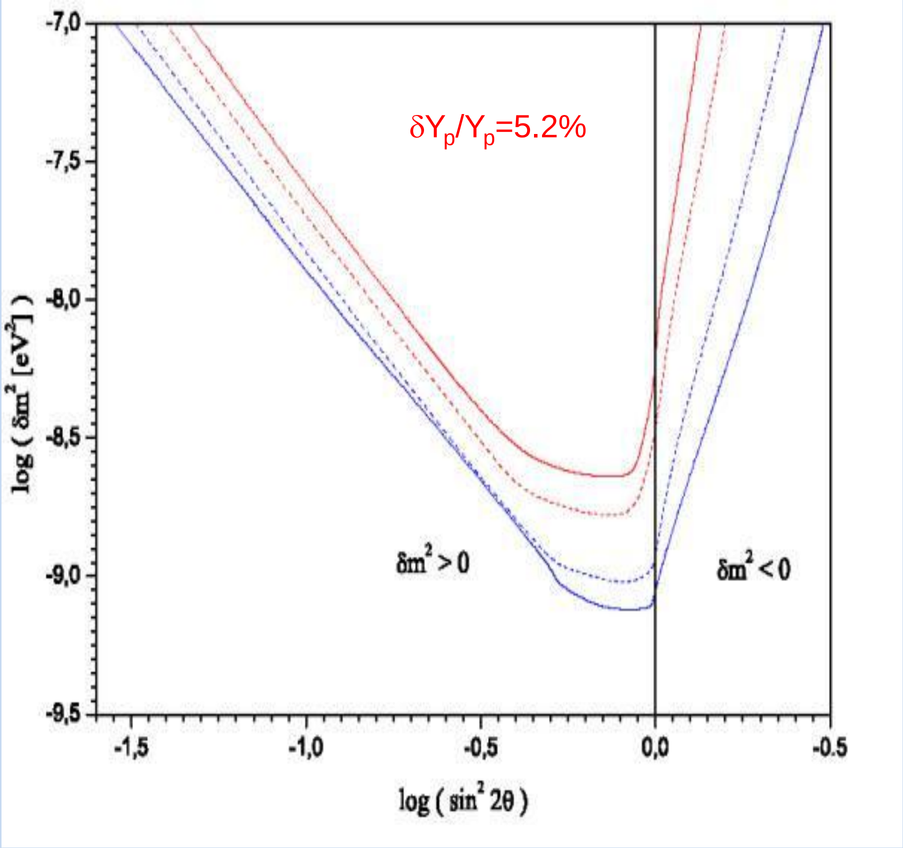
Barbieri, Dolgov 91 – depletion account
Dolgov 2000 – dashed curve;
DK, Enqvist et al. 92 – one p approx.
Dolgov, Villante, 2003 - spectrum distortion

DK.,Chizhov 2001 – distortion and asymmetry growth account

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

BBN constraints relaxed or strengthened?

Additional ν_s population may strengthen or relax BBN constraints.



DK&Panayotova JCAP 2006;DK IJMPD 07

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.

BBN - Most Exact Leptometer

Lepton Asymmetry

Lepton asymmetry of the Universe

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

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

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

Though usually assumed $L \sim \beta$, big L may reside in the neutrino sector $L \sim \sum_i L_{\nu_i}$

(universal charge neutrality implies $L_e = \beta$) .

CNB has not been detected yet, hence L is measured/constrained only indirectly through its effect on other processes, which have left observable traces in the Universe:

light element abundances from Big Bang Nucleosynthesis

Cosmic Microwave Background

Large Scale Structure, etc.

Effects on BBN

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

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

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

leading to faster expansion $H=(8/3\pi G\rho)^{1/2}$, delaying matter/radiation equality epoch …

⇒ influence BBN, CMB, evolution of perturbations i.e. LSS

Lesgourgues&Pastor, 99

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

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

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

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

⇒ influence BBN, outcome is L sign dependent

Simha&Steigman, 2008:

$$Y_p \sim (0.2482 \pm 0.0006) + 0.0016\eta_{10} + 0.013\Delta N_{eff} - 0.3\xi_{\nu_e}$$

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

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

- L changes the decoupling T of neutrino, etc.

Asymmetry - Oscillations Interplay

- ✓ Neutrino active-sterile oscillations change neutrino-antineutrino asymmetry of the mediun
  - suppress pre-existing asymmetry
    - *Barbieri&Dolgov 90.91; Enqvist et al. 1992*
  - enhance L (MSW resonant active-sterile oscillations) *L-T=M*
    - *Kirilova&Chizhov 96; Foot&Volkas 96* *-L-T=M*

L enhancement in MSW resonant active-sterile neutrino oscillations was first found for

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

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

- Flavor oscillations equalize L in different flavors before BBN

Dolgov et al., NPB, 2002

- ✓ Asymmetry effects neutrino oscillations
  - suppresses them
    - *Foot&Volkas, 95; Kirilova&Chizhov 98*
  - enhances them
    - *Kirilova&Chizhov 98*

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

L influence on neutrino 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 $f = e, \mu, \tau$

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 influences, E>10 MeV, Q>L if L is of the order of B.

In the adiabatic case the effect of the medium can be hidden in matter oscillation parameters: $\sin^2\theta_m = \sin^2\theta/[\sin^2\theta + ((Q/M^2_W \pm L)T^3/\delta m^2 - \cos 2\theta)^2]$

In general the medium suppresses oscillations.

