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Cosmological Constraints on Beyond Standard Model Neutrino Physics

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Why neutrino?

Why do we study neutrino?

Elusive (weak interactions) but important particle:

Constituent of SM of particle physics

f: quarks, charged leptons, neutrino ν_e ν_μ ν_τ

b: interaction mediators γ, g, W, Z

Higgs boson – generates particles' mass

Physical characteristics of neutrino are not yet fully studied:

m_ν (not H generated, too small), KATRIN, Troitsk, Gerda

Dirac or Majorana? Solar and atmospheric ν problems:

Neutrino oscillations (hierarchy?,CPV) SNO, Kamiokande, Super K, SAGE

Astrophysical importance: sources of neutrino are the Sun, other stars, SN, AGN, early Universe CNB, etc….

Sterile ν? BSM physics!

Can explain small m_ν DM problem, LSS formation, baryogenesis

BUT: difficult to study by exp– not interacting besides gravitationally

Cosmology provides complimentary and unique physical knowledge

Outline

- Neutrino influence on early Universe processes at pre-BBN and BBN epoch
- BBN - the deepest reliable early Universe probe of New Physics
- BBN constraints on neutrino BSM physics

  BBN with neutrino oscillations
  BBN with neutrino oscillations and lepton asymmetry
  dark radiation problem - eV neutrino saga
  decoupling temperature of ν_s

  BSM interactions

BBN constraints on beyond SM neutrino physics, based on primordial helium-4 values with 1% uncertainty.

We consider several models representing beyond SM physics and present updated constraints on new physics:

- ➢ 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 *DK&panayotova, 2022*
- ➢ We present BBN constraints on lepton asymmetry analyzing BBN model with neutrino oscillations and accounting for the lepton asymmetry (generated or primordial) *Kirilova, 2018*
- ✓ We present BBN based constraints on the freezing temperature of the light sterile neutrinos. *D. Kirilova, E. Chizhov, 2019, IJ Mod. Phys. Lett.*
- ✓ Constraints on new interactions *D. Kirilova, E. Chizhov, 2022*

Neutrino at RD stage in SM

- Universe is filled with massless non-oscillating neutrinos

three neutrino flavours exist

(confirmed for weakly interacting species lighter than Z/2 by LEP).

- The lepton asymmetry is zero (*an assumption*)

- Neutrinos have the equilibrium Fermi-Dirac distribution (*an assumption*).

➢ Neutrino contributes to the energy density of the Universe and thus influences the expansion rate of the Universe

At T<m$_e$, the radiation content of the Universe is

$$\boxed{\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15} T_\gamma^4 + 3 \times \frac{7}{8} \times \frac{\pi^2}{15} T_\nu^4 = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} 3 \right] \rho_\gamma}$$

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

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

Neutrino at RD stage in SM

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

❖ T>> 1 MeV neutrinos are in equilibrium due to weak interactions

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

❖ T~ 2 MeV $\Gamma \sim H$ neutrino decoupling

Weak interactions ineffective to keep neutrinos in good thermal contact with the e.m. plasma. Since decoupling neutrino were free streaming

❖ Electron neutrino effects nucleon kinetics in pre-BBN epoch

❖ T~m$_e$, $e^+e^- \rightarrow \gamma\gamma$, photons but not neutrinos were heated $T_n=(4/11)^{1/3} T_{cmb}$.
CNB today is expected with temperature ~ 1.9 K, $n_n = 3/11\, n_{cmb}$

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

Effective number of relativistic neutrino species

Since **T$_{dec}$(ν)** is close to **m$_e$,** neutrinos shared a small part of the entropy release :
neutrino species – 3.044 instead of 3

Dolgov, Hansen & Semikoz,1997
Mangano et al,2002,2005

Neutrino Oscillations Effects

- Dynamical effect: Excite additional light particles into equilibrium

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

$\nu_a \leftrightarrow \nu_s$ effective before ν_a decoupling *Dolgov 1981*

- Distorting the neutrino energy distribution from the equilibrium FD form

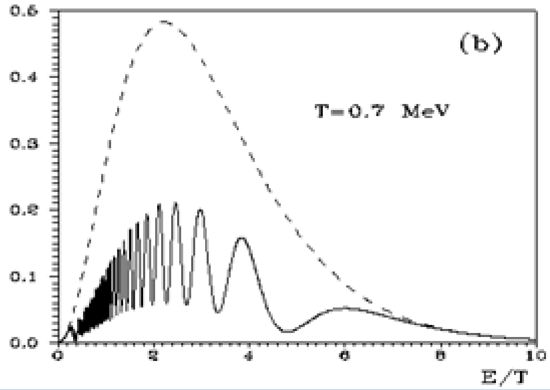
$$n_\nu^{cnb} \neq n_\nu^{eq} = \exp(-E/T)/(1+\exp(-E/T))$$

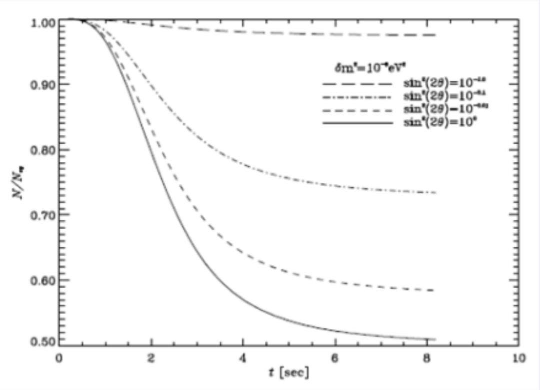
$$\Gamma \sim G_F^2 E_\nu^2 N_\nu$$

$\nu_a \leftrightarrow \nu_s$ effective after ν_a decoupling

Kirilova 1988

Kirilova&Chizhov,1997





Active-sterile neutrino oscillations neutrinos may considerably deplete active neutrino and distort its energy spectum from the equilibrium Fermi-Dirac form.

