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BBN Cosmological Constraints on Physics Beyond the Standard Model

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Astrophysical and cosmological observations data – necessity of BSMs physics

The contemporary LCDM contains already considerable

DE+DM, unknown nature components constitute 95% of Universe matter!

Inflation, Baryon Asymmetry, etc.

to understand these puzzles beyond SM physics is required

to propose the DM, DE, inflaton candidates , etc

OR

change the theoretical basis of SCM (alternative grav. theory, etc.)

Neutrino : experimental data firmly established beyond SM physics

SMP assumptions: m=0, N_{eff}=3, L=0, equilibrium FD distribution

. Neutrino oscillations experiments challenged all these

This talk : BBN constraints on beyond SMP

Outline

- BBN - the deepest reliable early Universe probe and SMP test
- BBN baryometer – constraints on matter content of the Universe
  hidden baryons, nonbaryonic dark matter
  baryogenesis, antimatter in the Universe
- Neutrino beyond SMP and BBN constraints
  inert neutrino, number of families,
  neutrino oscillations, lepton asymmetry
  dark radiation problem - eV neutrino saga
- Chiral tensor particles cosmological influence and BBN constraints

Primordial Nucleosynthesis

George Gamow

1904 – 1968

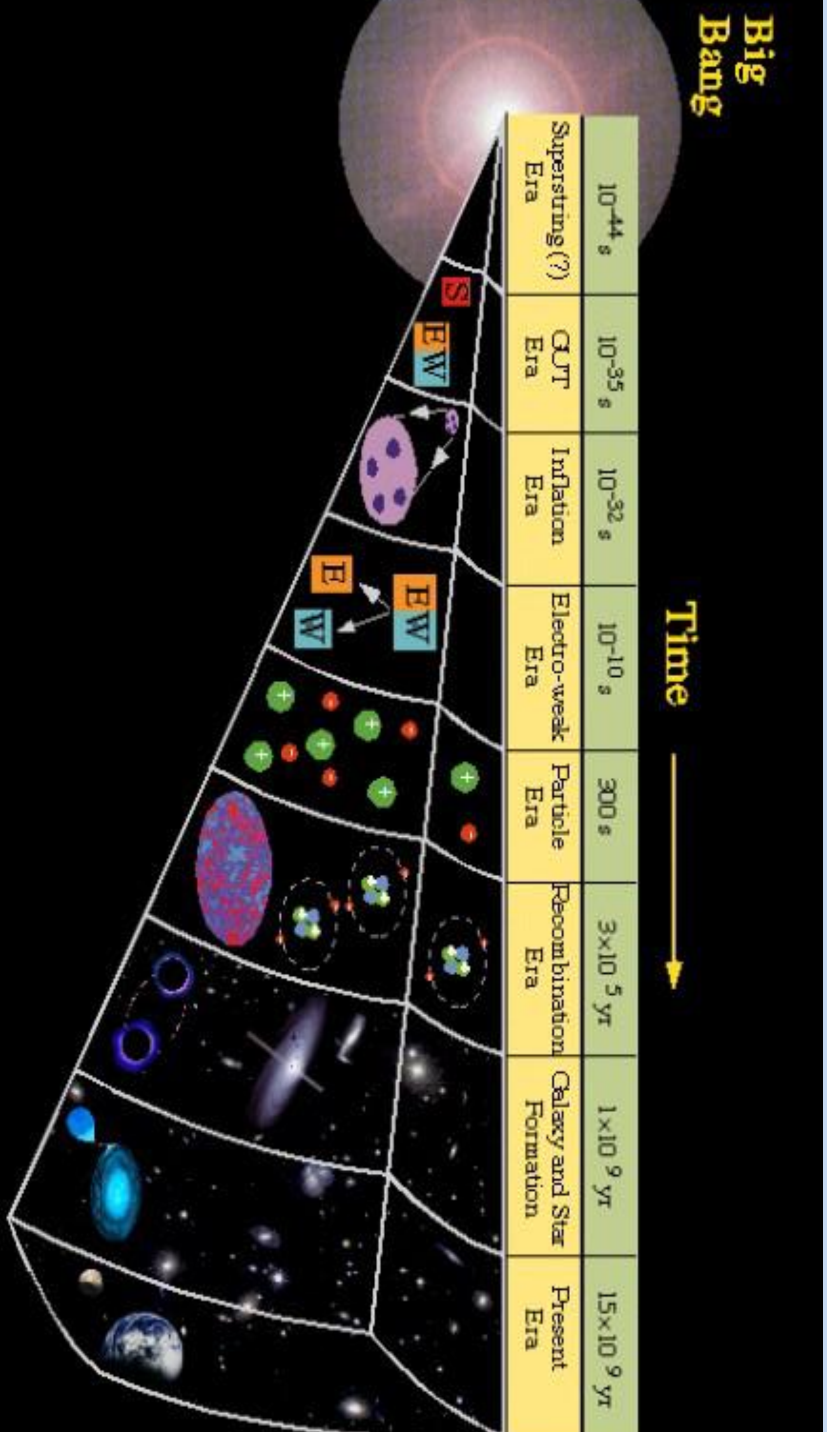
In 1946–1948 develops BBN theory.
In the framework of this model
predicts CMB and its T.

Theoretically well established - based on
well-understood SM physics
Precise data on nuclear processes rates
from lab expts at low E (10 KeV – MeV)
Precise observational data on light elements abundances
Predicted abundances in good overall agreement
with the ones inferred from observational data

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

Universe baryometer
the best speedometer at RD stage
the most exact Universe leptometer

Baryon fraction, N_{eff}, L, etc. measured by CMB



BBN – the only reliable probe of RD epoch

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

The Abundances of Light Elements

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

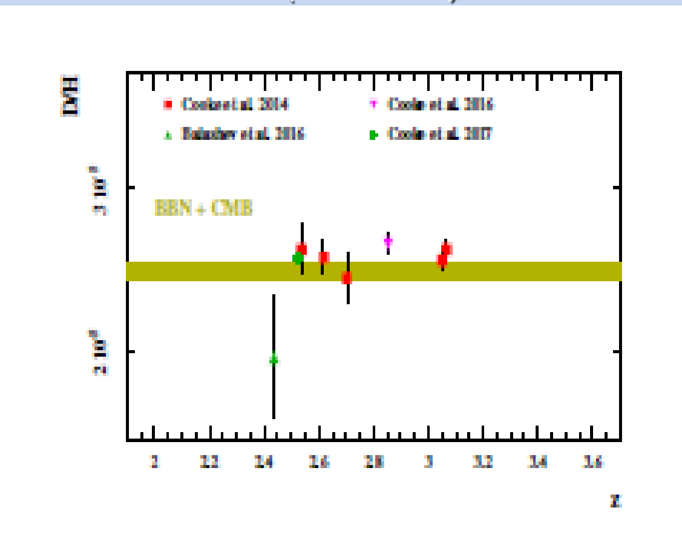
- D is measured in high z low-Z H-rich clouds absorbing light from background QSA.

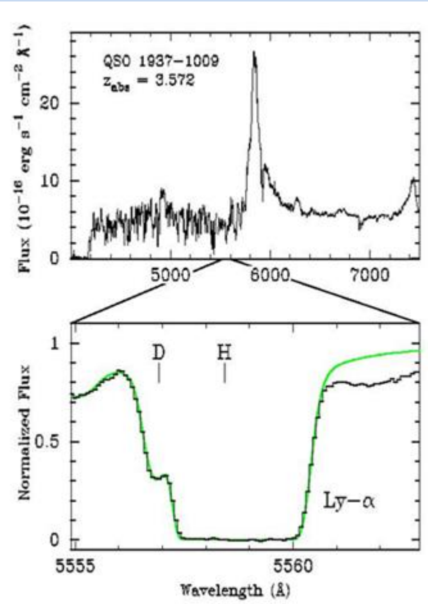
Observations

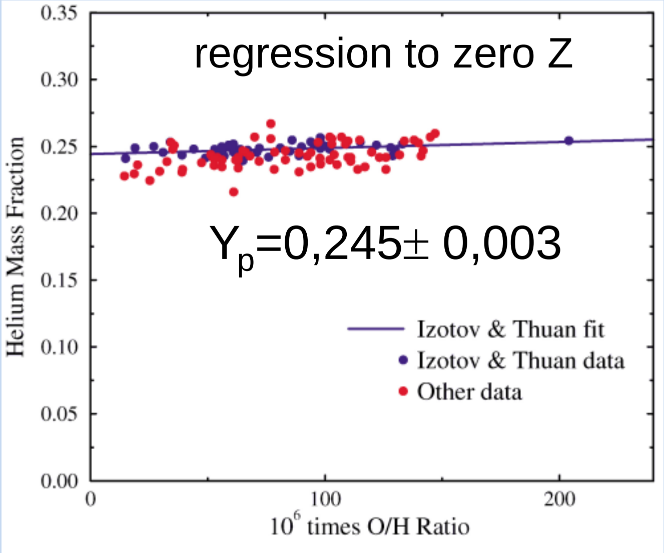
in systems least contaminated by stellar evolution.

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

lCooke et al. (2014-2017)







Account

for galactic chemical evolution

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

Cooke et al. 2017	Peimbert,2016;Aver et al. 2015	Sbordone et al. 2010
$D/H=(2.527\pm0.03)\ 10^{-5}$	$Y_p=0{,}245\pm 0{,}003$	$Li/H=(1.58\pm0.31)\ 10^{-10}$

According to SBBN 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:

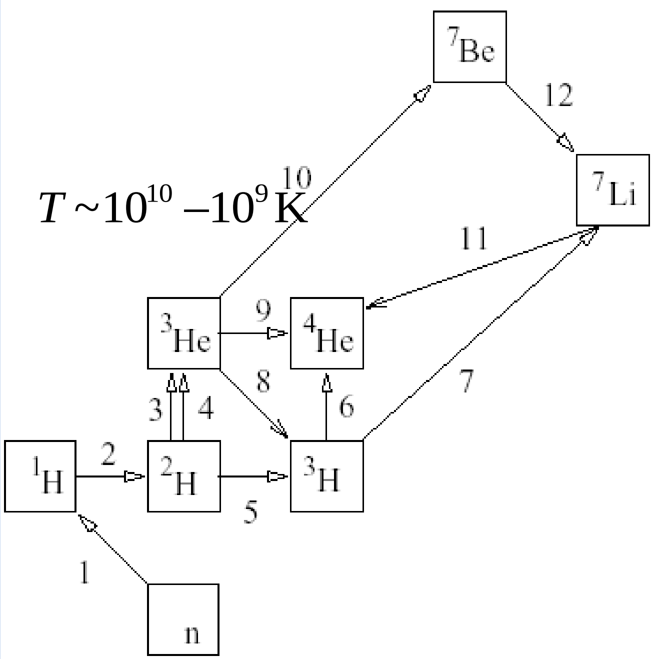
✓ baryon-to-photon ratio (CMB measured now),

✓ relativistic energy density (effective number of neutrino)

(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: 879.5±0.8s *(Serebrov et al. 2015)*



$T \sim 10^{10} - 10^{9}$ K

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

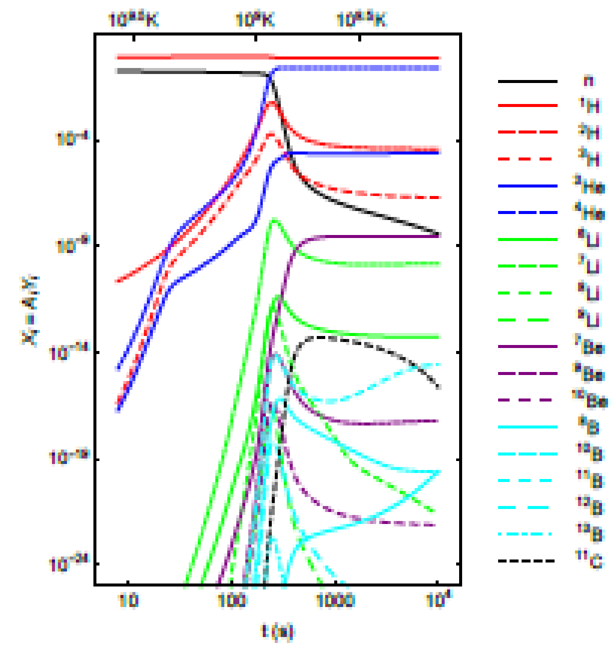


FIG. 25 *Left* : Evolution of light elements abundances. *Right*

Evolution of Light element abundances

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

PArthENoPE, AlterBBN, PRIMAT $Y_P(N_\nu,\eta)$, $X_D(N_\nu,\eta)$

Over 400 reactions considered.