When $(Q/M^2_W \pm L)T^3 = \cos 2\theta \delta m^2$ mixing in matter becomes maximal independent of mixing in vacuum - enhanced oscillation transfer.

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

- The medium influences the propation of neutrino. The evolution of the oscillating ν and ν_s, accounting simultaneously for Universe expansion, neutrino oscillations and neutrino forward scattering is described by:

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

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

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

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

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

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

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

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

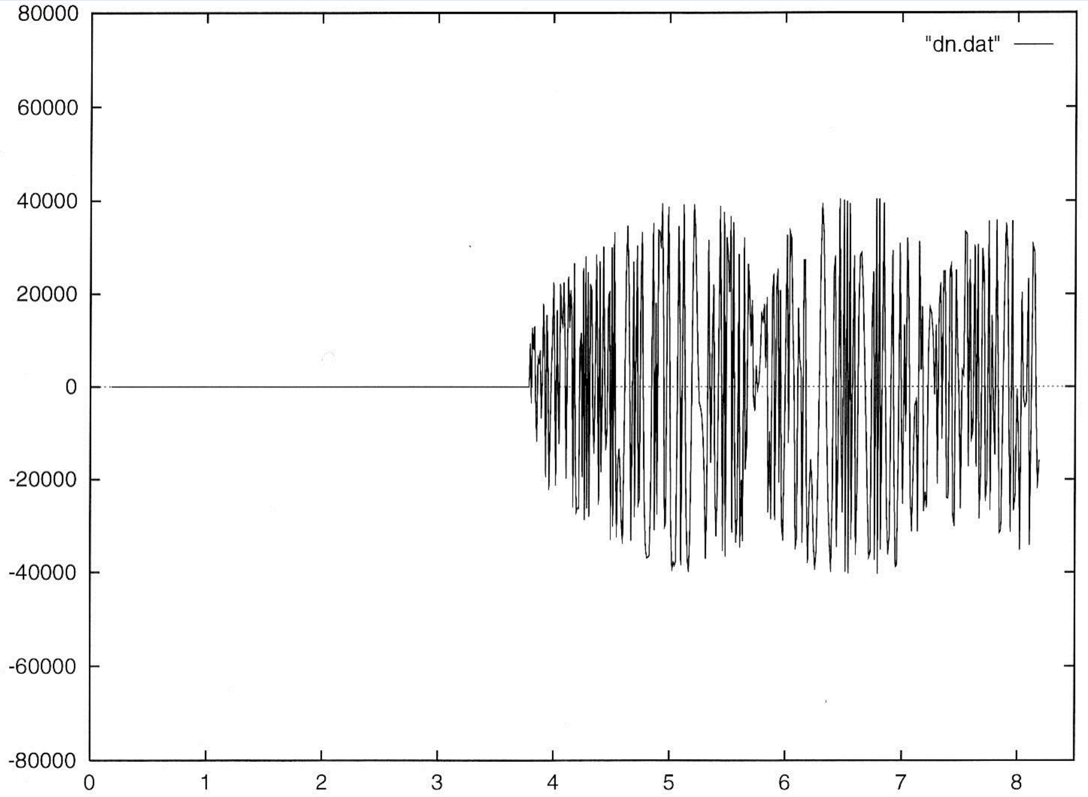
Oscillations generated lepton asymmetry

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

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

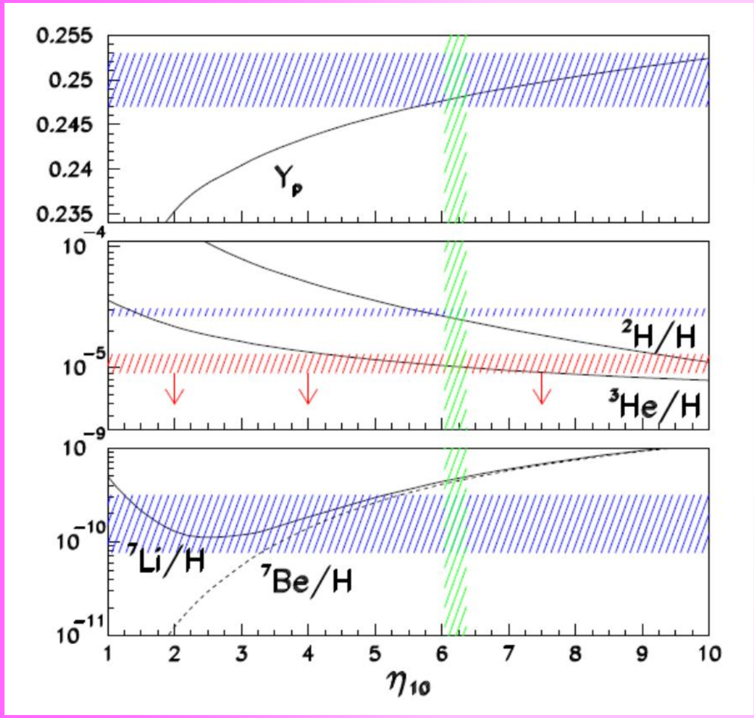
Generation of L by 4-5 orders of magnitude is found possible: $L \sim 10^{-5}$

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



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

BBN with L and ν oscillations



Big Bang Nucleosynthesis

Theoretically well established

Precise data on nuclear processes rates

from lab expts at low E (10 KeV – MeV)

Precise data on D, He, Li

Baryon fraction measured by CMB

COSMOLOGY

ASTROPHYSICS

→ **MICROPHYSICS**

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

The Best Speedometer at RD Stage

BBN probes neutrino oscillations

The Most Exact Leptometer

BBN Constraints on L

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

In case neutrino oscillations degeneracies equilibrate due to oscillations before BBN $|\xi_\nu| < 0.1$