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

Foot&Volkas 95 *Kirilova&Chizhov,19*

Active-sterile oscillations may have considerable cosmological influence!

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

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.

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

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

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

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.

Standard BBN

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.

Standard BBN

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)

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

- ✓ 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*).

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

Y_T = 0,24709± 0,00017

D/H =(2.459 ± 0,036) 10^{-5}

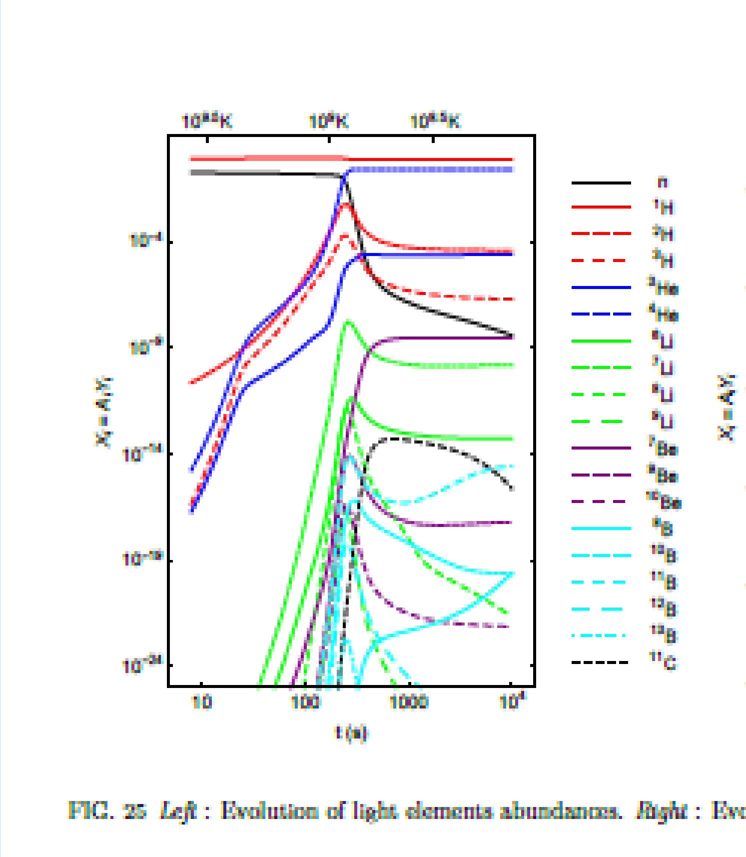
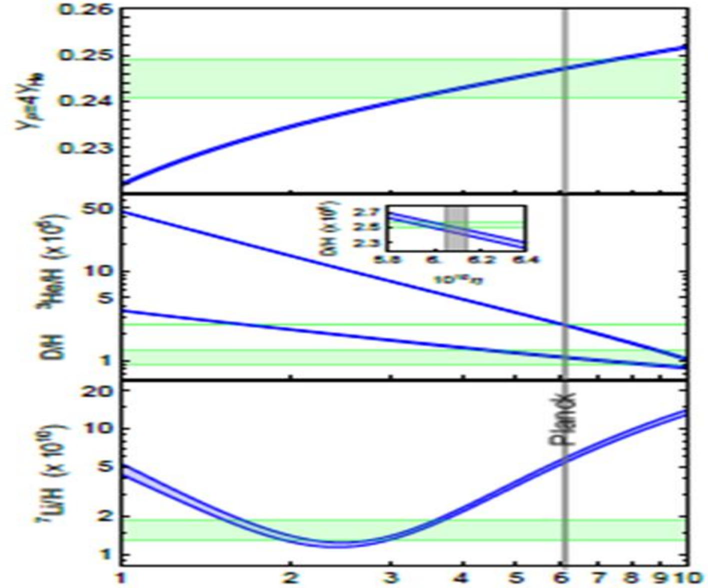


FIG. 25 *Left* : Evolution of light elements abundances. *Right* : Evo

Evolution of Light element abundances.

Pitrou, Coc et al. 2018

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).

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

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

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 conditions in early Universe and a unique test for new physics due to the remarkable concordance between theoretically predicted and derived from observation abundances of light elements produced primordially.

The Best Speedometer at RD Stage

BBN probes neutrino oscillations

The Most Exact Baryometer and Leptomet

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

DK&panayotova, 2006, 2011;

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 neutrino physics beyond Standard Model.

BBN with ν oscillations

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 $\nu_e \leftrightarrow \nu_s$

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

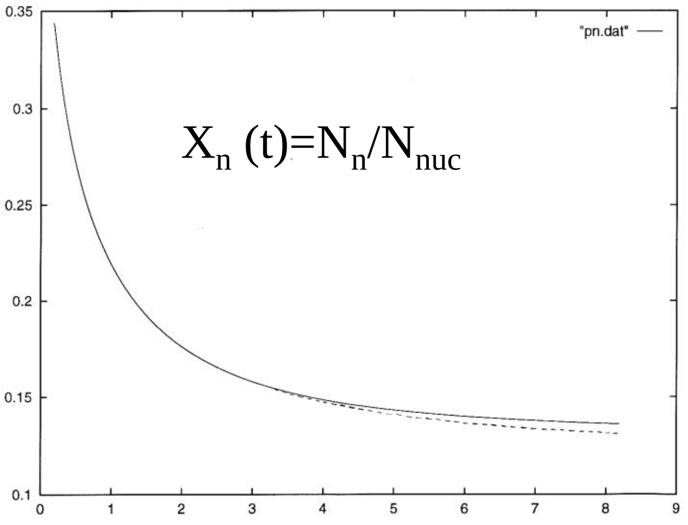
$$- \int d\Omega(e^+, p, \tilde{\nu}) \left| A(e^+ n \rightarrow p \tilde{\nu}) \right|^2 (n_{e^+} n_n - n_p \bar{\rho}_{LL})$$

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

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

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

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



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 and for $\delta N_s=0$.