More and more precise BBN codes used.

Y_T=(H(ρ(g)),Γ) = 0,24709± 0,00017

D/H =(2.459 ± 0,036) 10^{-5} *Pitrou, Coc et al. 2018*

Pitrou, Coc et al. 2018

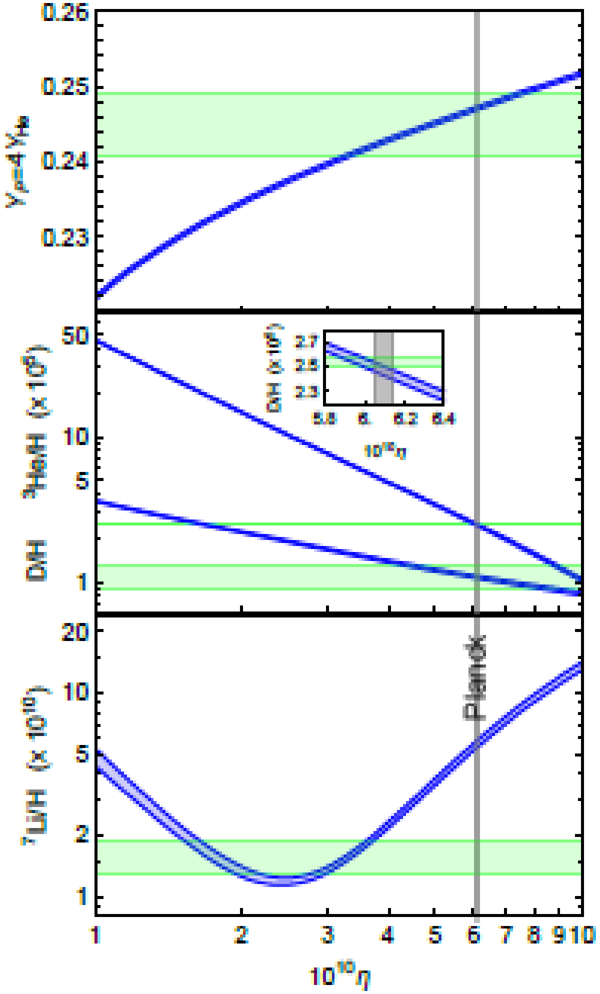
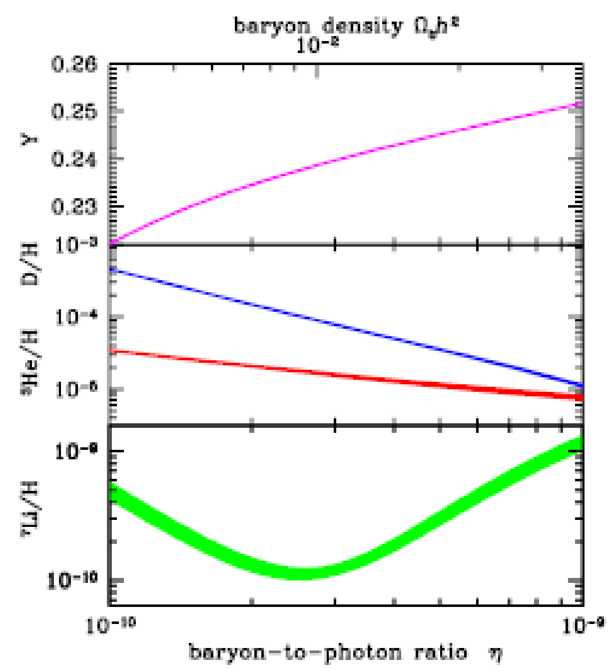


FIG. 26 *Top* : Dependence of $Y_P = 4Y_{^4\mathrm{He}}$ in η and observational constraints. *Middle* : Dependence of deuterium (top curve) and ^{3}He (bottom curve) in η with observational constraints. The ^{3}H has been added since it decays radioactively in ^{3}He. *Bottom* : Dependence of ^{7}Li in η with observational constraints. The ^{7}Be has been added since it decays radioactively in ^{7}Li. In all these plots, the width of the curves represents the $\pm\sigma$ uncertainty from nuclear rates and neutron lifetime.

The primordially produced abundances of the light elements as functions of $\boldsymbol{\eta}$.

Observational data (horizontal bands) compared with theory predictions for He-4 (top)., D and He-3 (middle) and Li-7 (bottom) .
Vertical band gives baryon density measured by CMB (Planck).



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

BBN - observational milestone of SCM

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

- 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.

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

- The cosmic microwave background radiation

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.)
- SUSY, string models, extradimensional models,

BBN is the most early and precision cosmology probe for physical conditions in the early Universe, and for constraining new physics, relevant at BBN energies.

BBN - the Best Baryometer at RD Stage

BBN baryometer

❖ Deuterium – the most sensitive baryometer.

$$\eta = n_b / n_\gamma \sim 6.10^{-10}$$

$5.8 \times 10^{-10} < \eta_{BBN} < 6.6 \times 10^{-10}$ 95%

$$\Omega_b h^2 = 3.65\times10^7\eta, \quad \Omega_b = \frac{\rho_b}{\rho_c}, \quad \rho_c = \frac{3H^2}{8\pi G_N}$$

$$0.021 \le \Omega_b h^2 \le 0.024 (95\% C.L.)$$

$$\Omega_b h = 0.0219 \pm 0.00025 (95\% C.L.)$$

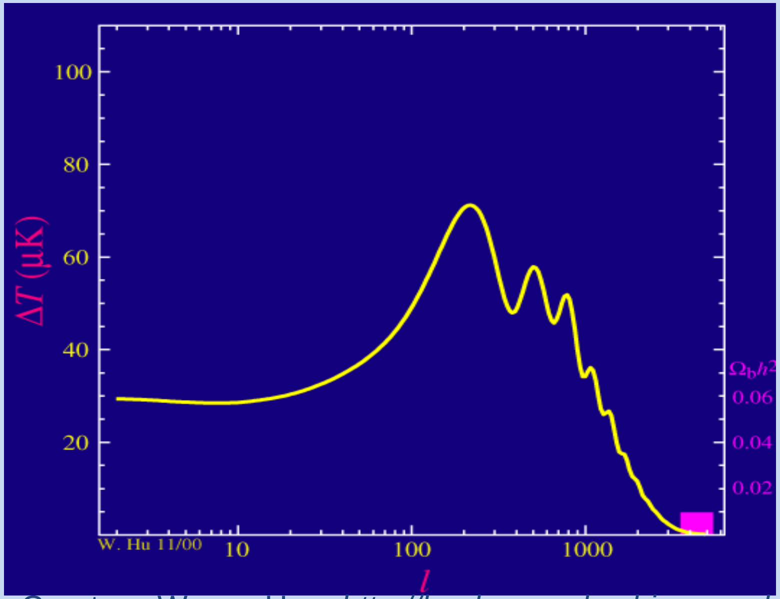
matter budget of the Universe
baryonic ~ 0.05 visible ~ 0.005,
gravitating ~ 0.3.

❖ CMB anisotropy measurements: Planck

(Planck2016) - $\eta_{CMB} = 6.11 \pm 0.04 \times 10^{-10}$, 68% CL

$$\Omega_b h = 0.0223 \pm 0.0002 (95\% C.L.)$$

Form of maxima depends on density of matter and baryons.



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

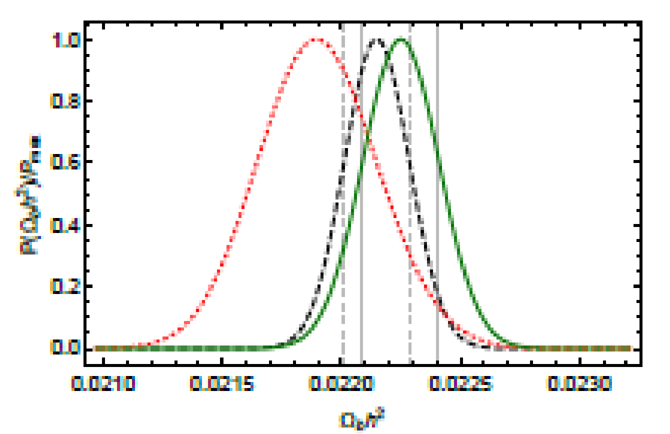
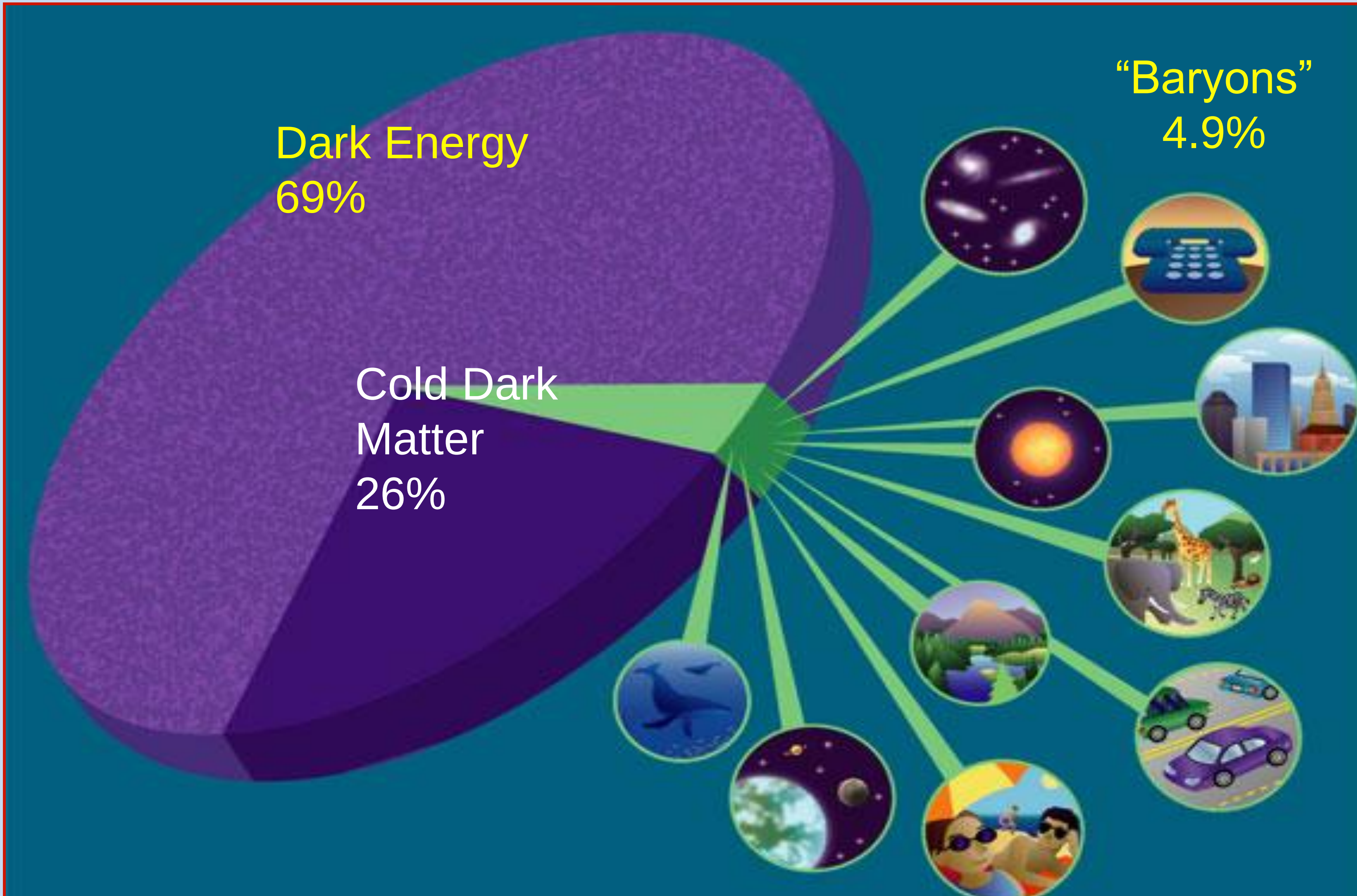


