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Precision cosmology and neutrino properties

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Abstract

I give an overview of what we do know from astrophysical data about some of neutrino properties and their role in cosmology. In particular, I focus on the number of effective neutrino species, active neutrino mass bounds and constraints on neutrino –antineutrino asymmetries. Finally, I also discuss the possibility of a non negligible abundance of eV mass scale sterile neutrino species in the early universe.

Keywords: neutrino properties, cosmological models, BBN, CMB and neutrinos, sterile neutrinos

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1. Introduction

The reader will not be surprised if I start this brief summary by stating a point which is usually adopted in the incipit of many scientific papers on the topic I am going to discuss: which is that Cosmology, the theory of gravitation applied to the biggest system we can deal with – the universe as a whole – is a surprisingly rich source of information on physics at the most fundamental level, the one of interactions among elementary particles and their properties. This is particularly true in view of the impressive amount of astrophysical data which have been accumulated in the last decades, as well as their equally impressive quality and precision. This allowed to pinpoint a remarkably simple cosmological model which fits the large majority of these data in terms of a limited number of free parameters: the baryon density, dark matter density, the amplitude of primordial perturbations, the cosmological constant, and few others. Although we do not understand so far the nature of the dark side of the model, the ΛCDM scenario is so succesful that it deserves the name of the *standard* cosmological model. In this framework it is meaningful to speak about *precision cosmology*, by which I simply mean: precise experimental data and a robust theoretical model.

Precision often also means *predictivity*: we can exploit cosmological observations and look for hints for (or constraints to) physics beyond our present understanding of fundamental interactions, again provided by a *standard* model. Indeed, a huge activity is going along this direction since many years, and within this research line one of the most lively example is definitely *Neutrino Cosmology*, see e.g. [1].

Neutrinos are predicted to be quite abundant since the early times of the expansion, and their weak and gravitational interactions with other species leave a clear signature on several cosmological observations, such as the Big Bang Nucleosynthesis (BBN), the Cosmic Microwave Background (CMB) anisotropies, and Large Scale Structure (LSS) formation. More than this, some of their yet undisclosed properties – mass scale, oscillation features with sterile states, primordial abundances, exotic interactions etc. – may impact the standard cosmological model in a way which is detectable, with the present precision level of data. They can thus, be constrained, and provide an useful set of information, complementary to that coming from laboratory efforts.

In the following I review a bunch of these properties, how they intervene in cosmological observables,

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and corresponding constraints, in the framework of *minimal* extension of ΛCDM models. The word *minimal* is a caveat which should not be underestimated. The point is that if we move around in the space of cosmological models by introducing extra parameters, the effect on some neutrino property constraints may remain quite small, but in other cases it would completely spoil predictivity. First class of parameters can be named *robust*, while the others can be referred to as *weak* parameter class. Just to give an example which I discuss in the next section, the bound on effective number of neutrinos, i.e. the amount of relativistic energy density at some particular stage of the evolution of the universe, is not so strongly depending on the model we choose. Allowing for one single extra parameter $N_{\rm eff}$, in addition to those of the minimal ΛCDM model, or further enlarging it, allowing for extra massive species and/or the effect of active neutrino mass, will give bounds on $N_{\rm eff}$ which remain quite stable. Furthermore, combining different observations, related to different evolution stages of the universe, provide consistency checks and may result in a refined constraints. Unfortunately, this is not what happens always, mainly because of the appearence of degeneracies. As we leave our comfortable cosmological model, or simple extensions of it, the quality of constraints can rapidly degrade.

2. Active neutrinos and other relativistic species in the early universe, i.e. the value of $N_{\rm eff}$.

From a theoretical point of view there are few doubts about the fact that neutrinos populate the universe since the very early stages of the expansion. At high temperatures and densities weak interactions are in equilibrium and neutrinos are excited in the thermal bath as electrons, positrons, photons and all strong and electromagnetically interacting species do. As the temperature decreases with the expansion, at about 1 MeV neutrinos decouple, when the typical interaction rate falls below the value of the Hubble parameter. After that stage they move as freely falling particles till today. We will discuss later that even in this late phase they are not passive spectators and leave their imprint via gravitational interactions. For the time being we start by asking if this theoretical picture is correct: are there and have been there neutrinos in the universe? And how many species of them?

As usual I define a single parameter encoding a large part of the effect of neutrinos, more generally relativisitc species, on two main observables, the light yields produced during BBN, and the CMB map produced at recombination

$$\rho_R = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\rm eff} \right) , \tag{1}$$

with ρ_R the energy density of relativistic species and $\rho_\gamma = \sigma T^4$ the photon contribution to it. The standard expectation is $N_{\rm eff} = 3.046$ for the three active neutrinos, with a small correction due to neutrino reheating during $e^\pm$ pair annihilation. A larger value for $N_{\rm eff}$ would be a clear evidence in favour of extra species, such as sterile neutrinos, of active neutrino chemical potentials or finally, non–thermal features in their distribution in phase space. Notice that $N_{\rm eff}$ is a time dependent quantity, since a particular species might count as radiation at some early stage, but as matter when it becomes non relativistic.

For a homogeneous universe the only effect of a radiation excess (or deficit) is encoded in their contribution to the Hubble expansion rate H. In fact, during BBN the role of perturbations on primordial light yields is completely negligible, and their eventual value is a combination of two simple effects related to neutrinos: how fast the universe is expanding and how many electron neutrinos are around and their distribution. Both effects are easy to understand. The value of H, and so of $N_{\rm eff}$, fixes the neutron to proton ratio at weak interaction freeze–out, while the ν_e's directly enter the value of these interaction rates which maintain neutrons and protons in chemical equilibrium. The net effect is that both nuclei abundances whose primordial abundance is measured with a good (^{2}H) or reasonable (^{4}He) precision, are increasing function of $N_{\rm eff}$.

There are several analysis of primordial ^{4}He mass density Y_p using regression to zero metallicity of low metallicity environments. For the sake of brevity I choose to only mention the recent estimate of [2] with a careful analysis of the systematic error budget

$$Y_p = 0.2465 \pm 0.0097 , \tag{2}$$

and the upper limit found in [3], assuming a flat regression to zero metallicity

$$Y_p \leq 0.2631 \ \ (95\%\mathrm{C.L.}) . \tag{3}$$

Primordial deuterium is quite remarkably well measured in high redshift Quasar Absorption Systems. The most recent determination of [4] has a less than 2 % error

$$^2\mathrm{H/H} = (2.53 \pm 0.04) \cdot 10^{-5} . \tag{4}$$

By fixing the baryon density parameter in the range obtained by the first data release of the Planck experiment,