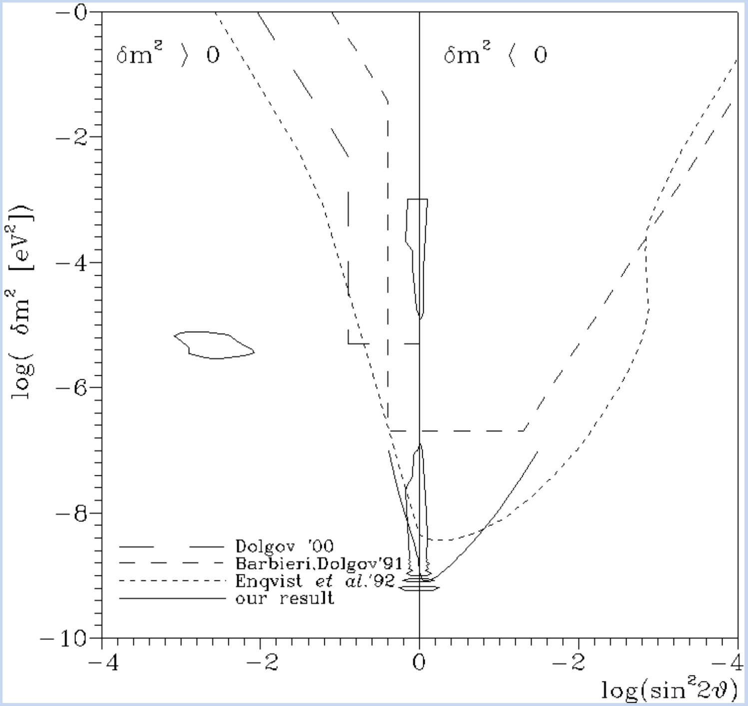
Barbieri, Dolgov 91 – depletion account
Dolgov 2000 – dashed curve;
DK, Enqvist et al. 92 – one p approx.
Dolgov, Villante, 2003 - spectrum distortion

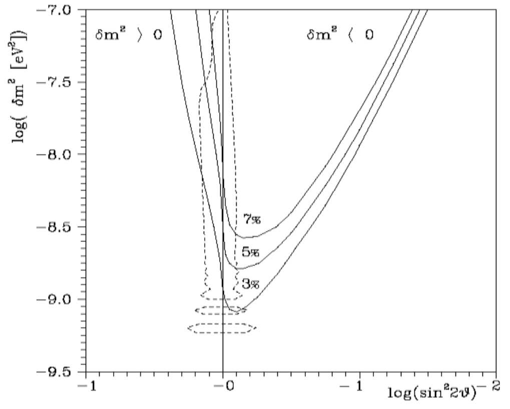
$\delta m^2 > 10^{-6}$ eV^2

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

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

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





DK, Chizhov NPB2000,2001

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

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

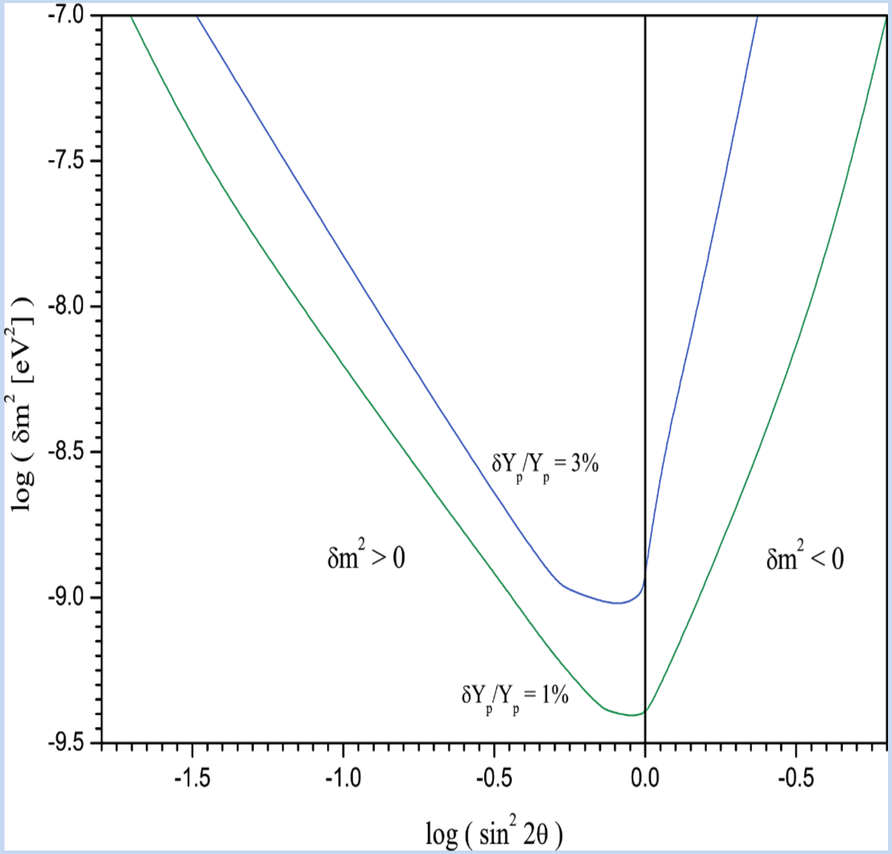
$$\delta m^2 \left(\sin^2 2\theta\right)^4 \leq 1.5\times10^{-9} eV^2 \quad \delta m^2 > 0$$

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

BBN constraints were by 4 orders of magnitude more stringent than experimental ones

Excluded LMA and LOW active-sterile solutions (1990, 1999) years before experimental results.

Updated BBN constraints on neutrino oscillation parameters



DK, Panayotova 2022, 2023

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

Y_p= 0.2453±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 stes of oscillation parameters.
- We present the updated BBN contraints on neutrino $\nu_e \leftrightarrow \nu_s$ oscillations parameters, based on 1-3% ^{4}He uncertainty.