FIG. 27 $P(\Omega_b h^2)$ normalized to a unit maximum. *Green continuous line* : CMB prior distribution. *Black dashed line* BBN posterior distribution (BBN+CMB). *Red dotted line* : baryon abundance distribution determined only from BBN. The vertical gray lines are the $\pm\sigma$ CMB (continuous) and CMB+BBN (dashed) bounds.

Baryon density is 0.05 of the total density → Nonbaryonic matter exists!

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



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

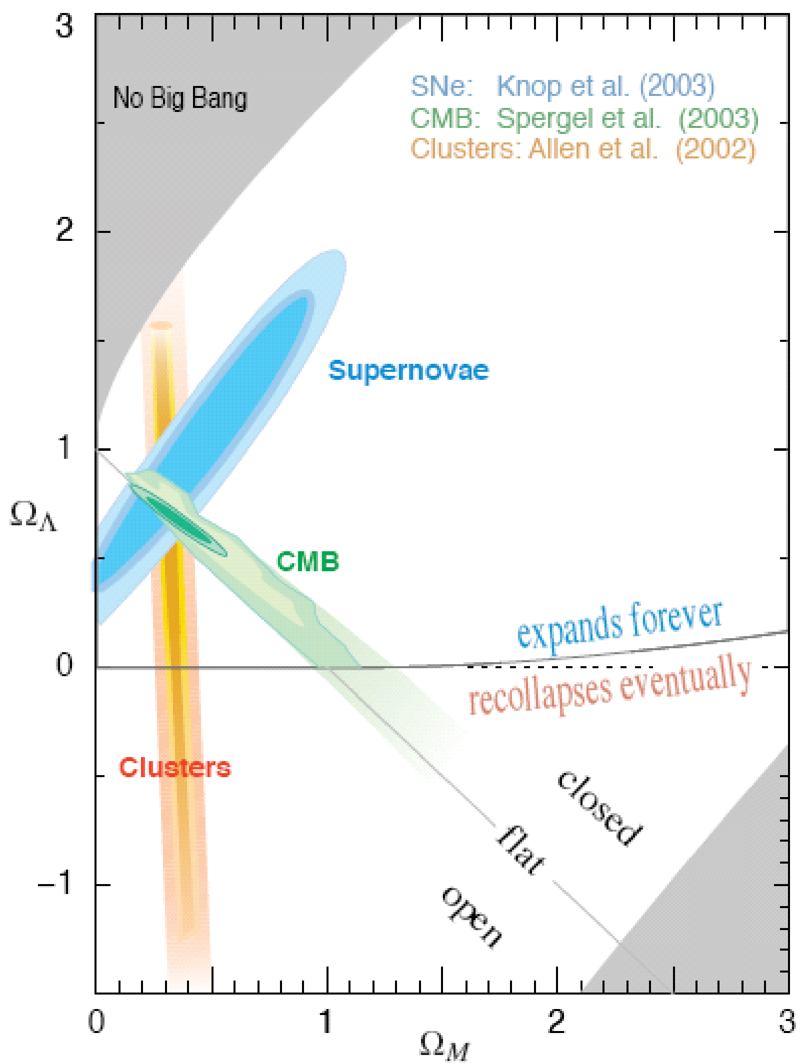
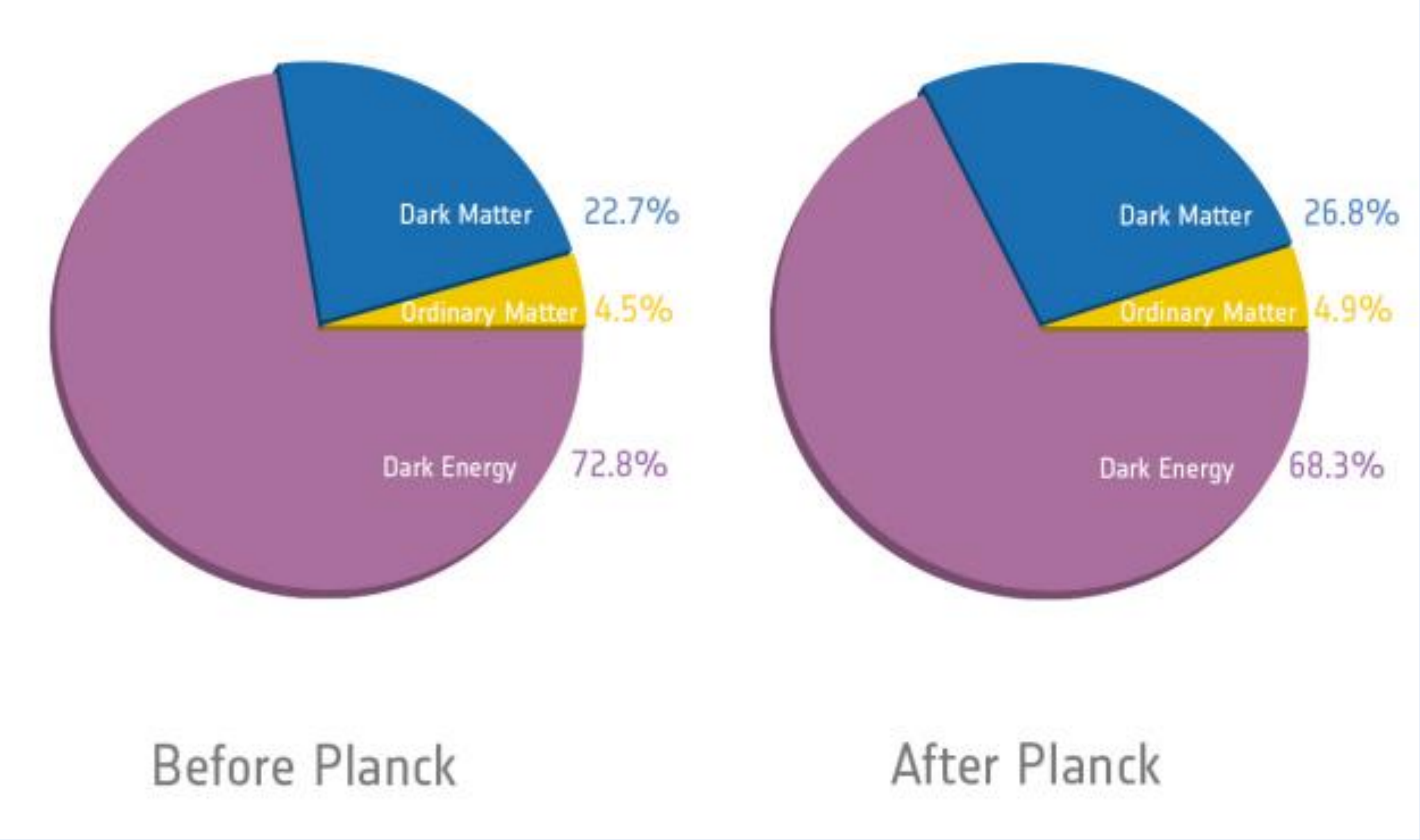


Figure 21.1: This shows the preferred region in the Ω_m–Ω_Λ plane from the compilation of supernovae data in Ref. 18, and also the complementary results coming from some other observations. [Courtesy of the Supernova Cosmology

Matter budget of the Universe



The 'before Planck' figure is based on the WMAP 9-year data release presented by Hinshaw et al., (2012).

$$0.001 < \Omega_\nu < 0.02$$

Baryon density is 0.05 of the total density → Nonbaryonic matter exists!

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 Dark Matter.