Dolgov et al., NPB, 2002

Serpico&Raffelt,2005

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

Recent Y measurements and WMAP7 data relax the constraints*:* $-0.14 < \xi_{\nu e} < 0.12$

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

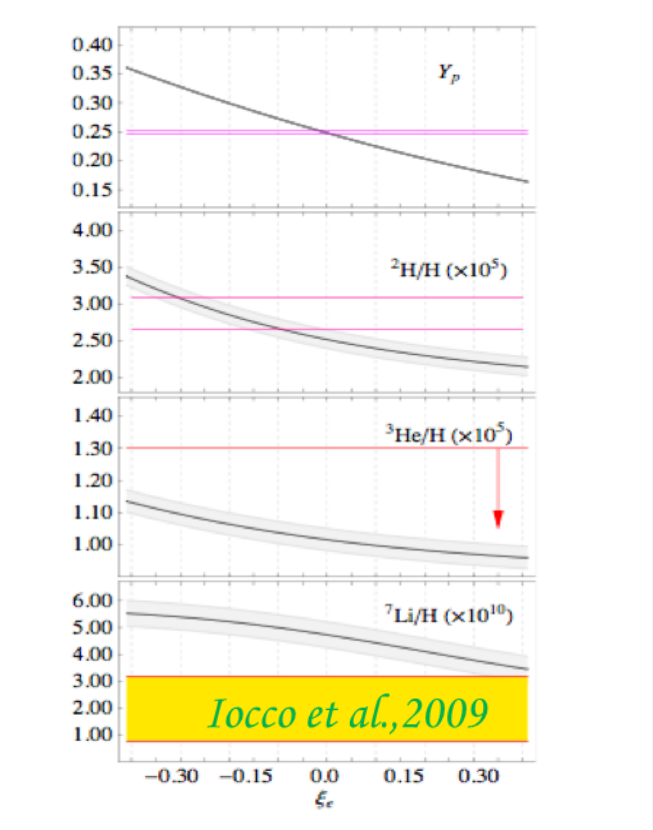
  otherwise the bound may be relaxed

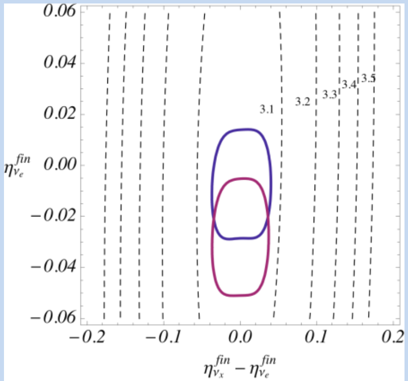
for $\theta_{13} = 0$ $-0.7 < L < 0.6$ *Miele et al.,2011*

CMB and LSS provide much looser bounds

- Recent measurement $\theta_{13} \sim 9^0$ $|L| < 0.1$

  → extra d.o.f. during BBN !





BBN with L for

$\theta_{13} = 0$ ΔN <1.4

Mangano et al.,2011

L cannot be the excess

density

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

- Neutrino electron-sterile oscillations

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

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

- Two different cases of L were explored:

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

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

Oscillations generated LA and BBN

❖ In BBN with $\nu_e \leftrightarrow \nu_s$ and L neutrino spectrum distortion and the density of electron neutrino may considerably differ from the standard BBN one, leading to different nucleon kinetics, and modified BBN element production.

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

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

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

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

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

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

Numerical analysis:

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

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

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

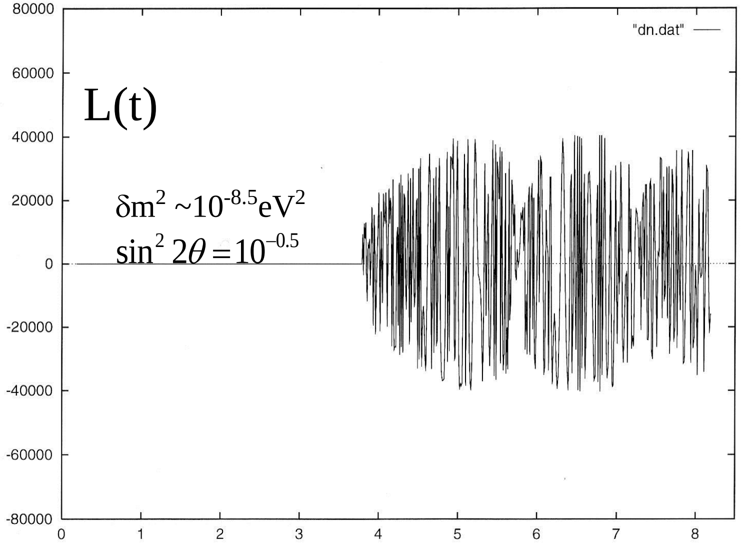
Oscillations generated LA and BBN

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:

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

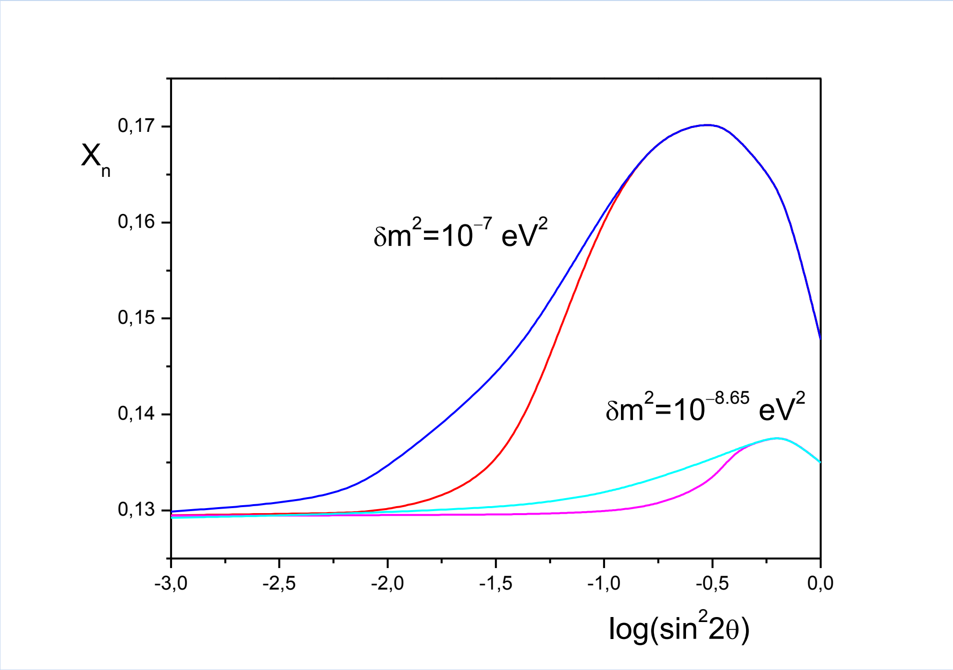
Generation of LA up to 5 orders of magnitude larger than β is possible, i.e. $L \sim 10^{-5}$



DK, PNPP,2010; 2011

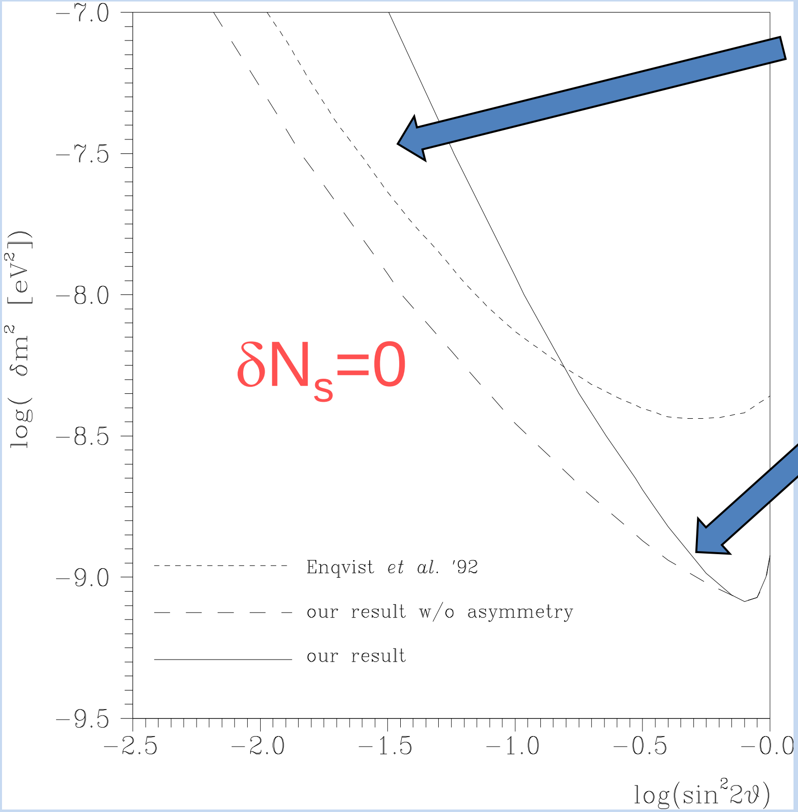
- In BBN with $\nu_e \leftrightarrow \nu_s$ neutrino spectrum distortion and asymmetry generation lead to different nucleon kinetics, and modified BBN element production.

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



BBN constraints dependence on L and SD

❖LA changes energy spectrum distribution and the number densities of ν_e from standard BBN case. This influences the kinetics of nucleons during BBN and changes the produced light element abundances.



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

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

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

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

He-4 is the preferred element:

$Y_p = 0{,}2565 \pm 0.001(\text{stat}) \pm 0{,}005(\text{syst})$

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

- ✓ 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, L..)

Barbieri, Dolgov 91 – depletion account

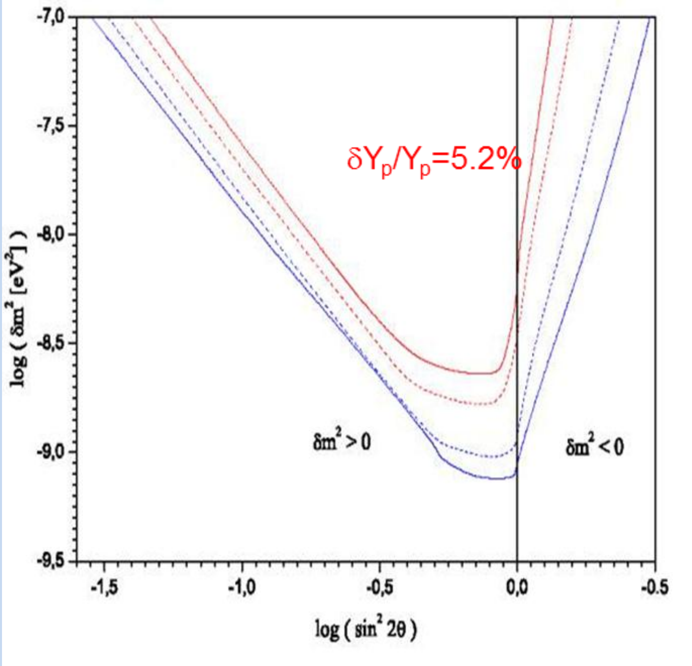
Enqvist et al. 92 – one p approx.

