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Updated BBN Cosmological Constraints on Beyond Standard Model Physics

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Standard BBN introduction

The chemical composition of the baryonic component of Universe now is mainly 24.7% He^4 and H.

This content is synthesized during the hot early stage of the Universe evolution when its temperature T (1–0.1 MeV) and density were suitable for nuclear reactions to proceed, i.e. during primordial nucleosynthesis BBN.

Besides He-4 several light elements with negligible quantities were synthesized: D, He^3, Li^7 , and even less abundant C, N and O.

Y_p~0,247, D/H ~ 3×10^{-5} , He^3/H ~ 3×10^{-5} , Li/H ~ H~10^{-10}

Heavier than Li-7 nuclei were not produced during BBN in considerable quantities mainly because of the fast decrease of the baryon density and T due to Universe expansion.

Heavier elements were produced much later in star cores, during SN bursts and in CR.

Standard BBN introduction

The primordially produced abundances depend on:

- ✓ baryon-to-photon ratio, η_{CMB} = (6.104 ± 0.055) 10^{-10}
- ✓ relativistic energy density (effective number of neutrino)

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

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

- ✓ n lifetime: 880.3±0.1s *(Serebrov et al. 2015)*

Over 400 reactions considered.
More and more precise BBN codes used.

Modern analyses of nuclear rates for BBN have been provided (NACRE compilation of *Angulo et al. 1999*; NACRE-II, *Xu et al. 2013*).

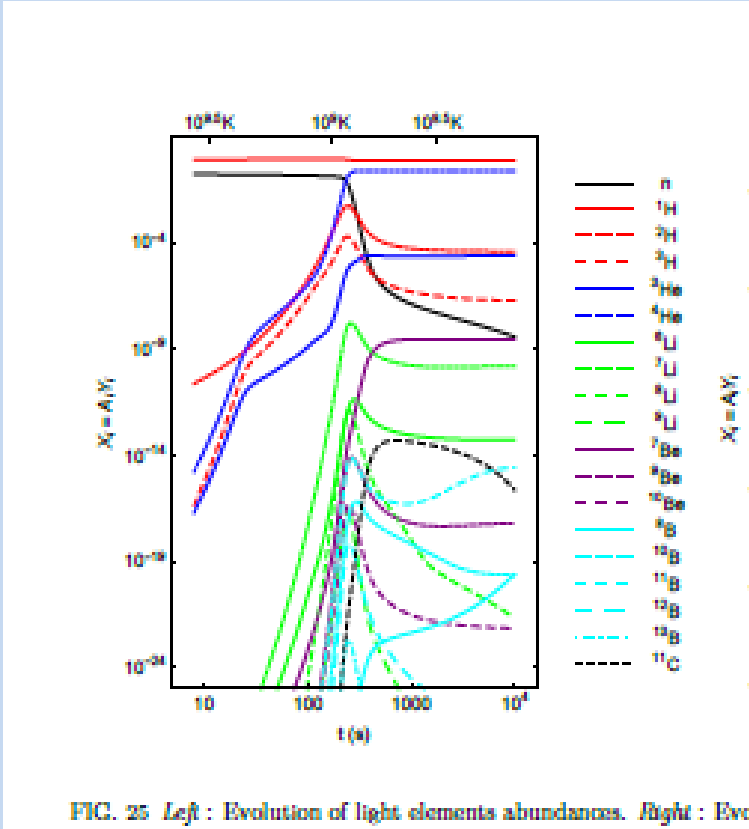


FIG. 25 *Left* : Evolution of light elements abundances. *Right* : Eve

Evolution of Light element abundances.

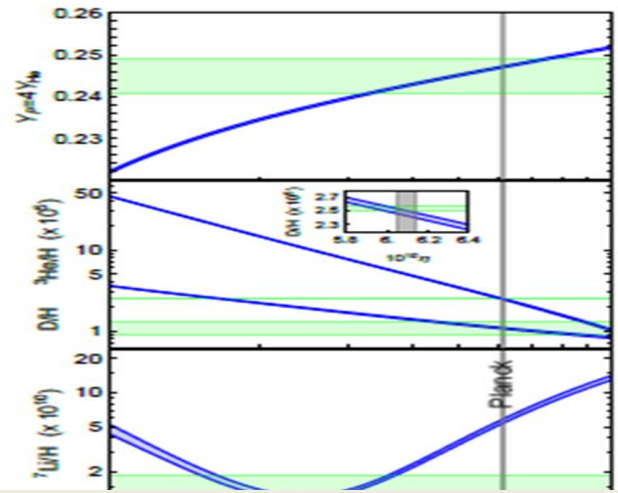
Pitrou, Coc et al. 2018

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

Y_P = 0,24709± 0,00017

D/H =(2.459 ± 0,036) 10^{-5}

BBN reliable test of BSM physics



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).