Influence of partially filled sterile neutrino $0<\delta N_s<1$

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

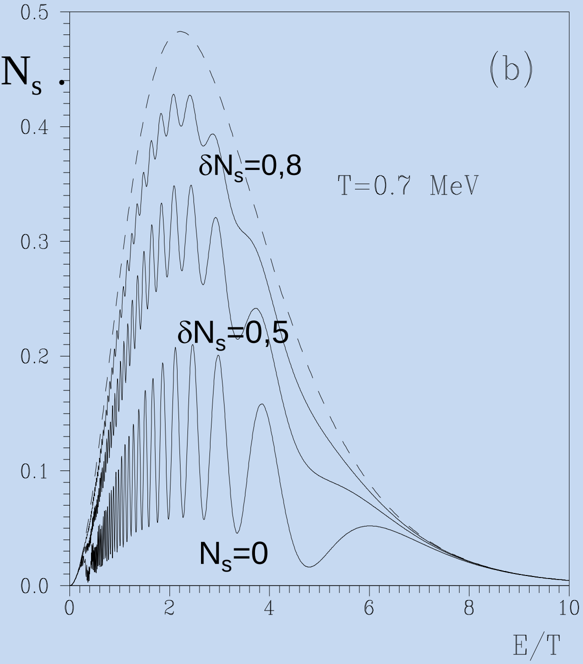
The biggest effect $\delta N_{k,0}$ is achieved for $\delta N_s=0$, the effect decreases with δN_s .

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

Role of sterile neutrino:

dynamical effect– increasing H(g)

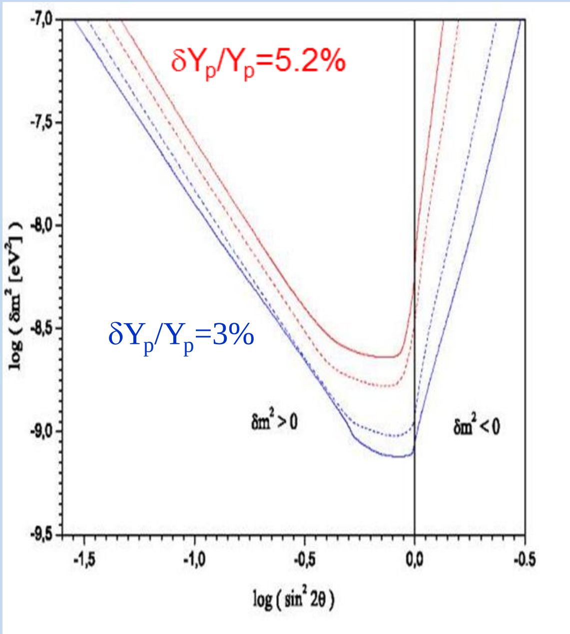
suppressing the osc kinetic effect



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.