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

Dolgov, Villante, 2003 - spectrum distortion

Kirilova, Panayotova, 2006 – δN_s effect

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



DK&Panayotova JCAP 2006;DK IJMPD 07

Additional inert population may strengthen or relax BBN constraints.

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

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

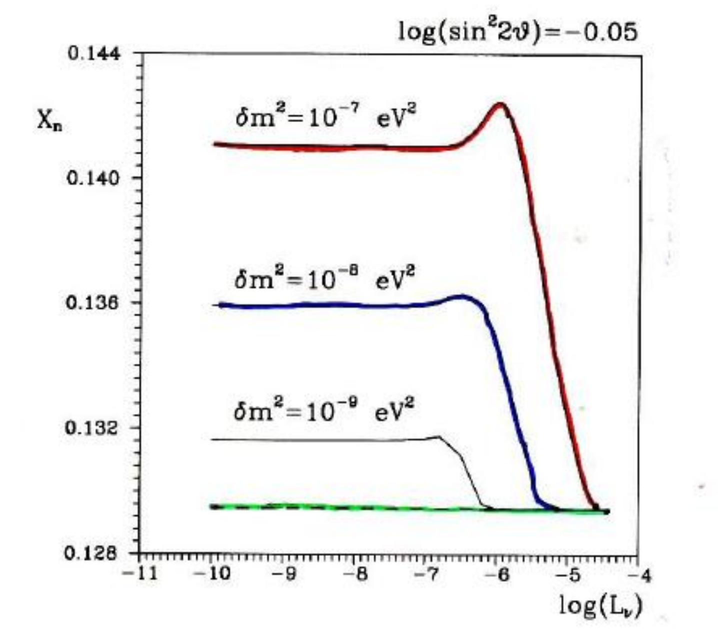
Initial LA and BBN with oscillations

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

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

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

$Y_p\left(\delta m^2, \theta, L\right)$ *DK, JCAP2012*



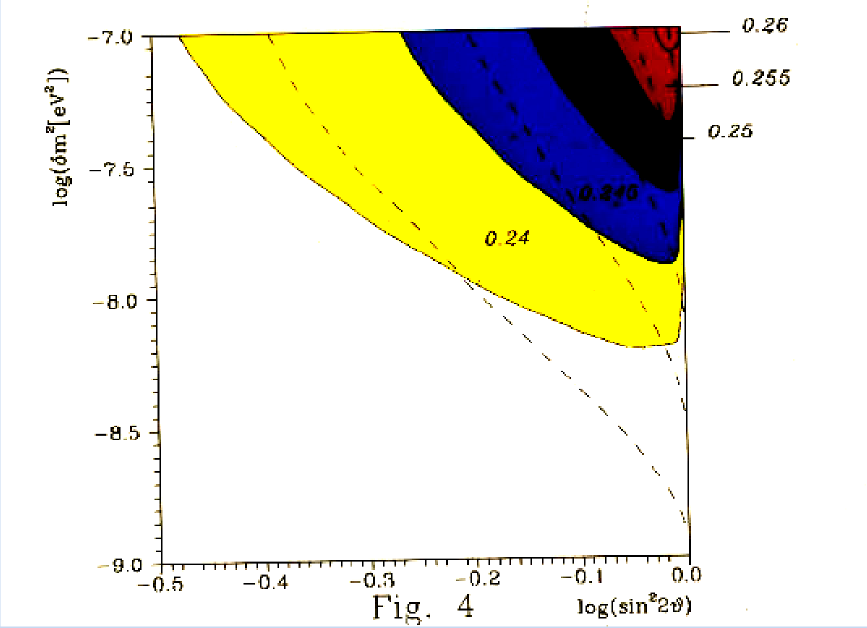


Fig. 4

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

DK&ChizhovNPB98

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

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

BBN with oscillations is the best known leptometer.

Summary

- In case of active-sterile oscillations after decoupling of active neutrinos

  the number densities of CNB neutrinos may be reduced, the spectrum may differ from FD.

  CNB neutrinos may have the equilibrium number density or be depleted

  depending on the type of oscillations and their parameters.

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

  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 bound on N_{eff} is strengthened in case of neutrino oscillations.

- BBN constraints on neutrino oscillations parameters depend nontrivially on the population of sterile neutrino and the lepton asymmetry in the Universe.

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

Summary

- Considerable L generation in active-sterile Mikheyev-Smirnov-Wolfenstein oscillations, effective after neutrino decoupling, is found. The region in the oscillation parameter space of considerable L growth was determined.
- Small lepton asymmetry LA << 0.01, either relic or generated by active-sterile neutrino oscillations, which do not have direct effect on nucleons kinetics during BBN, may have considerable cosmological influence. Such small asymmetries are invisible by CMB, but may be felt by BBN: L as small as 10-8 may be felt by BBN via oscillations.
- The effect of the dynamically generated and initially present L on BBN with oscillations was studied. Lepton asymmetry is able to enhance, suppress or inhibit oscillations. The parameter range for which relic L is able to enhance, suppress or inhibit oscillations is determined.
- LA provides relaxation or enhancement of BBN constraints on oscillations.