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

Most reliable precision probe for physical condi
in early Universe and a unique test for new phys
due to the remarkable concordance between
theoretically predicted and derived from observ
abundances of light elements produced primordi

The Best Speedometer at RD Stage

BBN probes neutrino oscillations

The Most Exact Baryometer and Lepto

DK&Chizhov 98,2000, DK 07,12, 13,18

DK&Ipanayotova, 2006, 2011;

Y_p=0.245± 0,003 , D/H=(2.527±0.03) 10^{-5}

Peimbert,2016;Aver et al. 2015 Cooke et al. 2017

He-4 – preferred for BBN constraints on new physics

- The post BBN evolution of ^{4}He is simple: only produced in the stellar and galactic chemical evolution.
- It is the most abundantly produced (after H)
- most precisely calculated (0.1% uncertainty)

$$Y_p = 0{,}2482 \pm 0{,}0007$$

- very sensitive to nucleons kinetics before BBN

sensitive to neutrino characteristics (n, N, sp, L.)

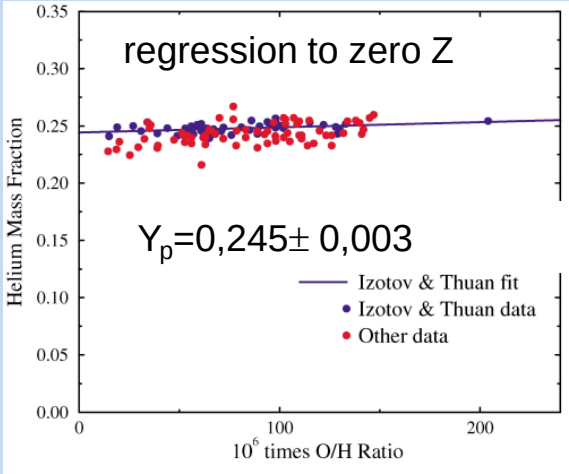
- precisely measured element

The accuracy of the determination is limited by systematic errors.

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

The primordial abundance of ^{4}He is obtained from observations of He and H emission lines from metal poor HII regions, like compact blue dwarf galaxies.

Linear fit of all the data obtained from spectra of HII regions is made and then extrapolated to zero metallicity. The linear correlation between ^{4}He, produced in stars and metals Z (C, N and O) is used to derive the primordial mass fraction helium.



In the previous decade primordial He-4 was known with 3-7% precision, and the constraints on beyond SM physics used this precision. During the last decade the precision of helium measurements increased. Many systematic effects were corrected in recent observations in order to derive from the observed intensities of He spectral lines its primordial value .

Recently primordial He-4 was determined with better than 3% accuracy.

- Inclusion of He 10830 infrared emission line which shows a strong dependence on the electron density and is thus useful to break the degeneracy with the temperature, allowing for a more robust helium abundance determination;

- the underlying 4He stellar absorption, and/or the newly derived values of the HeI-recombination and H-excitation-collisional coefficients were considered

- New observations of HeI λ10830 emission line in the brightest HII region in the extremely metal poor galaxy Leo P were made.

These observations combined with previous ones allowed to derive an improved helium abundance:

$$Y_p = 0.2453 \pm 0.0034.$$

Aver E. et.al., JCAP 2015,2021; Hsyu et.al., ApJ 2020, Valerdi et.al., ApJ 2019

This allows to update and strengthen the Big Bang Nucleosynthesis constraints on physics beyond Standard Model.

Here we present previous BBN constraints on beyond SM physics, based on primordial helium-4 values with 3-7% uncertainty and our recently updated BBN constraints corresponding to the latest data on primordially produced ^4He, which correspond to Y_p/Y_p=1-2% uncertainty.

We consider several models representing beyond SM physics and provide updated constraints on them:

- We analyze the model of BBN with neutrino oscillations and derive stringent BBN constraints on neutrino oscillations parameters corresponding to the present accuracy of He-4 determination *DKirilova,MPanayotova, 2022.*
- ✓ We discuss the cosmological constraints on the number of the effective degrees of freedom of light particles during the BBN epoch
- ✓ We present BBN based constraints on the freezing temperature of the light sterile neutrinos. *DKirilova, EChizhov, 2019, 2022*

BBN with Neutrino Oscillations

Neutrino Oscillations

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

It has been observationally and experimentally proved that *neutrinos oscillate*. *Hence*, mass eigenstates are distinct from the flavor eigenstates.