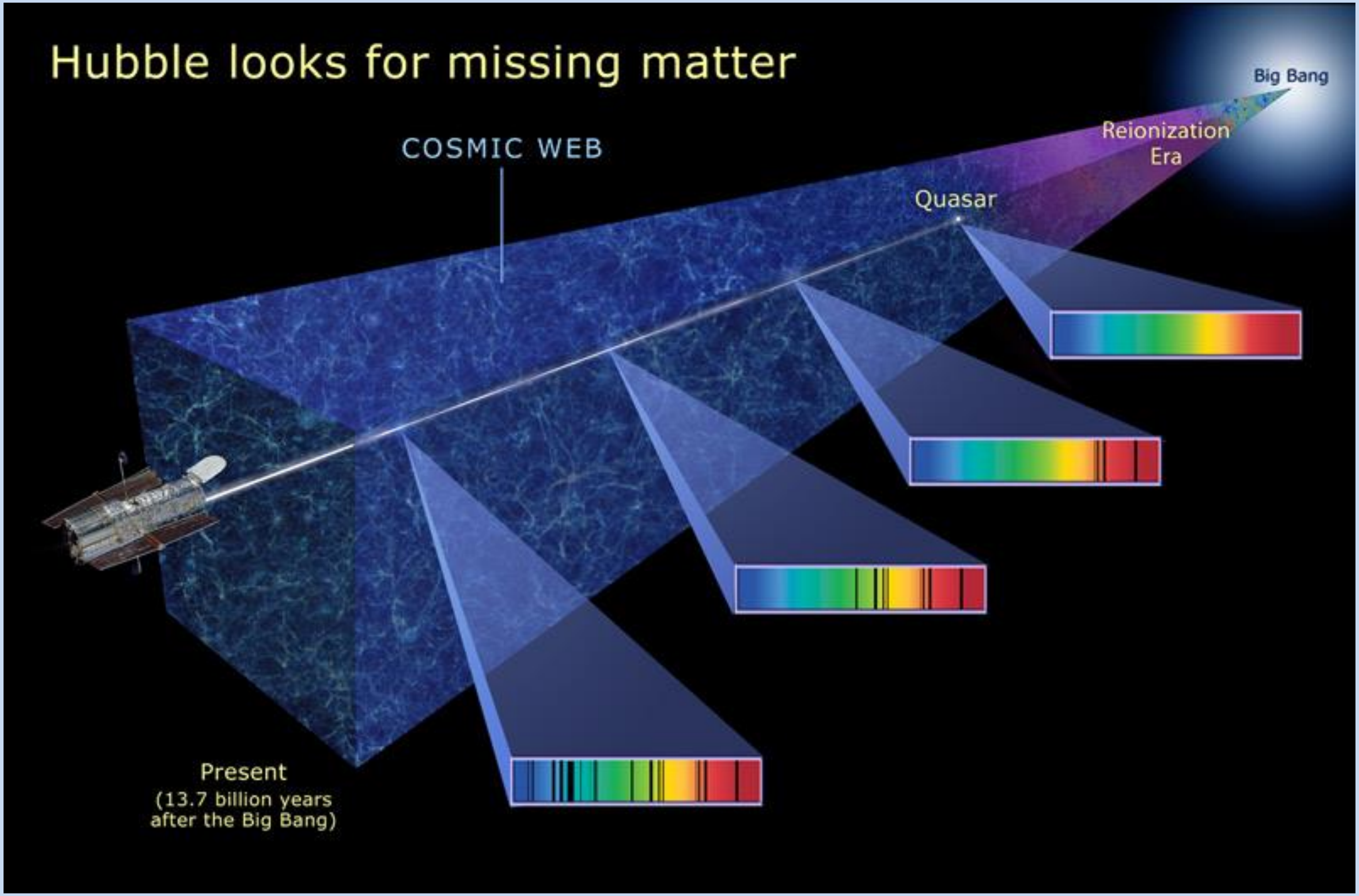
Why baryonic matter is such a small fraction?

What is the nature of nonbaryonic matter?

Where are the dark baryons?

Where are the antibaryons?`How and when the net baryon number was generated?

Half of the dark baryons are in the space between galaxies



In the spectra of the light from distant quasars (several billion ly away) the absorption lines of ordinary baryonic matter were found.

Where is the other half of dark baryons? MACHOS, BH,..

C. Danforth & M. Shull, ApJ, 2008

The analysis of HST FUSE observations taken along sight-lines to 28 quasars represents how the intergalactic medium looks within 4 billion ly of Earth.

Baryon Asymmetry of the Universe

Standard cosmology 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 are the antibartyons?

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..)

If the symmetry is local what were the separation mechanisms?

Dolgov, DK 89 ; DK, Chizhov MNRAS 2000; DK, NPB2002

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

PAMELA, BESS, AMS, AMS 2, PEBS, 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;08, 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

^{4}He – speedometer

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

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

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

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

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

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

$$\Delta m = 1.293 MeV$$

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

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

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

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

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

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

$Y_T = (H(\rho(g)), \Gamma) = 0{,}24709 \pm 0{,}00017$

$Y_o = 0{,}245 \pm 0{,}003$

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

Shvartsman 1969

^{4}He is the best speedometer. BBN constrains additional species.

BBN Speedometer

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

A maximum likelihood analysis:

$2.3 < N_{eff} < 3.4$

$5.6 < \eta < 6.6$

Cyburt, 2016

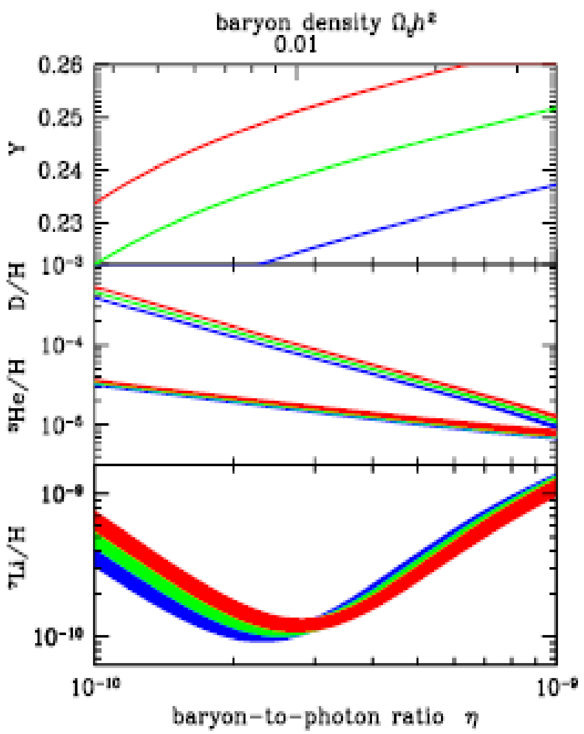


FIG. 7. The sensitivity of the light element predictions to the number of neutrino species, similar to Figure 1. Here, abundances shown by blue, green, and red bands correspond to calculated abundances assuming $N_\nu = 2, 3$ and 4 respectively.

Cyburt et al. 2016

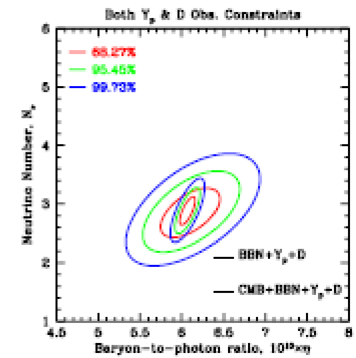


FIG. 10. The resulting 2-dimensional likelihood functions for the baryon to photon ratio (η) and the number of neutrinos (N_ν), marginalized over the helium mass faction Y_p, assuming different combinations of observational constraints on the light elements.

BBN and CMB constraints on additional light species

BBN $2.3 < N_{eff} < 3.4$

$5.6 < \eta < 6.6$

$N_{eff} = 2.88^{+0.27}_{-0.27}$ (95%) *Pitrou, 2018*

4

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

Planck Collaboration 2015

$N_{eff} = 3.13^{+0.31}_{-0.31}$ (95%)

$N_{eff} = 2.88^{+0.16}_{-0.16}$ (95% Planck +D+He-4) *Cyburt, 2016*

$N_{eff} = 3.01^{+0.15}_{-0.15}$ (95% Planck +BBN)

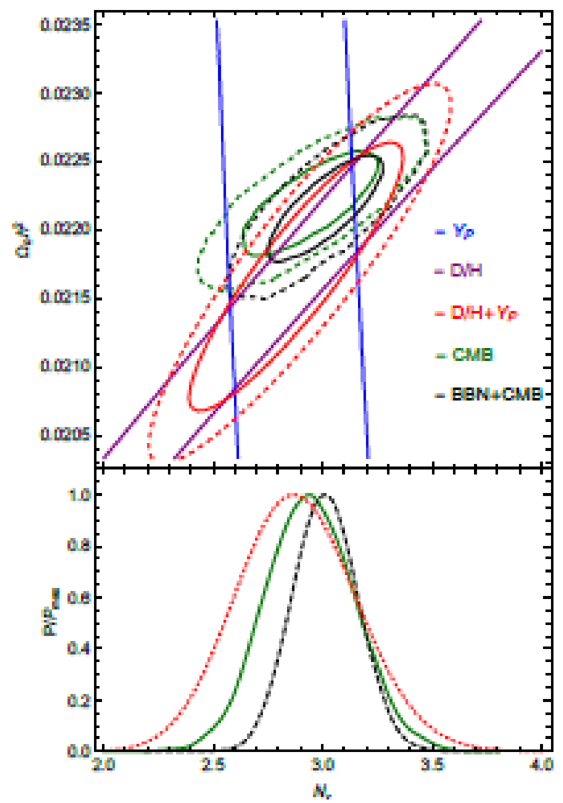


FIG. 29 Top : $P(\Omega_b h^2, N_\nu)$. with 68.27% and 95.45% contours for different combinations of data. Bottom : $P(N_\nu)$ from marginalization. Continuous green is from CMB only, dotted red from BBN only, and dashed black is the combination of BBN and CMB. Note that the average value of N_ν for the combination of BBN and CMB is not between the corresponding averages obtained from CMB and BBN considered separately. There is no contradiction since the nearly elliptic preferred regions in the $(\Omega_b h^2, N_\nu)$ space for BBN and CMB taken separately overlap away from the line defined by their respective average points.

BBN beyond SMP constraints

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

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

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

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

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

$\Delta N_{eff} < 0.4$

Schwartzman 1969

- **Constrains chemical potentials** $\Delta N_{eff} \doteq 15/7[([\mu/T)/\pi]^4 + 2[(\mu/T)/\pi]^2$

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

- **Constrains sterile neutrino decoupling production, right handed bosons**
- **Constrains neutrino oscillations parameters**
- **Constrains supersymmetric scenarios (lightest particle neutralino or gravitino), string theory, large dimensions**
- **Constrains decaying particles, SUSY metastable particles (solution to Li problem?)**

BBN with Neutrino Oscillations

Neutrino Oscillations Overview

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

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

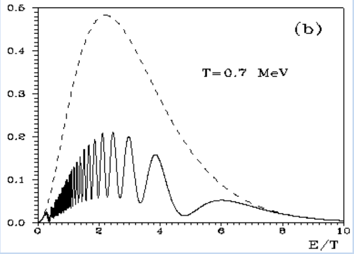
Oscillations imply

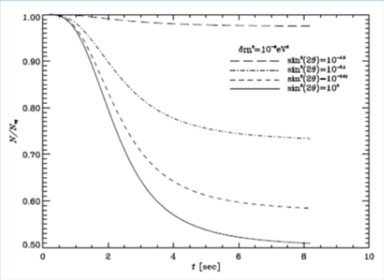
✓ non-zero neutrino mass and mixing

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

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

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





✓ L change

depletion $N_e < N_{eq}$

Neutrino anomalies are well described in terms of flavor neutrino oscillations, but sub-leading sterile oscillations may provide better fit.

additional species may be brought into equillibrium

✓ sterile neutrino $N_{eff} > 3$

Neutrino oscillations influence Universe processes. BBN constrains $\nu_s \leftrightarrow \nu_e$.

Neutrino oscillations effects on BBN

❖ **Active-sterile oscillations** considerable cosmological influence

✓ Dynamical effect: Excite additional light particles into equilibrium δN_s

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

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

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

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

✓ 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 $\rightarrow$ n/p freezes earlier $\rightarrow$ ^{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 to additional species and to distortions in the neutrino distribution.

BBN stringent limits on oscillation parameters.

DK&Chizhov 98,2000, Dolgov&Villante 03, DK04,07 ,DK&panayotova, 2006, DK07

Active-sterile oscillations may play crucial role for neutrino involved processes in the Universe during BBN, CMB, LSS, CNB.

Evolution of oscillating neutrino

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

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

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

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

Evolution of *nonequilibrium light oscillating neutrino* $\nu_e \leftrightarrow \nu_s$

effective after active neutrino decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ eV^2 *DK, Chizhov, 1996* *DK, Chizhov, PLB 1997*

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

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

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

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

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

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

In case of late oscillations distortion of neutrino momentum distribution by oscillations is possible.