  Large enough LA alleviates BBN constraints on oscillation parameters.

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

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

Future experimental and observational data will choose among different possibilities.

Conclusions

BBN is one of the most precise probes of physics at the RD stage and the most reliable cosmological test of physics beyond SM.

BBN (particularly D and He-4) is the best speedometer and leptometer. 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, new interactions, etc.

Future cosmic missions and observations and expts at accelerators and colliders are expected to improve our knowledge about the Universe and in particular to solve the riddles about baryon asymmetry, dark matter, measure lepton asymmetry, find the reason for additional radiation density, etc.

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 and on the presence of additional light neutrino species.

Благодаря за вниманието!

Thanks for the attention!

BBN

- well established: supported by the contemporary observational data
- precision cosmological model

But many questions persist and motivate further studies

- baryon density – precise determination, but baryogenesis mechanism?
- Li problems
- modified (non-standard) BBN, inhomogeneous BBN, …

  BBN with neutrino oscillations, BBN with sterile neutrino, BBN with decaying particles, BBN with L
- dark radiation

- Astrophysical solutions

  OR
- Signatures for necessity of alternative BBN, new physics, astrophysics, etc.?
- …………………

Future observations and experimental and theoretical studies are expected to answer part of the BBN puzzles.

Sterile Neutrinos Status

Sterile – that does not couple to standard model W or Z boson.

Hints for sterile from tension with 3 neutrino paradigm: LSND, MiniBooNE, reactor expts (10-100m), Cr and Ar solar neutrino detectors

cosmology hints: CMB and BBN Neff>3; LSS and SMB Σ m < (0.17 -1.0) eV

- 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 H_2 and speed up the star formation, causing earlier reionization – observational feature predicted to search with X-ray telescopes
- Pulsar kicks from anisotropic SN emission
- 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.
- In case of oscillations with active neutrino it exerts major effect on expansion rate and nucleons kinetics during pre-BBN and its mixing parameters are constrained by BBN+CMB
- Et cetera…..

Solving numerically BBN dynamics

1. Weak interactions freeze out at T ~1 MeV
2. Deuterium forms via p n →D γ at T ~ 0.1 MeV
3. Nuclear chain

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

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

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

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

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

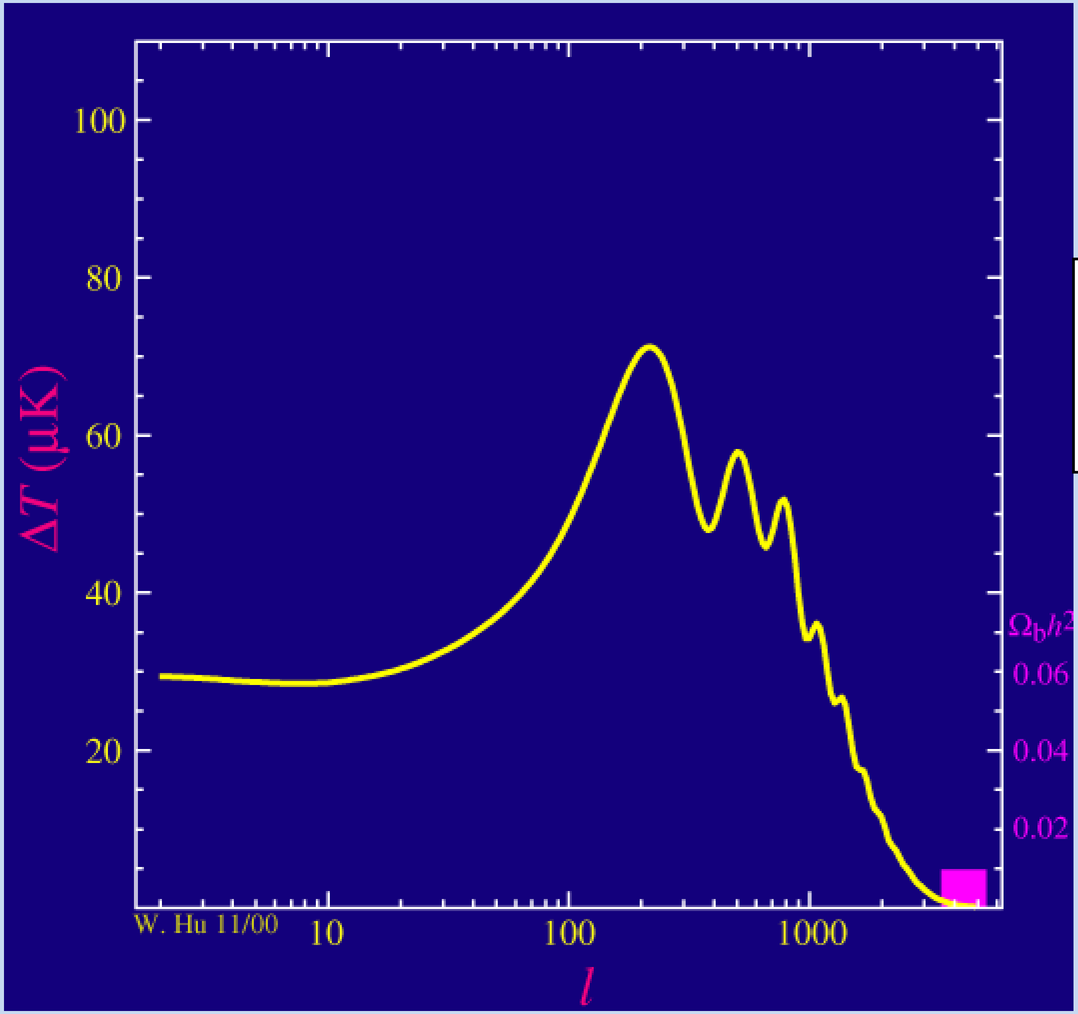
$$\boxed{\left(\frac{\partial}{\partial t} - H\,|\mathrm{p}|\frac{\partial}{\partial|\mathrm{p}|}\right) f_{\nu_\alpha}(|\mathrm{p}|,t) = I_{\nu_\alpha}\left[f_{\nu_e}, f_{\bar\nu_e}, f_{\nu_x}, f_{\bar\nu_x}, f_{e^-}, f_{e^+}\right]} \quad ,$$