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

✓ Combined neutrino oscillations data including reactor exps+LSND+MiniBooNe+Gallium:

hint to 1 light ν_s with eV mass (in eq. before BBN),

Neutrino oscillations influence Universe processes.

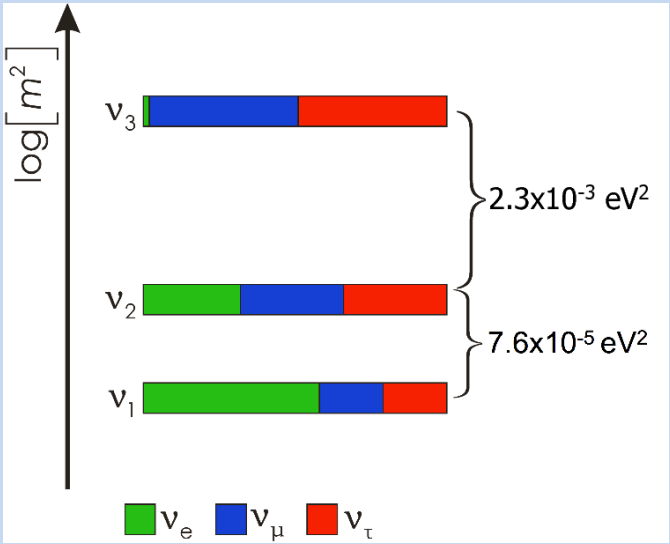
Cosmology constrains oscillations b/n light $\nu_s \leftrightarrow \nu_e$.

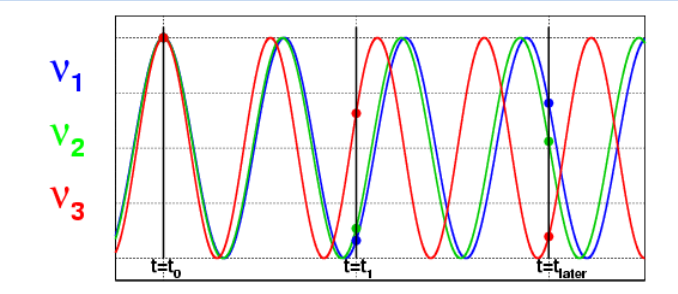
$$P\,(\theta, \delta m^2, E, t)$$

Oscillations imply

✓ non-zero neutrino mass and mixing

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





Neutrino Oscillations Effects

- Dynamical effect: Excite additional light particles into equilibrium δN_s

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

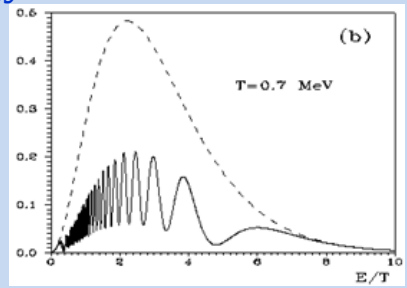
Fast $\nu_a \leftrightarrow \nu_s$ effective before ν_a decoupling - effect BBN through increasing H

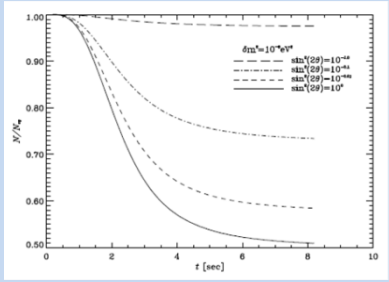
Dolgov 81. Kirilova 88, Barbieri, Dolgov 90, Kainulainen 91, Enqvist et al.,92

- ✓ Distorting the neutrino energy distribution from the equilibrium FD form

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

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





DK 88, D.K&Chizhov,96,PLB 97

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)

D.K&Chizhov,96; Foot&Volkas 95,96; Shi 96

BBN is a sensitive to additional species and to distortions in neutrino distribution
BBN constrains oscillation parameters.

DK&Chizhov 98,2000, Dolgov&Villante 03, DK04,07 DK 04, 2012, DK&Panayotova 06

Evolution of neutrino in presence of late $\nu_e \leftrightarrow \nu_s$

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

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

DK 1988, Chizhov, DK, 1997

- 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*

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

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

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

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

In case of late oscillations distortion of neutrino momentum distribution by oscillations is possible.
Precise description of neutrino momenta distribution is needed: 1000 bins used to describe it in non-resonant case, and up to 10 000 in the resonant case.