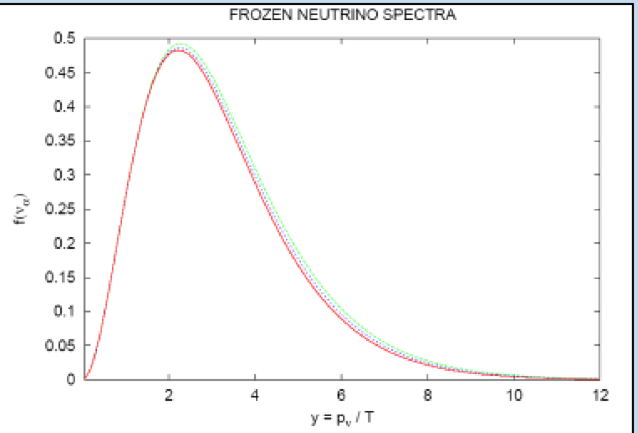
Approach: *follow the evolution of neutrino for each momentum and account for oscillations, expansion, neutrino forward scattering and interactions with the medium simultaneously.*

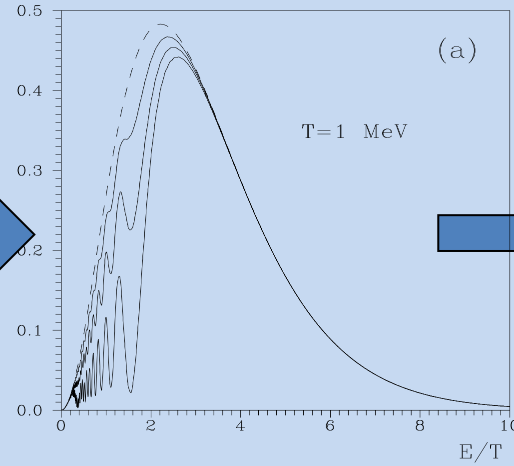
Even for fast oscillation case <p> approximation – not suitable, L growth overestimated.
Approximate solutions of L(t) were developed. *Foot&Volkas 97, Bell,Volkas&Wang,99*

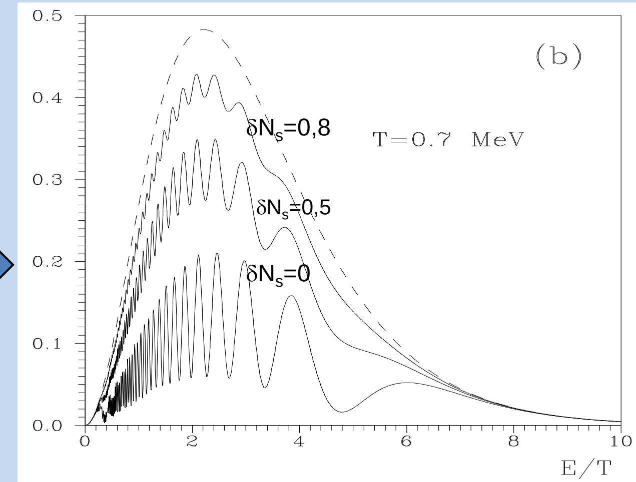
- Active-sterile oscillations proceeding after decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ may strongly distort neutrino distribution and deplete electron neutrino.

Kirilova 88, Kirilova&Chizhov PLB,97

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

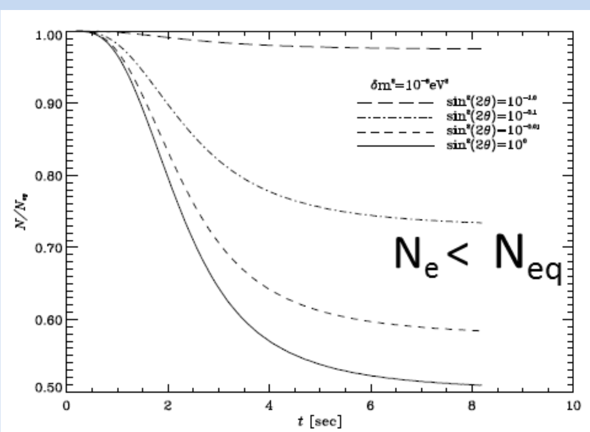






Kirilova,IJMPD,2004

The distortion due to active-sterile oscillations and the kinetic effect caused δN_k depends on the degree of initial population of ν_s.



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.

BBN with late $\nu_e \leftrightarrow \nu_s$ and L

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

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

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

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

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

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

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

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.

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

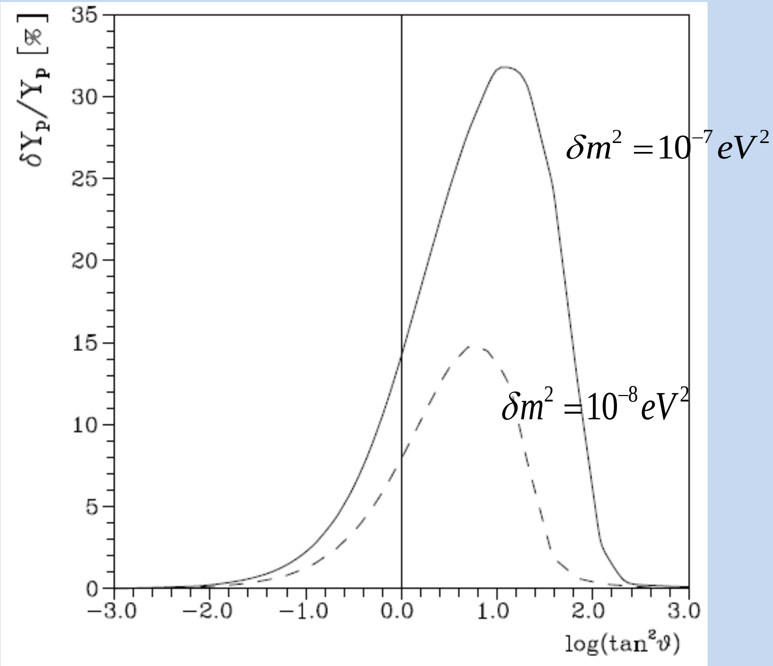
Maximum He-4 overproduction in BBN with oscillations due to spectrum distortion

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

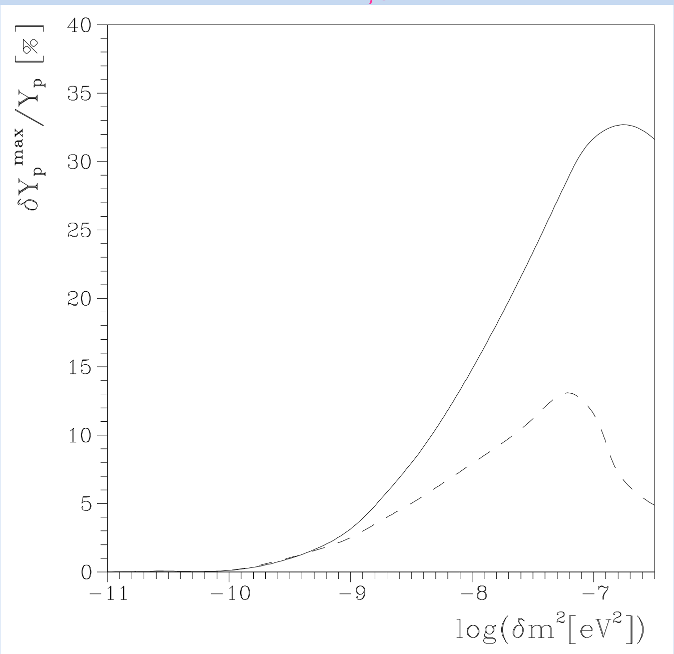
DK, Astrop.Phys.,2003

$\delta Y/Y \leq 32\%$ for resonant oscillations $\delta N_{k,0} \leq 6$

$\delta Y/Y \leq 14\ \%$ for non-resonant oscillations $\delta N_{k,0} \leq 3$



Dependence of maximum overproduction on the mixing



Dependence of maximum overproduction on mass

BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ allows to constrain ν oscillation parameters for He-4 uncertainty up to 32% (14%) in resonant (non-resonant) case.

BBN constraints on $\nu_e \leftrightarrow \nu_s$

He-4 is the preferred element:

Y_p=0,2565 ± 0.001(stat)± 0,005(syst)

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

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

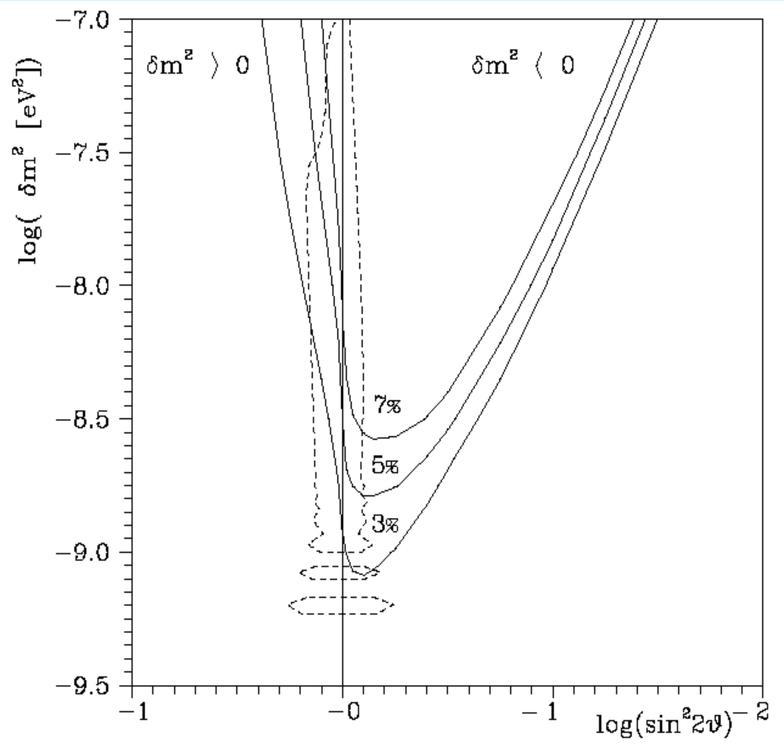
Y_p=0,2482± 0,0007

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

Fit to BBN constraints corresponding to $\delta Y_p/Y_p$=3%:

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

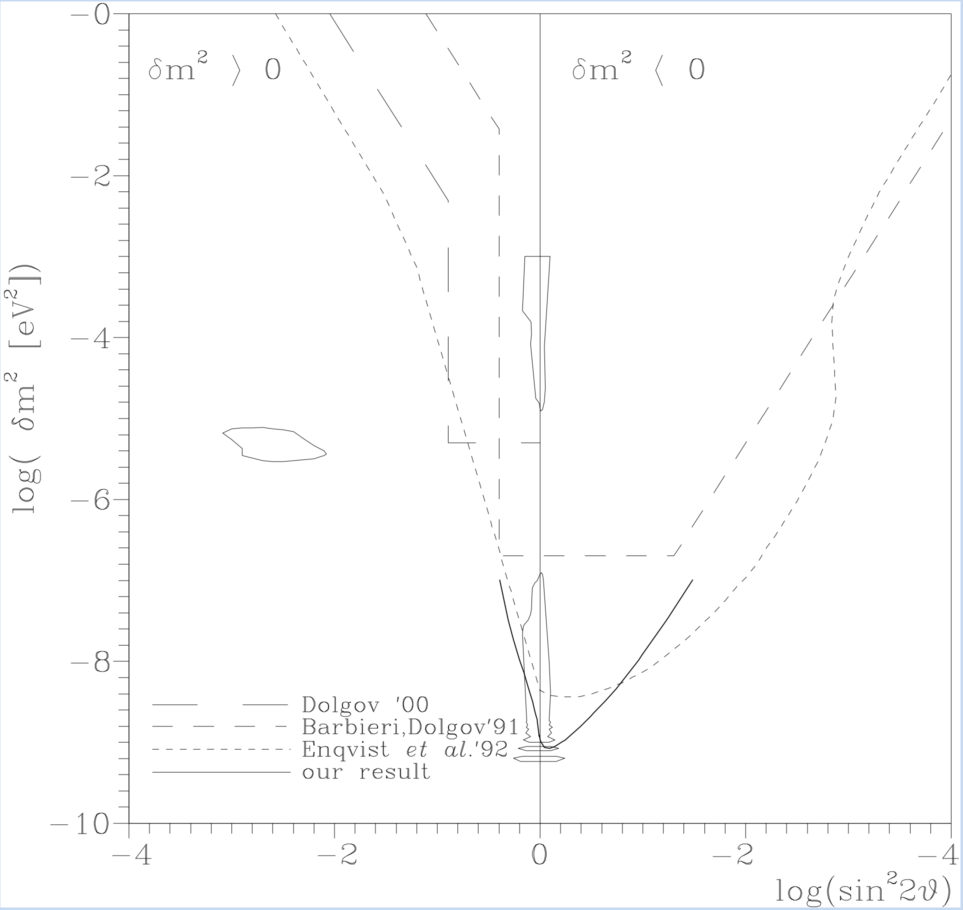
$$\delta m^2 < 8.2\times10^{-10}\,eV^2 \quad \text{large } \theta, \ \delta m^2 < 0$$



DK, Chizhov NPB2000,2001;

BBN constraints on oscillations

BBN with neutrino oscillations between initially empty ν_s and ν_e



BBN constraints on $\nu_e \leftrightarrow \nu_s$:

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

Fits to BBN constraints

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

$\delta m^2 > 10^{-6}$ eV^2

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

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

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

DK.,Chizhov 2001 – distortion and asymmetry growth account

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

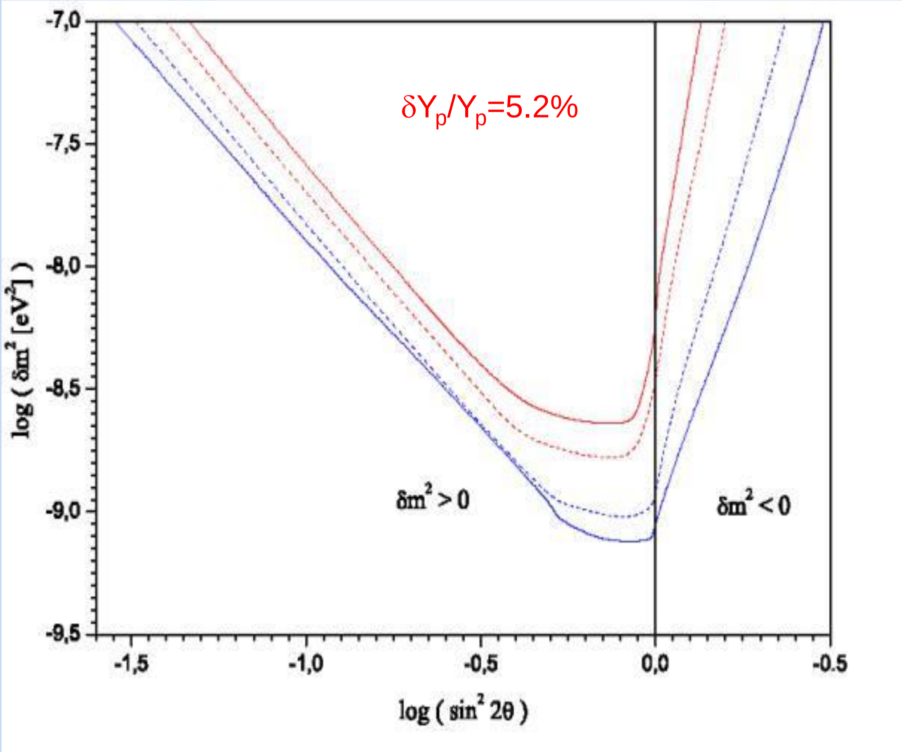
$$\delta m^2 < 8.2\times10^{-10} eV^2 \quad \text{large } \theta, \ \delta m^2 < 0$$

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

Generalized BBN constraints on $\nu_e \leftrightarrow \nu_s$

Additional ν_s population may strengthen or relax BBN constraints.

Constraint contours for 3 and 5% He-4 overproduction



Due to interplay b/n the effects of non-zero initial population of ν_s (partially filled) on BBN,

BBN bounds change non-trivially with δN_s:

In case the dynamical effect dominates, He-4 overproduction is enhanced and BBN constraints strengthen.

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

DK&Panayotova 2006;DK07

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

BBN constraints relaxed

Additional ν_s population relax BBN constraints.

Constraint contours for >5% He-4 overproduction

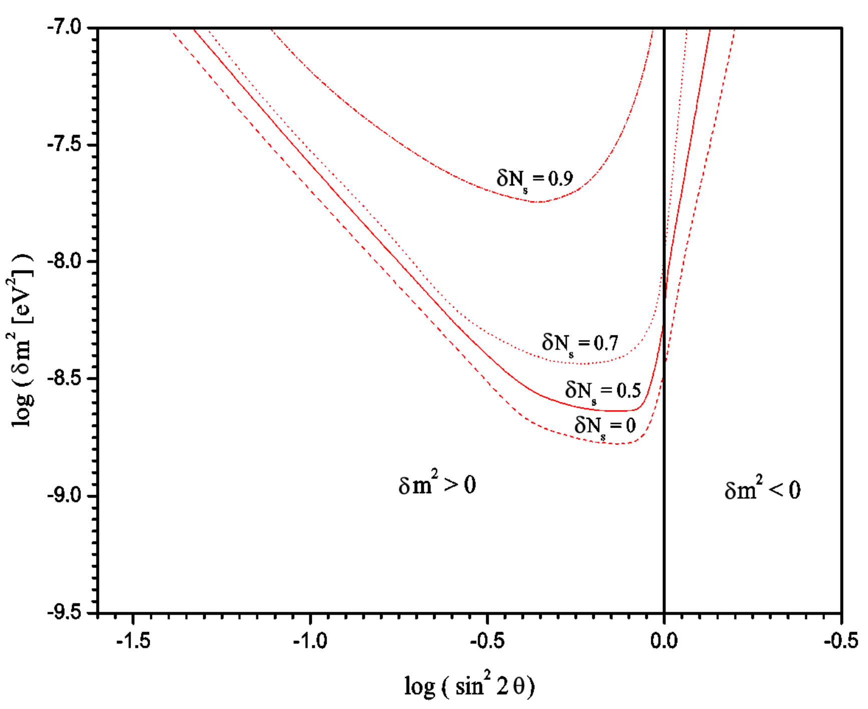


Fig.1 - The resonant ($\delta m^2>0$) and non-resonant ($\delta m^2<0$) iso-helium contours for $\delta Y_p/Y_p=5.2\%$ and $\delta N_s=0$ – dashed contour, $\delta N_s=0.5$ – solid contour, $\delta N_s=0.7$ – dotted contour and $\delta N_s=0.9$ – dotted-dashed contour are presented .

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

DK&Panayotova JCAP 2006;DK IJMPD 07,

BBN - Most Exact Leptometer

Lepton Asymmetry Effects

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

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

- 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

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

⇒ influence BBN, outcome is L sign dependent

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

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 - $0.01> L \geq 10^{-8}$ effects neutrino evolution, its number density, spectrum distribution, oscillations pattern and hence n/p kinetics and BBN

DK&ChizhovNPB98,2000;DK PNPP, 2010, 2011, DK JCAP,2012.

- L changes the decoupling T of neutrino, etc.

BBN Constraints on L

❖ BBN provides the most stringent constraint on L

In case neutrino oscillations degeneracies equilibrate due to oscillations before BBN

Dolgov et al., NPB, 2002 $|\xi_\nu| < 0.1$

❖ Accounting for flavor oscillations and ν decoupling and

Miele et al.,2011 $\sin^2\theta_{13} > 0.03$

Steigman, 2012

|ξ|<0.09 at 2 σ ΔN_{eff}^{L} ~ <0.011 at 2 σ; consistent with L=0 at 1.5 σ

Castorini et al. 2012 -0.071<L<0.054 *Mangano et al., 2013* |L|<0.2 big θ_{13}

❖ CMB provide looser bounds $\xi_\nu = 0.002 \pm 0.06$

❖ for θ_{13}~9^0 $|L| < 0.1$ $\xi_\nu < 0.3$

❖ Improvement on D and He measurement – stringent BBN constraints:

$\xi_\nu = 0.001 \pm 0.016$ $|\xi_\nu| < 0.016(68\%CL)$ $L < 0.01$

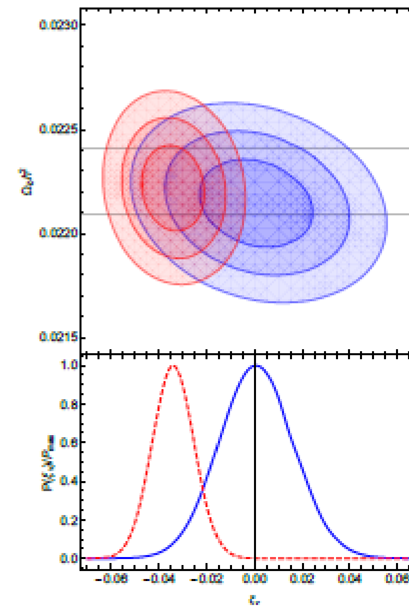


FIG. 28 Top: $P(\Omega_b h^2, \xi_\nu)$ with 68.27%, 95.45% and 99.7 contours. Blue: using the ⁴He bounds (4). Red: using bounds $Y_P = 0.2551 \pm 0.0022$ of Izotov et al. (2014). T gray horizontal bars are the ±σ CMB constraints on bary abundance. Bottom: marginalized distribution for ξ_ν. C tinuous line uses (4) whereas the dashed line uses the bou $Y_P = 0.2551 \pm 0.0022$ of Izotov et al. (2014).

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

Interplay between L and active-sterile oscillations allows to constrain strongly L.

Kirilova, Hyperfine Int. 2013 $L < (\delta m^2)^{2/3}$

L oscillations interplay

- ✓ Neutrino active-sterile oscillations change neutrino-antineutrino asymmetry of the medium

  suppress pre-existing asymmetry *Barbieri&Dolgov 90.91; Enqvist et al. 1992*

  enhance L (MSW resonant active-sterile oscillations) *L-T=M*

  -L-T=M

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

$\delta m^2 > 10^{-5} eV^2$ in collisions dominated oscillations *Foot, Thompson&Volkas 96; Bell,Volkas&Wang,99*

$\delta m^2 < 10^{-7} eV^2$ in the collisionless case *Kirilova&Chizhov 96;DK 2012*

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

Flavor oscillations equalize L in different flavors before BBN *Dolgov et al., NPB, 2002*

- ✓ Relic L effects neutrino oscillations

  suppresses them *Foot&Volkas, 95; Kirilova&Chizhov 98*

  enhances them *Kirilova&Chizhov 98*

In BBN with neutrino oscillations spectrum distortion and L generation lead to different nucleon kinetics, and modified BBN element production.