- **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 decoupling can be computed independently of nuclear abundances

CMB and baryons



Change of baryon density Reflects in change of ratio of odd and even peaks.

η_{WMAP}=6.16±0.16 x 10^{-10} at 68% CL

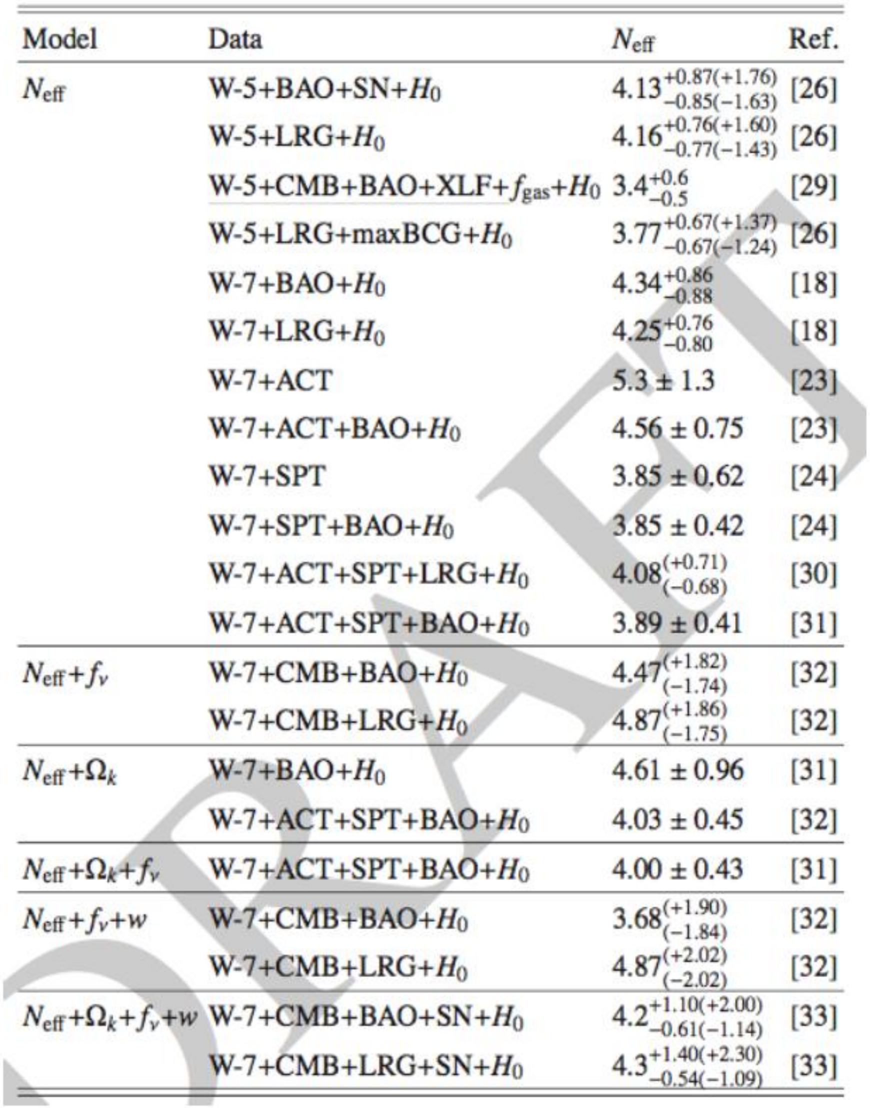
Form of maxima depends on density of matter and baryons.

Courtesy Wayne Hu – *http://background.uchicago.edu*

BBN constrains physics beyond SM

- BBN depend on all known interactions - constrains modification of those
- Additional light (relativistic during BBN, i.e. m< MeV) particles species (generations) effecting radiation density (H), pre-BBN nucleon kinetics or BBN itself
- Additional interactions or processes relevant at BBN epoch (decays of heavy particles, neutrino oscillations)
- Depart from equilibrium distributions of particle densities of nucleons and leptons (caused by nu oscillations, lepton asymmetry, inhomogeneous distribution of baryons, etc.)
- ……………..