Production of He-4 in BBN with $\nu_e \leftrightarrow \nu_s$

❖ 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.

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

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

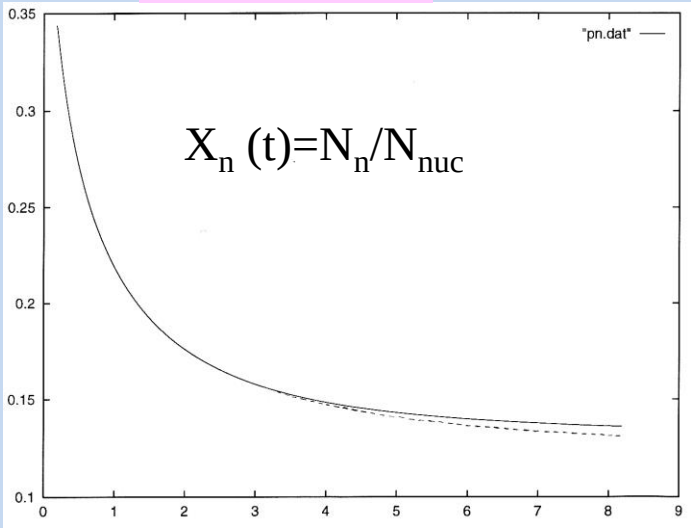
$$\frac{\partial n_n}{\partial t} = Hp_n \frac{\partial n_n}{\partial p_n} + \int d\Omega(e^-, p, \nu) \left| A(e^- p \rightarrow \nu n) \right|^2 (n_{e^-} n_p - n_n \rho_{LL})$$
$$- \int d\Omega(e^+, p, \tilde{\nu}) \left| A(e^+ n \rightarrow p \tilde{\nu}) \right|^2 (n_{e^+} n_n - n_p \bar{\rho}_{LL})$$

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

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

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

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



Neutron-to-nucleons freezing ratio evolution in the case of asymmetry growth (solid line) and in case asymmetry growth neglected (dotted line).

Numerical analysis:

- Evolution of oscillating neutrino
- Evolution of nucleons and n/p freezing
- He-4 production

Dynamical and kinetic effect of $\nu_e \leftrightarrow \nu_s$ on BBN were explored.

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

- Nucleons evolution in the pre-BBN period in the presence of $\nu_e \leftrightarrow \nu_s$ was numerically analyzed and He-4 was calculated for different sets of oscillation parameters.

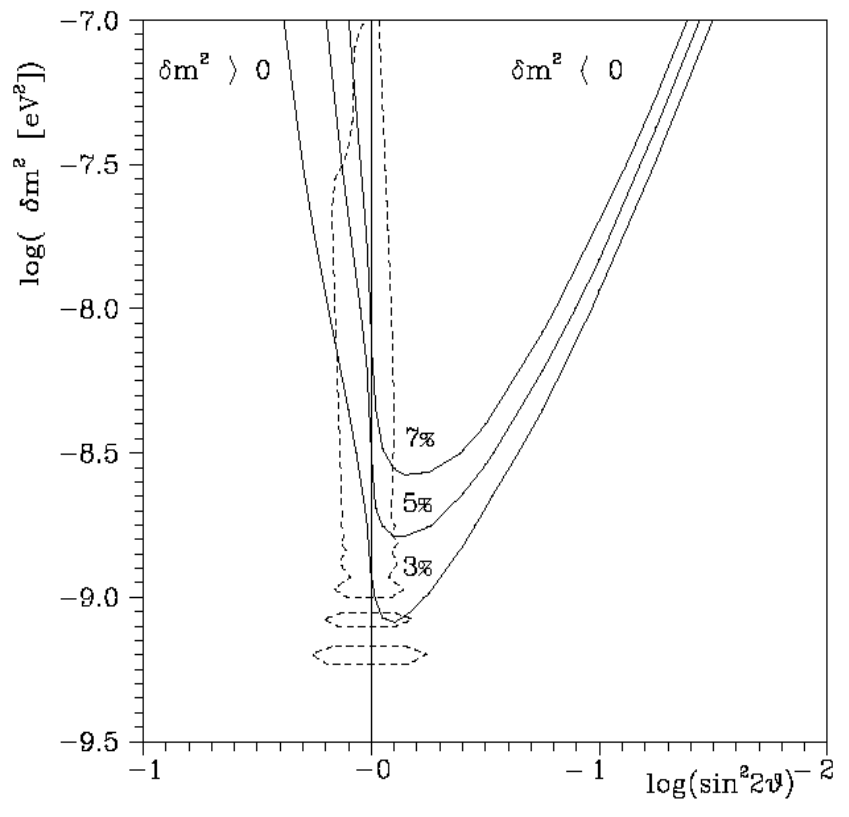
Previous BBN constraints on $\nu_e \leftrightarrow \nu_s$

In the 90ies ^{4}He ~ 3-7% accuracy → BBN constraints on δm^2 and $\sin^2 2\theta$ for 3-7% overproduction of ^{4}He.