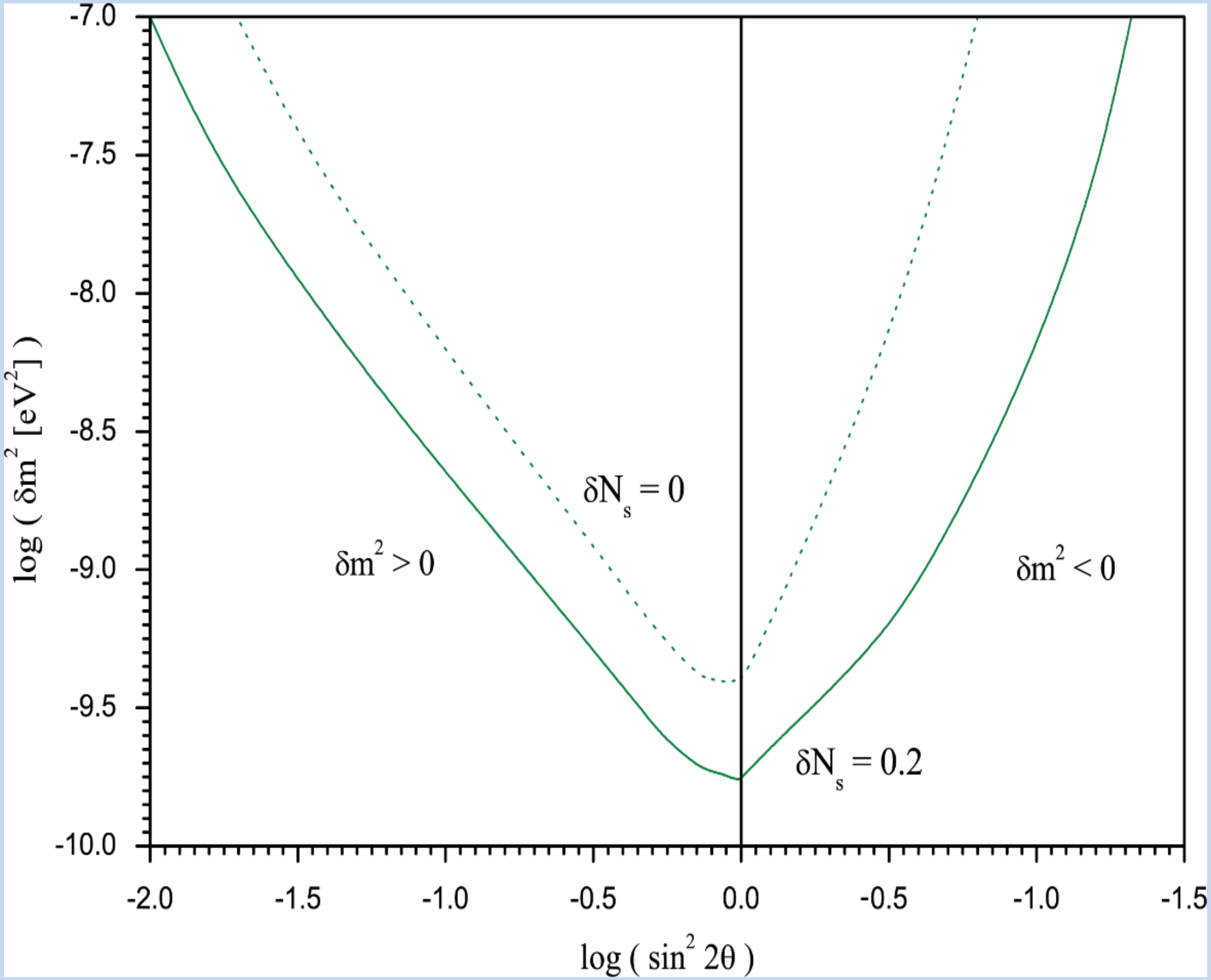
DK,Int.J.Mod.Phys.D,2007

DK&Panayotova JCAP 2006;DK IJMPD 07



Constraint contours for
3 and 5% He-4
overproduction

Updated BBN constraints on neutrino oscillation parameters for $\delta N_s \neq 0$



Contemporary BBN constraints on electron-sterile neutrino oscillations parameters corresponding to 1% He-4 overproduction and $\delta N_s=0$ (upper curve) and $\delta N_s=0.2$ (lower curve). BBN constraints strengthen with the increase of initial population of ν_s

Standard BBN with lepton asymmetry

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

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

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

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

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

leading to faster expansion, influence BBN

Lesgourgues&Pastor, 1999

- **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

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

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

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

BBN with L and ν oscillations

BBN with late neutrino oscillations and lepton asymmetry

Indirect kinetic effect of L

Small $10^{-8} < L << 0.01$, that do not effect directly BBN 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)

Interplay between L and neutrino oscillations was found *DK JCAP2012*:

- ➢ L (depending on its value) can suppress them or lead to their resonant enhancement. L may relax BBN bounds at large mixing and strengthens them at small mixing.

- ➢ Neutrino oscillations are capable of suppressing L or amplifying it.

We have numerically studied that interplay and determined the parameter range for which L is able to enhance, suppress or inhibit oscillations *DK 2018*.

$L > (0.01\delta m^2)^{3/5}$ inhibits oscillations and eliminates the BBN bounds on them.

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

Reactor experiments+LSND+MiniBooNe+Gallium expt+SAGE

Ice Cube, T2K , NOvA

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. $N_{eff} < 3.2$

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

δm^2	$=0.1$ eV^2	L<0.016
	1	L<0.25

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

Future experimental and observational data will choose among different possibilities.

Recent measurements of L

- EMPRESS survey of extremely metal poor systems

Matsumoto et al, EMPRESS VIII, 2203.09617

3σ lower primordial He-4 value than the predicted

$Y_p=0.2379^{+0.0031}_{-0.003}$

Can be interpreted as a hint for L: $\xi_{\nu e}=0.039\pm0.014$ at 3σ

PDG Yp=$0.245^{+0.003}_{-0.003}$ $\xi_{\nu e}=0.008\pm0.013$

In case of DR the preference for L>0 increases.

$\delta m^2(eV^2)<100L^{5/3}$ On the basis of our analysis if L~0.03 $\delta m^2 \le 0.345 eV^2$

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 are 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_d 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

$T_d > 354$ 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_d

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

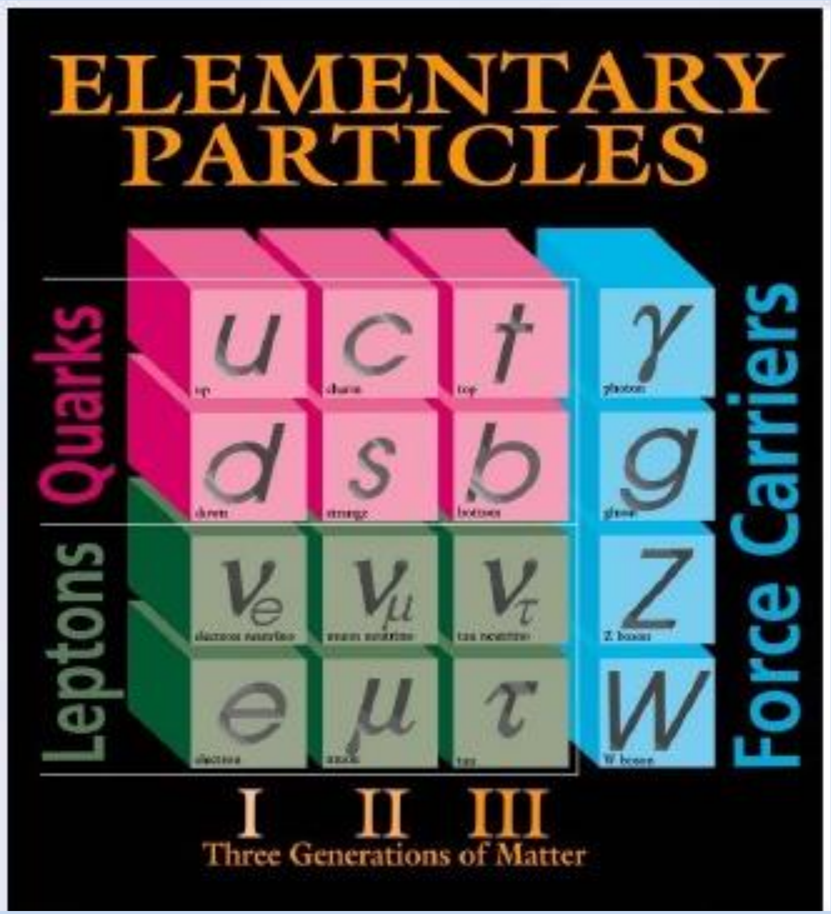
Constraints on new interactions

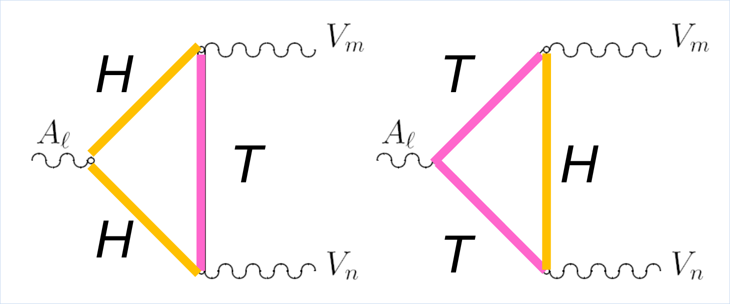
Chiral Tensor Particles in the Early Universe