$N_{\rm eff}$ From CMB

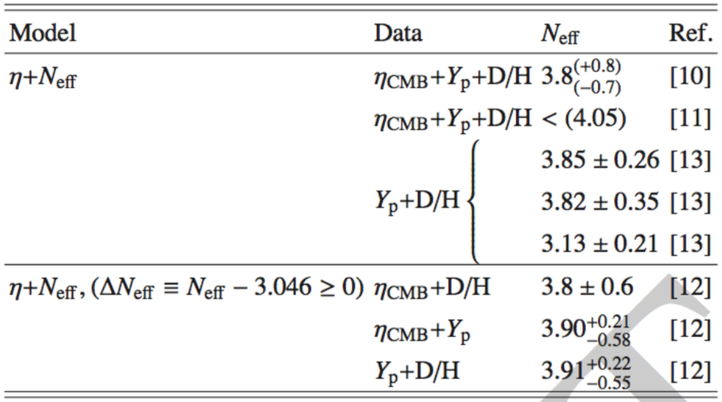


Model	Data	$N_{\rm eff}$	Ref.
$N_{\rm eff}$	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[26]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[26]
	W-5+CMB+BAO+XLF+$f_{\rm gas}$+H_0	$3.4^{+0.6}_{-0.5}$	[29]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[26]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[18]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[18]
	W-7+ACT	5.3 ± 1.3	[23]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[23]
	W-7+SPT	3.85 ± 0.62	[24]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[24]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[30]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[31]
$N_{\rm eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$	[32]
$N_{\rm eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96	[31]
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45	[32]
$N_{\rm eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43	[31]
$N_{\rm eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$	[32]
$N_{\rm eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[33]
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[33]

Tensions Subgroup Report

Boris Kayser, Fermilab
March 21, 2012

$N_{\rm eff}$ From BBN



Model	Data	$N_{\rm eff}$	Ref.
$\eta+N_{\rm eff}$	$\eta_{\rm CMB}+Y_{\rm p}$+D/H	$3.8^{(+0.8)}_{(-0.7)}$	[10]
	$\eta_{\rm CMB}+Y_{\rm p}$+D/H	$< (4.05)$	[11]
	$Y_{\rm p}$+D/H	3.85 ± 0.26	[13]
		3.82 ± 0.35	[13]
		3.13 ± 0.21	[13]
$\eta+N_{\rm eff}$, $(\Delta N_{\rm eff} \equiv N_{\rm eff} - 3.046 \geq 0)$	$\eta_{\rm CMB}$+D/H	3.8 ± 0.6	[12]
	$\eta_{\rm CMB}+Y_{\rm p}$	$3.90^{+0.21}_{-0.58}$	[12]
	$Y_{\rm p}$+D/H	$3.91^{+0.22}_{-0.55}$	[12]

Excess radiation density

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

✓ Cosmological indications suggesting additional relativistic density:

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

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

require 1 or 2 additional light sterile neutrino (in eq. before BBN),

participating into oscillations with flavor neutrinos with higher mass differences values,

than the ones required by solar and atmospheric neutrino oscillations experiments.

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

Reactor experiments+LSND+MiniBooNe+Gallium expt

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

Kopp, Maltoni,Schwetz, arXiv: 1103.4570

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

- Neutrino oscillations effect early Universe processes. Does cosmology allow 2 light ν_s?

Does cosmology favour non-zero ν_s ? L role?

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

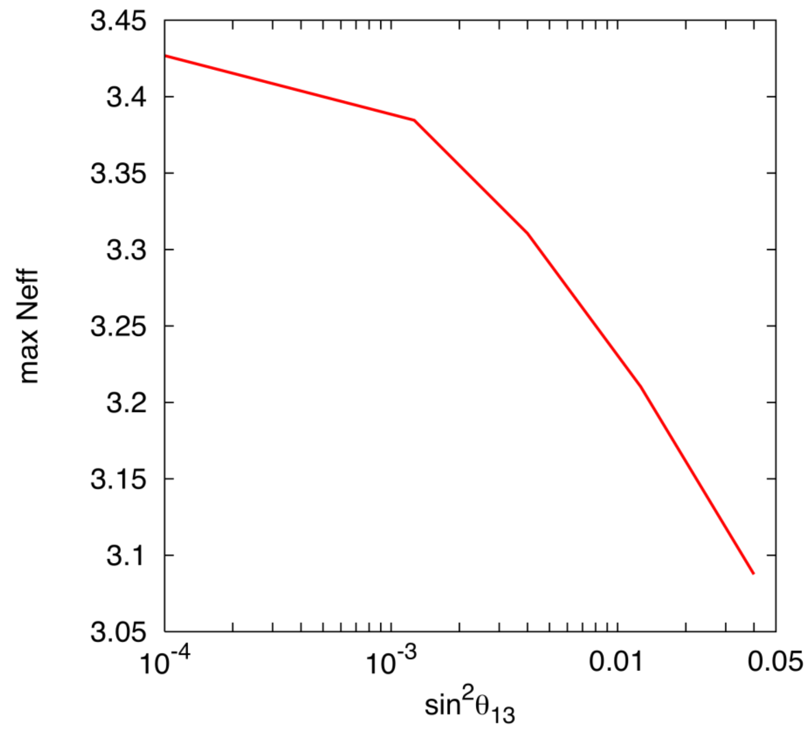
$$H \sim \sqrt{g_{eff} G T^2} \qquad g_{eff} = 10.75 + \frac{7}{4}\delta N_s \qquad \delta N_s = N_\nu - 3$$

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

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

$$\delta Y_d \sim 0.013\ \delta N_s$$

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



- Planck satellite will reach a sensitivity for N_{eff} of the order of 0.4 at 2σ
- A detection of a ΔN_{eff} = 0.4 – 0.5 could imply a large degeneracy but only for almost vanishing θ_{13}, but in this case a measurement of such angle larger than almost 0.03 would mean extra d.o.f.
- A detection of a $\Delta N_{eff} > 0.5$ would mean in anycase extra d.o.f.
- We have a robust limit from BBN: $\Delta N_{eff} \leq 1.2$ at 2σ arXiv:1103:1261v1 [astro-ph.CO]