We studied the interplay between small L 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)

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

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

- Different cases of L were studied:

relic initially present $L>10^{-10}$ and dynamically generated by oscillations

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

The evolution of the L was numerically studied. L influence on oscillations was explored in the full range of model oscillation parameters and a wide range of L values. Primordial production of He-4 was calculated. Modified BBN constraints on oscillation parameters in presence of L were presented.

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.

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

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

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

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

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

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

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

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

BBN with $\nu_e \leftrightarrow \nu_s$ and L

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

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

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

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

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

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

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

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.

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

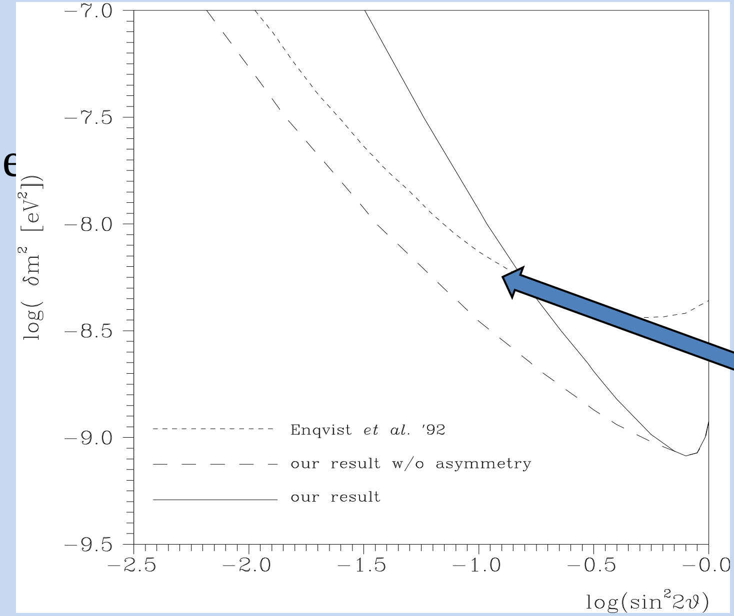
Leptogenesis by oscillations and BBN

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

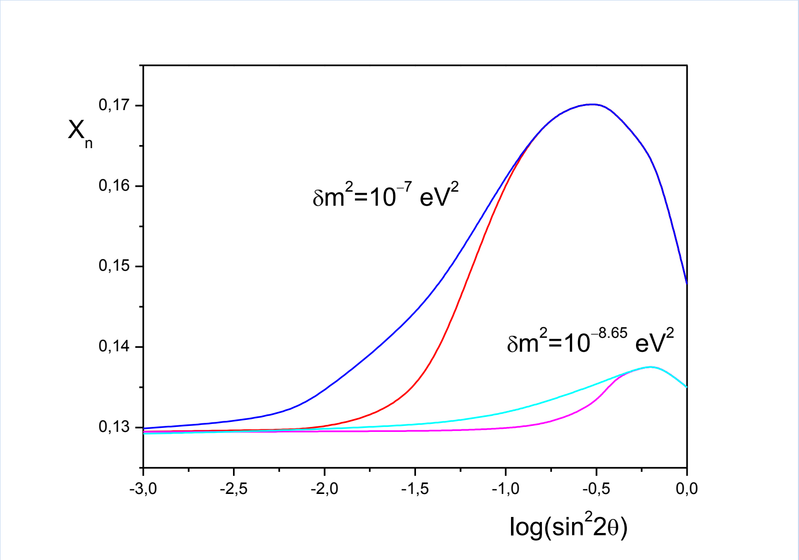
The region of parameter space for which large generation of L is possible:

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

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



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



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

DK, PNPP,2010; 2011

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

Relic L and BBN with neutrino oscillations

DK, JCAP 2012 BBN with oscillations can feel extremely small L: down to 10^{-8}

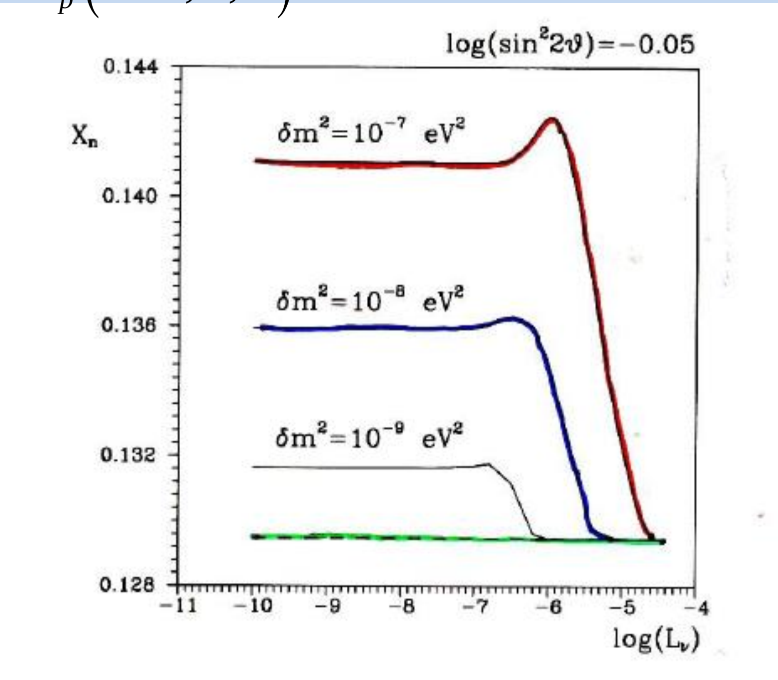
BBN with oscillations is the best known leptometer.

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

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

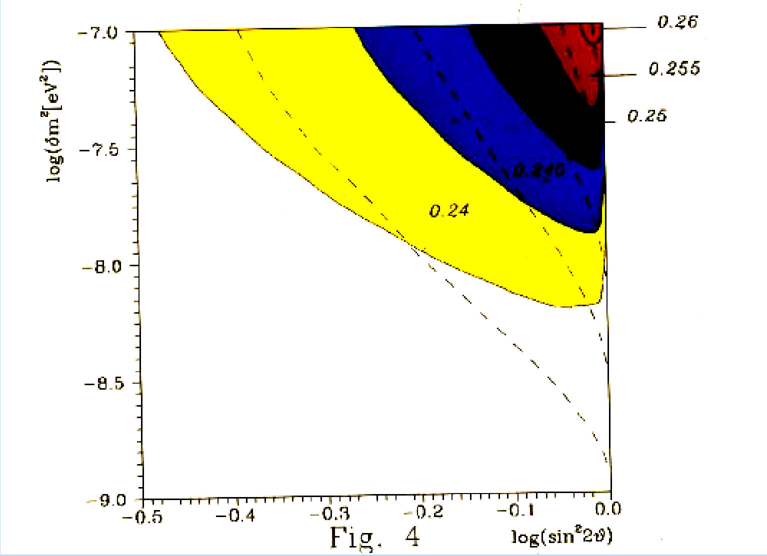
L change primordial production of He by enhancing or suppressing oscillations.

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



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

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

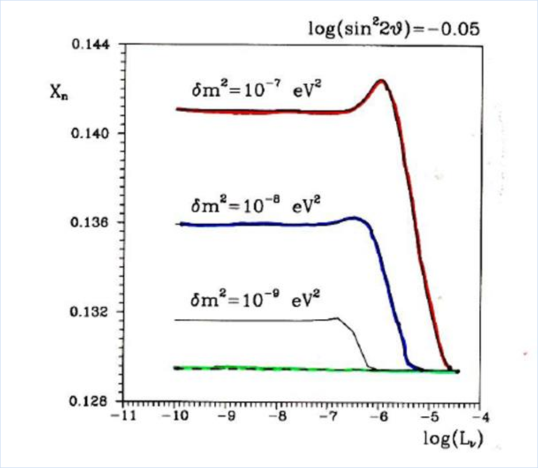


Lepton asymmetry L=10^{-6} relaxes BBN constraints at large mixings and strengthen them at small mixing. *DK&ChizhovNPB98, Kirilova JCAP 2012*