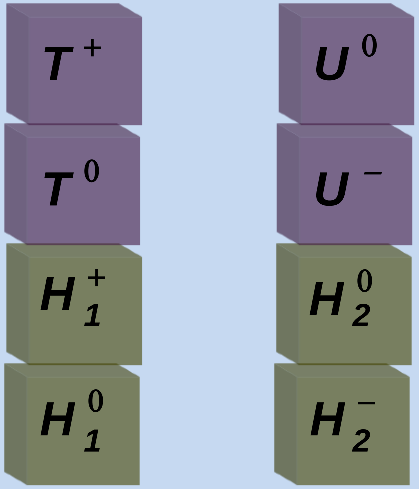
- CTP were introduced as an extension of SM for completeness of the representation of the Lorentz group, *M. Chizhov, 1993***.** These bosons are carriers of new interaction and have only chiral interactions with the known fermions, through tensor anomalous coupling. *Kirilova, Velchev T.1994, Kirilova, М .Chizhov, 1998, 2009; Kirilova, V. Chizhov, IJ Mod. Phys. Lett. A, 2017 Kirilova, E. Chizhov 2019, Int. J. Mod. Phys. A, Vol. 34 (2019) 1950065*
- *CTP dynamicsl effect* - contribute to the matter tensor in the right-hand side of the Einstein--Hilbert equation and change the dynamical evolution of the Universe.
- *CTP directly interact* with the particles present at the early high energy stage of the Universe. Using experimental constraints on CTP *Aad et al. (ATLAS Coll.) 2014*. the processes of CTP with the constituents of the early Universe plasma, their creation, decay, annihilation and scattering were considered, *Kirilova, V. Chizhov, 2017*.
- *Cosmological constraints on the CTP coupling constant* based on the possible interactions of CTP with right-handed neutrinos and their influence on the Big Bang Nucleosynthesis, *Kirilova, E. Chizhov, 2019, 2022*.

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

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

First experimental constraints on CTP masses were obtained, Aad et al. (ATLAS Coll.) 2014.

$M_{T0}{}^{exp} > 2.85$ TeV, $M_{T+}{}^{exp} > 3.21$ TeV 95 % CL

CTP effects

- Due to their contribution to the matter tensor in the right-hand side of the Einstein--Hilbert equation, CTP increase Universe density and change the dynamical evolution of the Universe.

$$g_*^{new} = 106.75 + 12_T + 12_U + 4_{H_2} = 134.75 \qquad H = \sqrt{\frac{8\pi^3 G_N g_*(T)}{90}}\, T^2$$

Using current experimental and theoretical findings the time interval of efficiency of CTP was determined 6.10^{-42} s < t < 5.10^{-14} s , T interval $1.8\ 10^{17}$ - $6.0\ 10^{3}$ GeV. CTP have been abundant at an early stage of Universe evolution, so they did not directly effect BBN, CMB, LSS.

- If right-handed neutrinos interact with the CTP, they may be produced through CTP exchange during BBN. The term of the effective Lagrangian corresponding to the right-handed neutrino coupling reads:

$$L = \frac{4}{\sqrt{2}} G_T \bar{e}_L \sigma_{\alpha\beta} \nu_R \cdot \bar{u}_L \sigma_{\alpha\beta} d_R + h.c.$$

where G_T is CTP interaction strength, $\sigma_{\alpha\beta} = \frac{i}{2}(\gamma_\alpha \gamma_\beta - \gamma_\beta \gamma_\alpha)$.

BBN Constraints on CTP Interactions Strength

- If we use conservative BBN constraint $\delta N_{eff} < 1$ at BBN epoch, and entropy conservation $gT^3 = const$, we can calculate T_f decoupling of right-handed neutrino, assuming dilution of the energy density of 3 neutrino species by factor

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

which corresponds to $T_f > 131$ MeV.

T_f depends on G_T : $\frac{\Gamma_R}{\Gamma_L} = \left(\frac{T_f}{3}\right)^3 \left(\frac{G_T}{G_F}\right)^2 \sim 1$ For 3 types ν_R $\left(\frac{G_T}{G_F}\right)^2 \sim \left(\frac{T_f}{2}\right)^{-3}$ $G_T \leq 10^{-2} G_F$

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

D. Kirilova, E. Chizhov, 2019, IJ Mod. Phys. Lett. $T_f > 354$ MeV

for 3 light right handed neutrinos

for 2 light right handed neutrinos $G_T \leq 8.4.\times 10^{-4} G_F$

for 1 light right handed neutrinos $G_T \leq 1.4.\times 10^{-3} G_F$

CTP interactions are expected to be milliweak or weaker from contemporary precise BBN data (alternatives: no interactions with fermions, or no light right handed neutrino,…).

BBN constraints on BSM neutrino

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

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

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

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

$\Delta N_{eff} < 0.2$

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

Schwartzman 1969

- **Constrains chemical potentials**

$L \sim 0.03$?

$\xi \sim 0.04$?