Y_p=0,2565 ± 0.001(stat)± 0,005(syst)

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

- We have calculated combined iso-helium contours for 3-7% ^{4}He overproduction, accounting for all oscillations effects on BBN, for initial population δN_s=0, for non-resonant δm^2<0 and resonant δm^2>0 cases
- We have derived cosmological constraints on oscillations parameters δm^2 and $\sin^2 2\theta$.

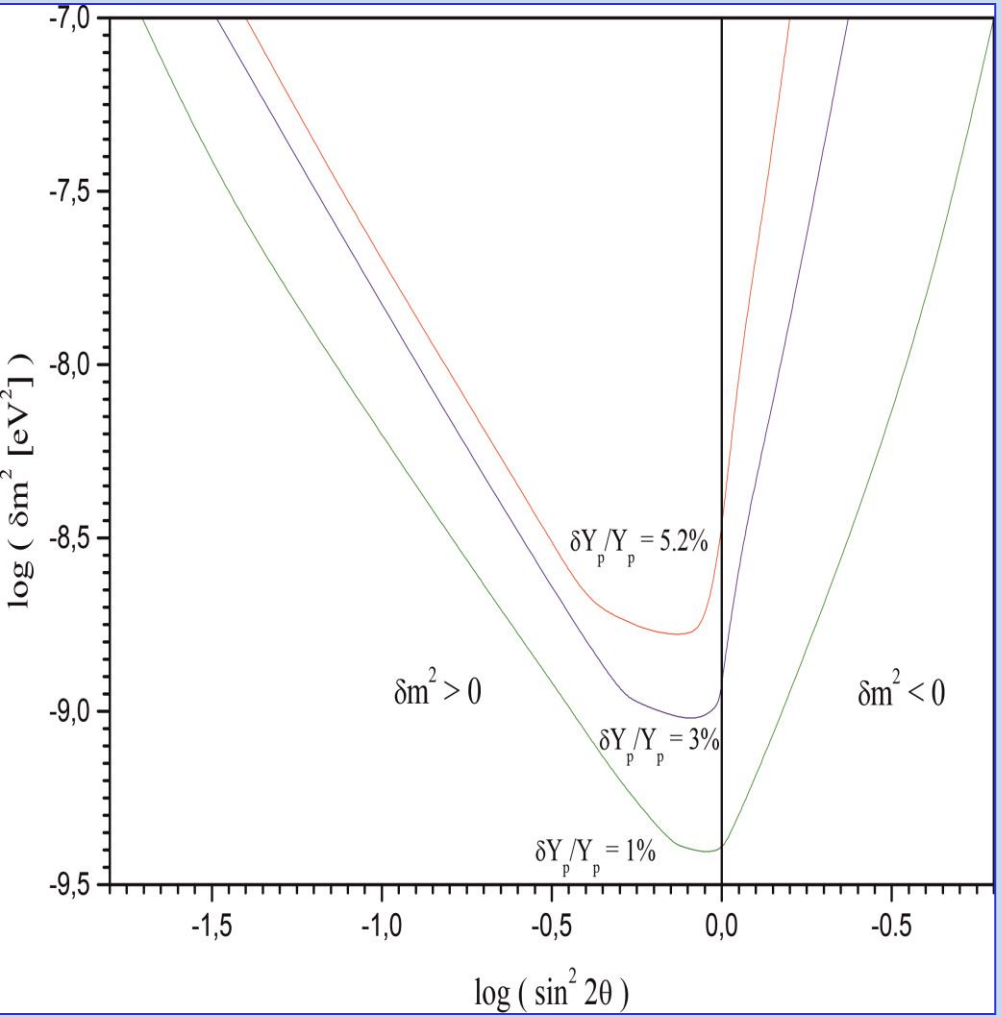


Fit to BBN constraints corresponding to $\delta Y_p/Y_p$=3%:

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

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

Updated BBN constraints on neutrino oscillation parameters



Recently the primordial ^{4}H∈ was determined with better than 3% accuracy (HeI λ10830 emission line in the brightest HII region in th extremely metal poor galaxy Leo P)

$Y_p = 0.2453 \pm 0.0034$

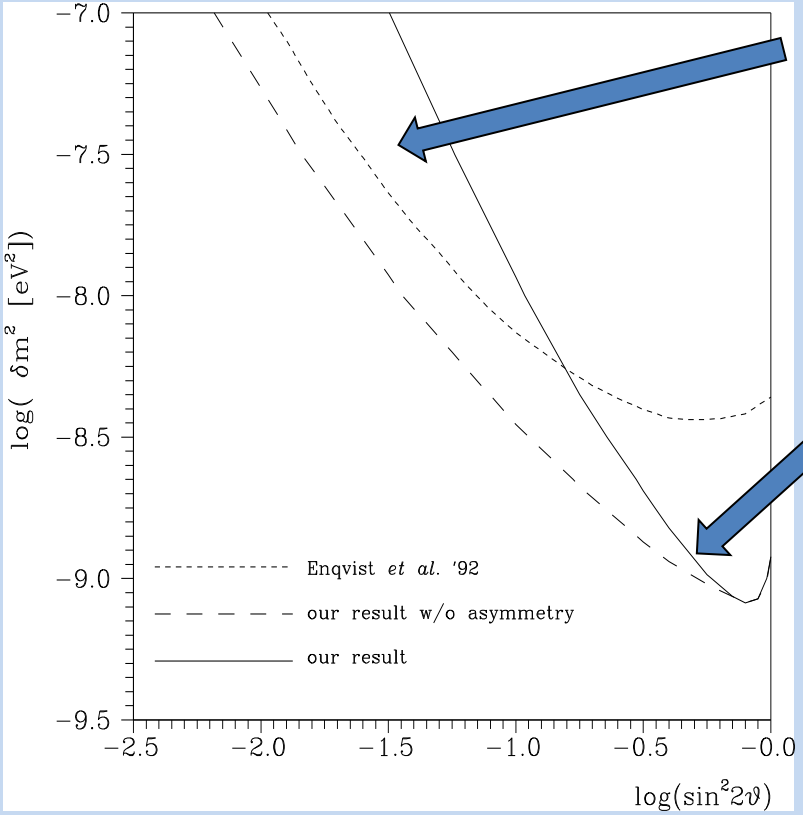
Hence, it is possible to obtain more stringent BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillations.

- We have provided numerical analysis of 135 BBN models with neutrino oscillations with different oscillation parameters.
- We present the updated BBN contraints on neutrino $\nu_e \leftrightarrow \nu_s$ oscillations parameters, based on 1-3% ^{4}H∈ uncertainty.

We have updated the data on baryon density and the neutron life time.

Precise BBN constraints on neutrino oscillations

❖More precise BBN constraints, orders of magnitude more stringent than previous ones, due to account for spectrum distortion, relaxed at small mixing due to L growth account



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

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

BBN and light neutrino types

Number of Light ν Types and BBN speedometer

❖ BBN constrains the effective number of relativistic species N_{eff} because additional light particles into equilibrium increase the expansion rate H

Schwartzman 1969

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

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

$$\rho_\nu = 7/8 (T/T_\nu)^4 N_{eff} \rho_\gamma(T)$$

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

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

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

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

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

$N_{eff} < 3.164$ 95% CL ***Yeh**, Olive, & Fields (2021)* BBN + Planck

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

BBN is a sensitive probe to additional species and it tests and constrains new physics.

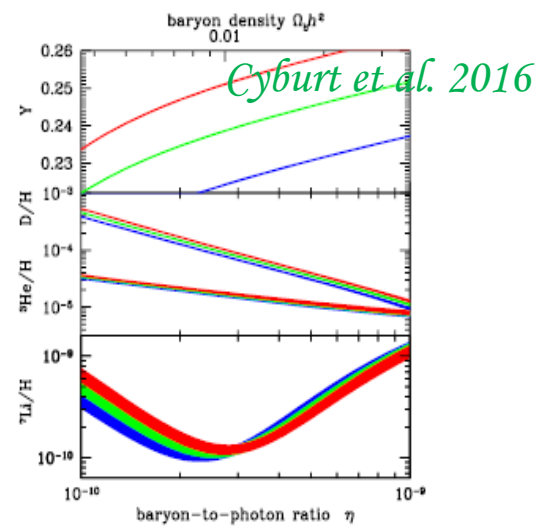


FIG. 7. The sensitivity of the light element predictions to the number of neutrino species, similar to Figure 1. Here, abundances shown by blue, green, and red bands correspond to calculated abundances assuming $N_\nu = 2, 3$ and 4 respectively.