Relic L and BBN with neutrino oscillations

$Y_p\left(\delta m^2, \theta, L\right)$ $10^{-11}<L<0.01$

Kirilova JCAP 2012

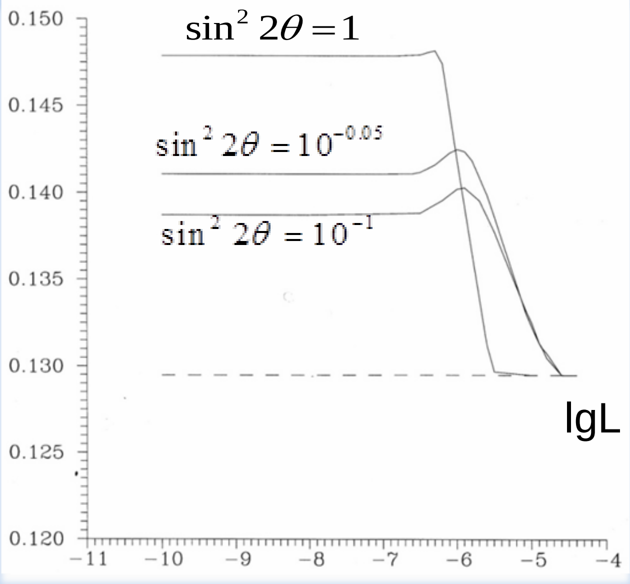


Constraints on L in case of electron-sterile oscillations with δm^2

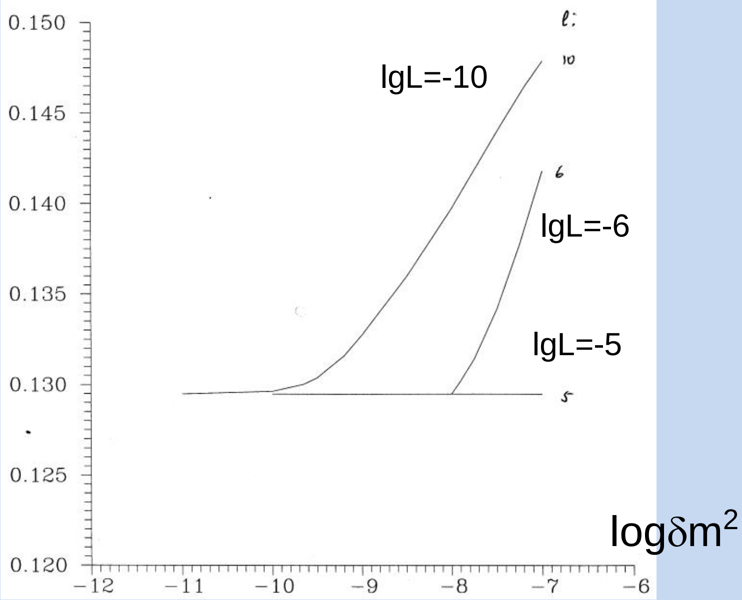
$$L < (\delta m^2)^{2/3}$$

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

❖ BBN with oscillations feels $L > 10^{-8}$



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

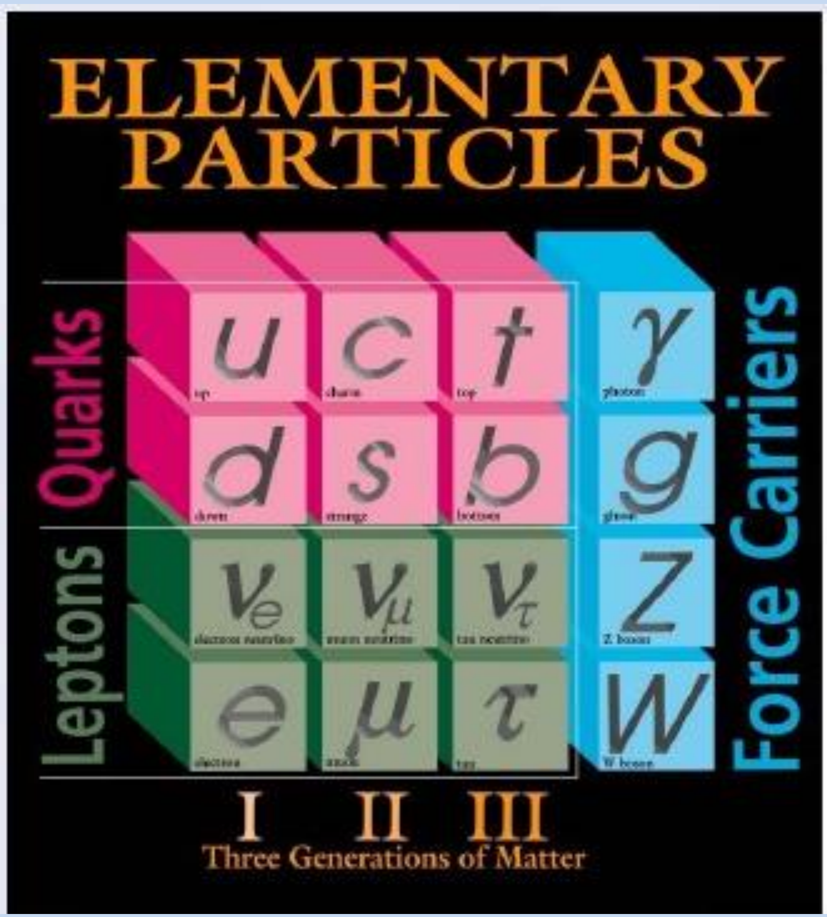


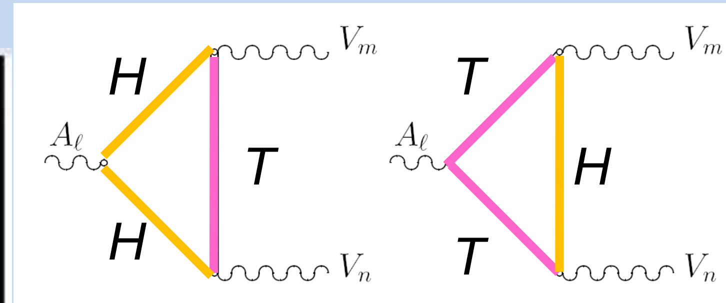
The dependences of helium production on δm^2 (for different L) .

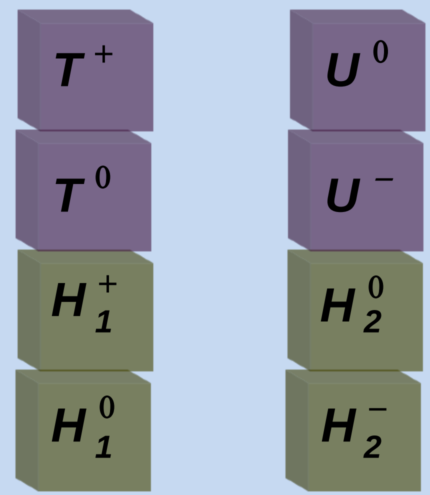
BBN and CTP

Standard Model extension

M. Chizhov, Mod. Phys. Lett. A, 1993







$$\tan\beta \equiv \frac{\upsilon_2}{\upsilon_1} \sim \sqrt{2}$$

$M_T \sim 1$ TeV, $M_U \sim 700$ GeV

$$g_*^{new} = 106.75 + 28 = 134.75$$

Chiral Tensor Particles Cosmological Place

M. Chizhov, D.K, IJMPA 09; D.K., V. Chizhov, IMPLett. 2017

- **characteristic interactions, cosmological t and T.**

$$\sigma_{if}(T)n(T) = H(T)$$

creation, ,

annihilation, decay

period of effectivness: **$1.9\ 10^{-40}$ s < t < t_d =$6.5\ 10^{-27}$ s**

T_c =$3.3\ 10^{16}$ GeV T_d =$5.7\ 10^{9}$ GeV

$$t_{eff} \approx 2.42/\sqrt{g_*}\,T_{eff}^2$$

- **Dynamical effects** – energy density increase, H and T(t)

$g_{ChT} = 28$

$$\rho_{ChT} = \frac{\pi^2}{30} g_{ChT} T^4$$

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

Conclusions: The provided analysis of the cosmological place of the chiral tensor particles showed, that

- cosmology allows the presence of tensor particles
- their direct interactions with the components of the high temperature plasma are effective for a short period during the Universe evolution
- they increase the effective degrees of freedom and hence speed the expansion of the Universe during that period

- **BBN constraint on the coupling constant**: $G_T \leq 10^{-2} G_F$

BBN constraint on new coupling constant

- BBN constrains sterile neutrino decoupling

From $\delta N_{eff} < 1$ at BBN epoch, and entropy conservation, we can calculate T_R decoupling of right-handed neutrino production:

$$N_{eff} = g_R(T_{\nu_R}/T_{\nu_L})^4 < 1 \qquad gT^3 = const$$

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

which corresponds to $T_d > 130$ MeV.

- BBN constraint on the new interaction

On the other hand T_d depends on G_T :

$$\frac{\Gamma_R}{\Gamma_L} = \left(\frac{T_d}{3}\right)^3 \left(\frac{G_T}{G_F}\right)^2 \sim 1$$

in case of 3 light right-handed neutrinos:

$$\left(\frac{G_T}{G_F}\right)^2 \sim \left(\frac{T_d}{3}\right)^{-3} \qquad G_T \le 10^{-2} G_F$$

Chiral Bosons Search at LHC

Summary

- Fruitful interplay b/n cosmology and particle physics exists.

  Cosmology can predict the influence of BSM characteristics and test them. In particular, BBN is the earliest and the most reliable probe of beyond SMP. It «measures» neutrino mass differences, number of neutrino species, neutrino oscillations patameters, deviations from equilibrium, baryon density, L, new interactions, etc.
- BBN is a reliable baryometer. The baryon density is measured with great precision and points to beyond SMP – necessity of nonbaryonic DM. Its nature is still an open issue both in cosmology and in particle physics.

  Though baryon density is measured with a high accuracy today, the exact baryogenesis mechanism is not known. The problem of BA of the Universe is still fascinating.The possibility for astronomically large antimatter objects is experimentally and theoretically studied.
- BBN is a very sensitive leptometer. Dynamical and kinetic effect of L on BBN lead to the SBBN bound $|L|<0.1$. BBN bounds on L are changed in case of neutrino oscillations. Stringent BBN constraints on L in case of electron-sterile oscillations exist. L as small as 10^{-8} may be felt by BBN via oscillations.
- BBN is the most sensitive spedometer. Stringent BBN constraints on additional light particle species N_{eff} exist. These constrain SUSY, string, extradim models, etc.

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

Summary

- BBN constrains neutrino oscillations parameters. Constraints exist even if He-4 uncertainty were over 5%. BBN provides the most stringent constraint on δm^2 . 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.

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

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

  Relic L may provide relaxation or enhancement of BBN constraints on oscillations.

- Large enough L may provide relaxation of BBN constraints on oscillations, by suppressing oscillations and causing incomplete thermalization of the sterile neutrino.

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

Now BBN presents the best test for New Physics. 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 density, etc.

Благодаря за вниманието!

Thanks for the attention!

Solving BBN dynamics

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

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

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

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

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

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

Miele et al. 2011

- **BBN codes (PArthENoPE, AlterBBN, PRIMAT) get $Y_P(N_\nu, \eta)$, $X_D(N_\nu, \eta)$**
- $Y_T = (H(\rho(g)), \Gamma) = 0{,}24709 \pm 0{,}00017$
- $D = (2.459 \pm 0{,}036)\ 10^{-5}$

Pitrou, Coc et al. 2018

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 and LSS

- 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…..

Sterile Neutrinos Status

- Sterile neutrino is not constrained by LEP
- Required for producing non-zero neutrino masses by most models
- Predicted by GUT models
- Hints from oscillations data: for better fit subdominant sterile oscillations channel required by Homestake data, Holanda, Smirnov, 2004), Chauhan, Pulido, 2004, variation of the flux with B, Caldwell D, Sturrock P.,2005
- required for explanation of LSND in combination with other expts
- Wellcomed by cosmology:

* may be the particle accounting for all DM (m<3.5 KeV if MSM produced)

* may play subdominant role as DM component (eV, KeV)

* Fast moving neutrinos do not play major role in the evolution of structure in the universe.

* 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) *Tegmark et al., 2004*

*plays major role in natural baryogenesis through leptogenesis

Oscillations in the Early Universe medium

- 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>>Q

$V_f = Q - L$ for neutrino

$V_f = Q + L$ for antineutrino

$Q = -bET^4/(\delta m^2 M^2_W)$ $L = -aET^3 L_\alpha/(m^2)$

- In the early Universe, 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: $\sin^2\theta_m = \sin^2\theta/[\sin^2\theta + (Q \pm L - \cos 2\theta)^2]$

In general the medium suppresses oscillations.

When $Q \pm L = \cos 2\theta$ mixing in matter becomes maximal independent of mixing in vacuum - enhanced oscillation transfer.

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

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

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 $L \sim \beta$, big L may reside in the neutrino sector (universal charge neutrality implies $L_e = \beta$) .

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

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

light element abundances from Big Bang Nucleosynthesis , CMB, LSS, etc.

Wagoner et al.1967….Terasawa&Sato, 1988 …

Dolgov,2002

Serpico&Raffelt, 2005; Pastor, Pinto&Raffelt,2009; Simha&Steigman, 2008

Lesgourgues&Pastor,1999; Shiraishi et al., 2009; Popa&Vasile, 2008

- Maximum He-4 overproduction in BBN with active-sterile neutrino oscillations may be much bigger than 5% due to kinetic effects.

BBN with $n_e \leftrightarrow n_s$ leads to max ^4He overproduction 32% in the resonant case (13% in the non-resonant) i.e. 6 times stronger effect than the dynamical oscillations effect. *DK., Astrop.Phys.,2003*

BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ allows to constrain ν oscillation parameters for He-4 uncertainty up to 32% (14%) in resonant (non-resonant) case.

- The kinetic effects of oscillations depend on the initial population of neutrino due to interplay b/n effects

Role of sterile neutrino: dynamical effect– increasing H(g)
suppressing the osc kinetic effect

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

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