BBN restricts chemical potential of all neutrino flavors

- **Constrains sterile neutrino decoupling** $T_R > 354\,\mathrm{MeV}$

$$G_T \le 4.2 \times 10^{-4}\, G_F$$

- **Constrains neutrino oscillations parameters**

BBN with $\nu \leftrightarrow \nu_s$ neutrino spectrum and densities differ, thus influencing kinetics of nucleons in BBN epoch, reducing weak processes rates overproducing He-4.

Summary

We present updated BBN constraints on several models of neutrino physics beyond SM : BBN with late electron-sterile neutrino oscillations, BBN with neutrino oscillations and lepton asymmetry, right-handed neutrinos interacting with chiral tensor particles.

- We analyzed the model of BBN with $\nu_e \leftrightarrow \nu_s$ neutrino oscillations and derived stringent BBN constraints on neutrino oscillations parameters corresponding to the present accuracy of He-4 determination

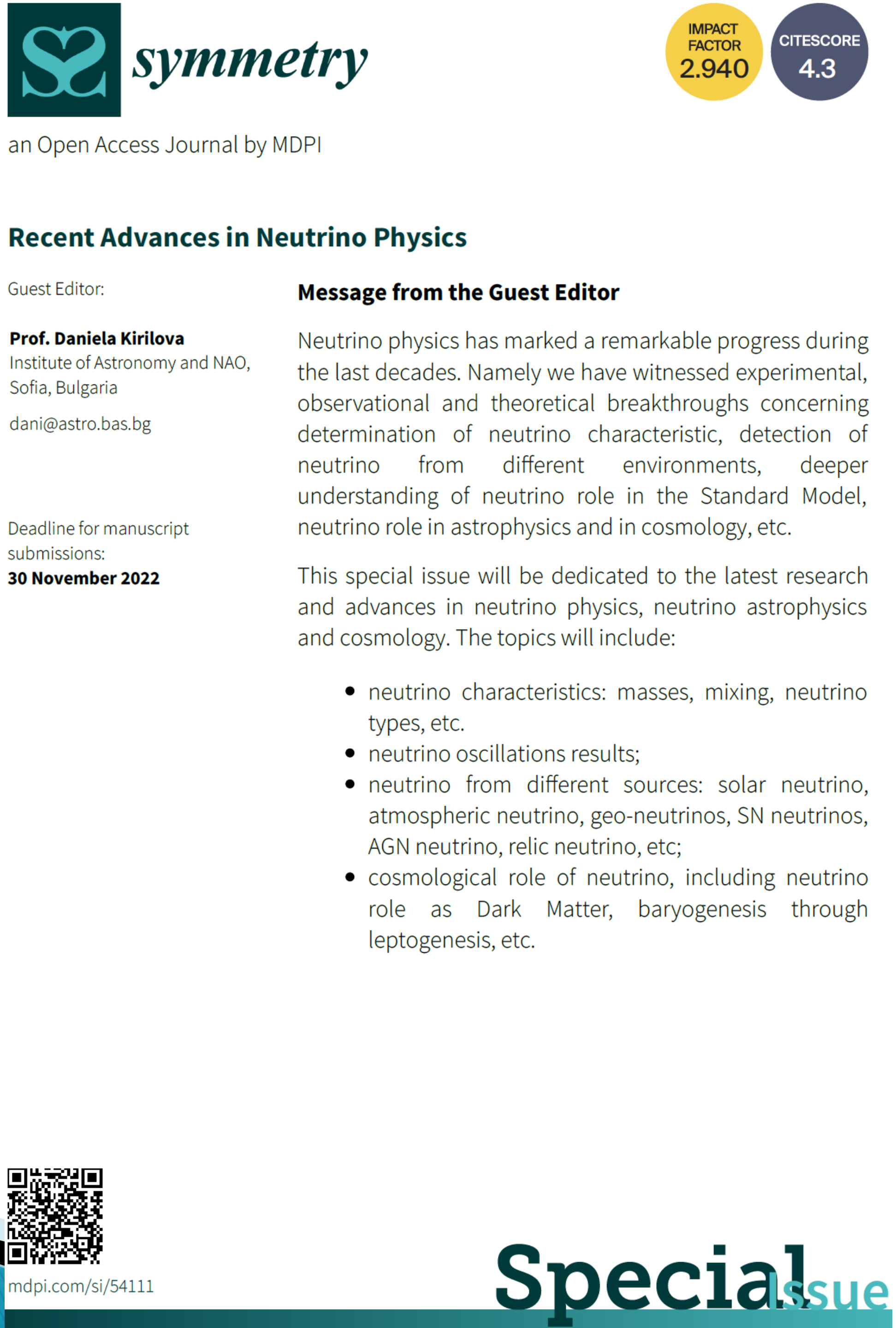
- The role of lepton asymmetry was studied. *Relic L* may relax BBN bounds at large mixing and strengthens them at small mixing. Large L may provide relaxation of BBN constraints on oscillations, by suppressing oscillations and causing incomplete thermalization of the sterile neutrino. Large enough L alleviates BBN constraints on oscillation parameters.

- A solution to the DR problem was proposed in model of neutrino oscillations and L.
- Cosmological constraints on the decoupling T of sterile neutrino were obtained

$$T_R > 354\text{MeV}$$

- In case CTP interact with right handed neutrinos stringent BBN constraints have been obtained on CTP interaction strength - it should be milli weak or weaker, depending on the number of light right-handed neutrino species.

Thank you for your attention!