2.3–3.2 95% CL *VERDE 17* *only* Planck Data

2 .88±0.20 95% CL ROSSI 15 BOSS Lyman alpha forest+Planck + BAO

BBN and CMB neutrino numbers are *consistent* with $N_{eff}=3$ within uncertainties

Influence of partially filled sterile neutrino on neutrino oscillations on BBN and on BBN constraints on neutrino oscillations

The distortion due to active-sterile oscillations and the kinetic effect caused δN_k depends on the degree of initial population of ν_s. due to interplay dynamical and kinetic oscillation effects . Additional inert population may strengthen or relax BBN constraints

DK&LPanayotova JCAP 2006;DK IJMPD 07

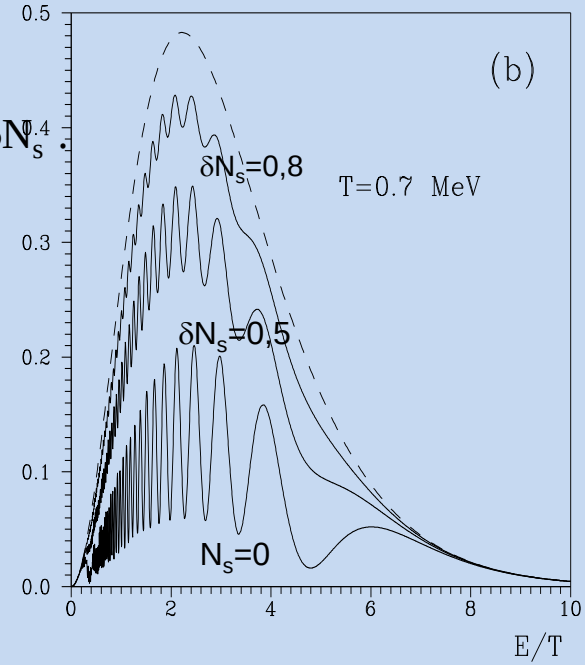
The biggest effect $\delta N_{k,0}$ is achieved for δN_s=0, the effect decreases with δN_s .

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

Role of sterile neutrino:

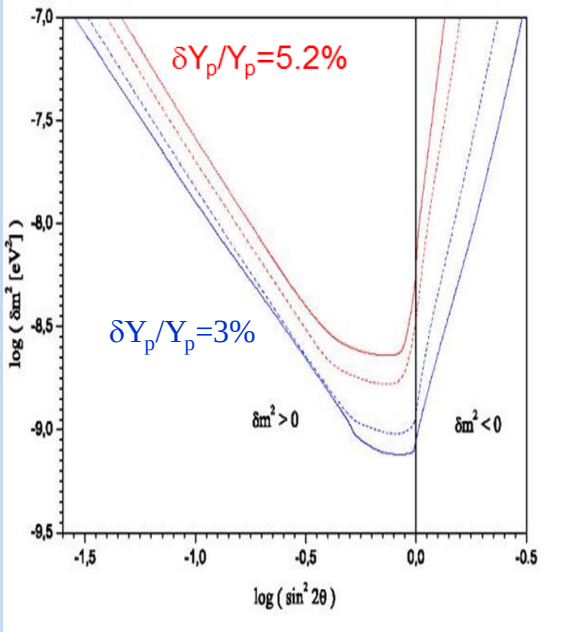
dynamical effect– increasing H(g)

suppressing the osc kinetic effect



Spectrum distortion for different initial population of ν_s.: δN_s=0 – lowest curve, δN_s=0,5 and δN_s=0,8 – upper curve. The dashed curve shows the equilibrium spectrum.

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



Constraint contours for 3 and 5% He-4 overproduction

Additional inert population may either strengthen or relax BBN constraints.

On the basis of our previous analysis we expect strengthening of the BBN constraints on neutrino oscillations, corresponding to 1% He-4 overproduction, when increasing initial population of ν_s

Excess radiation density

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

  require 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.