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Recent Advances in Neutrino Physics

Guest Editor:

Prof. Daniela Kirilova
Institute of Astronomy and NAO,
Sofia, Bulgaria

dani@astro.bas.bg

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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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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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

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

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

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

$$H \sim \sqrt{g_{eff}}\, GT^2$$

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

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

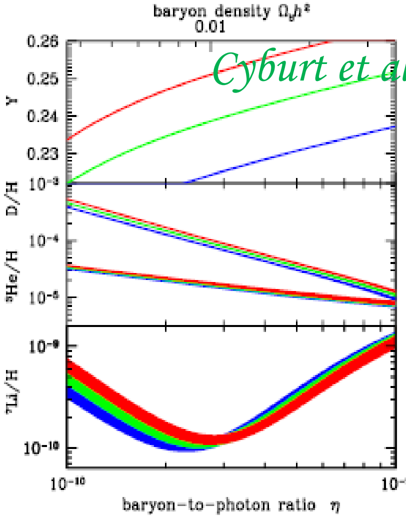
Y_p=0,2565 ± 0.001(stat)± 0,005(syst) *Izotov&Thuan, 2010* *93 Sp of 86 low Z HII*

$3.0 \le N_\nu \le 4.5$ (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.



Cyburt et al. 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.

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

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. *Kopp, Maltoni,Schwetz, arXiv: 1103.4570,*

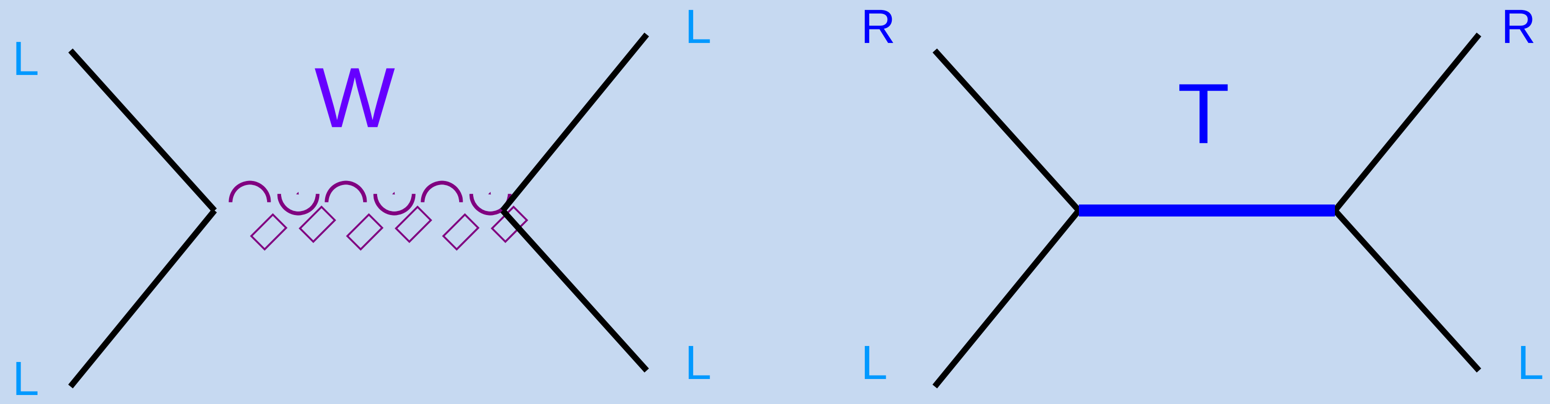
Hint of oscillations with ν_s with eV mass

- 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)
- 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*

EW Physics



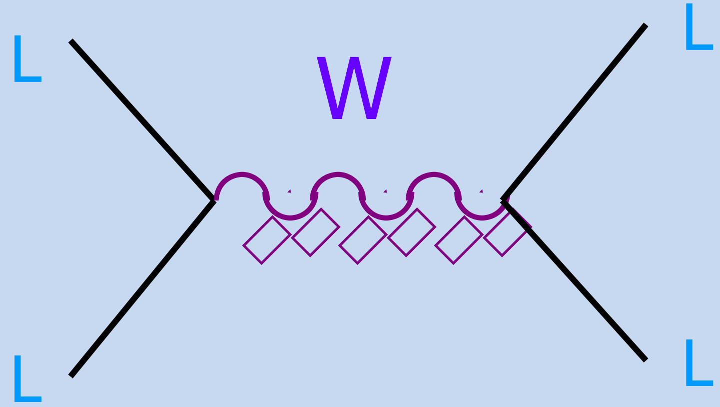
$G_F \sim (g\,/M_W)^2$

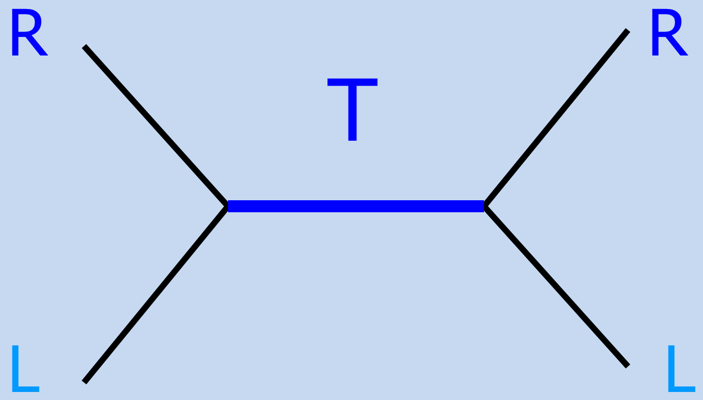
$G_T \sim (t\,/M_T)^2$

if $G_T \sim 10^{-2}\, G_F$ and $t \sim g$: $M_T \sim 10\, M_W$

Extended EW Physics

$$L = \frac{4}{\sqrt{2}} G_T \overline{e}_L \sigma_{\alpha\beta} \nu_R \cdot \overline{u}_L \sigma_{\alpha\beta} d_R + h.c. \qquad \sigma_{\alpha\beta} = \frac{i}{2}(\gamma_\alpha \gamma_\beta - \gamma_\beta \gamma_\alpha).$$





$G_F \sim (g/M_W)^2$ $\qquad$ $G_T \sim (t/M_T)^2$

if $G_T \sim 10^{-4}\, G_F$ and $t \sim g$: $\quad M_T \sim 100\, M_W$