  Hint of oscillations with ν_s with eV mass *Kopp, Maltoni,Schwetz, arXiv: 1103.4570,*

- Reactor experiments+LSND+MiniBooNe+Gallium expt+SAGE

S. Gariazzo et al., 1703.00860; M. Dentler et al., Updated Global Analysis of Neutrino Oscillations with eV-Scale Sterile Neutrinos*, arXiv:1803.10661*

- Ice Cube: $\sin^2(2\theta_{24}) = 0.10$ and $\Delta m^2_{41} = 4.5$ eV^2 M. G. Aartsen et al., eV-Scale Sterile Neutrino Search Using Eight Years of AtmosphericMuon Neutrino Data from the IceCube Neutrino Observatory, Phys. Rev. Lett. 125(14),141801 (2020) consistent with the no sterile neutrino hypothesis
- tension between data from T2K and NOvA: preference for $\Delta m^2_{41} = 10^{-2}$ eV^2 $\sin^2(2\theta_{24})$ =0.07 André de Gouvêa et al, 2204.09130
- the global analysis show significant tension between groups of different data sets, between appearance and disappearance results *M. Dentler et al., 2018,1803.10661*

Excess radiation density

- Does cosmology allow additional light neutrinos ν_s?

Neutrino oscillations effect early Universe processes.

Oscillations with ν_s with eV mass and large mixing lead to thermalization of ν_s at BBN.
BBN does not allow a thermalized light inert state. $N_{eff} < 3.2$

Kirilova&Chizhov, PRD 98, NPB 2000:

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

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

➢Lepton asymmetry is capable to suppress ν oscillations
Foot&Volkas, 95; DK&Chizhov , NPB 98

Solution: BBN with relic L – to suppress oscillations, so that new neutrinos are not thermalized. *Kirilova 2012, 2013*

Numerical analysis of BBN with neutrino oscillations and L *Kirilova, 2018*

$L > (0.01\delta m^2)^{3/5}$ inhibit oscillations

The additional relativistic density might point to L, decaying particles during BBN, etc.

Future experimental and observational data will choose among different possibilities.

BBN and sterile neutrino freezing

BBN constraint on sterile neutrino decoupling

In the expanding Universe particles are kept in thermal equilibrium while their interaction rates Γ is higher than the expansion rate $H \sim T^2/M_{Pl}$ $\Gamma(T) > H(T)$.

Freeze-out occurs when $\Gamma(T) \sim H(T)$.

The freezing temperature of r.h.neutrino T_R can be derived using the following considerations *DK&Chizhov, 2009*

BBN constraint on δN_{eff} at BBN epoch $N_{eff} = g_R (T_{\nu_R}/T_{\nu_L})^4 < 1$

entropy conservation: $gT^3 = const$ $g = g_b (T_b/T)^3 + g_f (T_f/T)^3$

If the evolution of the universe is adiabatic, the total entropy is conserved

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

which corresponds to $T_R > 131$ MeV.

Updated BBN Constraints on T_d

❖ Using BBN constraint, *Pitrou et al. 2018*, $\delta N_{eff} < 0.3$ at BBN epoch

$T_R > 354$ MeV *D. Kirilova, E. Chizhov, 2019*

❖ Recent BBN constraint $\delta N_{eff} < 0.1$ will lead to further increase of the lower bound of T_R

preliminary results *D. Kirilova, E. Chizhov, 2022*

Благодаря за вниманието!

Thanks for the attention!

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Recent Advances in Neutrino Physics

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Deadline for manuscript submissions:
30 November 2022

Message from the Guest Editor

Neutrino physics has marked a remarkable progress during the last decades. Namely we have witnessed experimental, observational and theoretical breakthroughs concerning determination of neutrino characteristic, detection of neutrino from different environments, deeper understanding of neutrino role in the Standard Model, neutrino role in astrophysics and in cosmology, etc.

This special issue will be dedicated to the latest research and advances in neutrino physics, neutrino astrophysics and cosmology. The topics will include:

- neutrino characteristics: masses, mixing, neutrino types, etc.
- neutrino oscillations results;
- neutrino from different sources: solar neutrino, atmospheric neutrino, geo-neutrinos, SN neutrinos, AGN neutrino, relic neutrino, etc;
- cosmological role of neutrino, including neutrino role as Dark Matter, baryogenesis through leptogenesis, etc.

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Special Issue

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Message from the Editor-in-Chief

Symmetry is ultimately the most important concept in natural sciences. It is not surprising then that very basic and fundamental research achievements are related to symmetry. For instance, the Nobel Prize in Physics 1979 (Glashow, Salam, Weinberg) was received for a unified symmetry description of electromagnetic and weak interactions, while the Nobel Prize in Physics 2008 (Nambu, Kobayashi, Maskawa) was received for the discovery of the mechanism of spontaneous breaking of symmetry, including CP symmetry. Our journal is named *Symmetry* and it manifests its fundamental role in nature.

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