Astroparticle Physics 63 (2015) 66–80

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Neutrino physics from the cosmic microwave background and large scale structure

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http://dx.doi.org/10.1016/j.astropartphys.2014.05.014
0927-6505/

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A R T I C L E I N F O

Article history:
Received 19 December 2013
Received in revised form 24 May 2014
Accepted 27 May 2014
Available online 3 July 2014

Keywords:
Neutrinos
Cosmology
Cosmic microwave background
Large scale structure

A B S T R A C T

This is a report on the status and prospects of the quantification of neutrino properties through the cosmological neutrino background for the Cosmic Frontier of the Division of Particles and Fields Community Summer Study long-term planning exercise. Experiments planned and underway are prepared to study the cosmological neutrino background in detail via its influence on distance-redshift relations and the growth of structure. The program for the next decade described in this document, including upcoming spectroscopic galaxy surveys eBOSS and DESI and a new Stage-IV CMB polarization experiment CMB-S4, will achieve $\sigma(\sigma m_\nu)$ = 16 meV and $\sigma(N_{\rm eff})$ = 0.020. Such a mass measurement will produce a high significance detection of non-zero σm_ν, whose lower bound derived from atmospheric and solar neutrino oscillation data is about 58 meV. If neutrinos have a minimal normal mass hierarchy, this measurement will definitively rule out the inverted neutrino mass hierarchy, shedding light on one of the most puzzling aspects of the Standard Model of particle physics — the origin of mass. This precise a measurement of $N_{\rm eff}$ will allow for high sensitivity to any light and dark degrees of freedom produced in the big bang and a precision test of the standard cosmological model prediction that $N_{\rm eff} = 3.046$.

Executive summary

The cosmological background of neutrinos thermally produced in the big bang has been definitively (albeit indirectly) detected. Measurements of the cosmic microwave background (CMB) alone have led to a constraint on the effective number of neutrino species of $N_{\rm eff} = 3.36 \pm 0.34$ Ade et al. [1], a value 10σ away from zero and consistent with expectations. Experiments planned and underway are prepared to study this background in detail via its influence on distance-redshift relations and the growth of structure. The program for the next decade described in this document, including upcoming spectroscopic surveys eBOSS and DESI and a new Stage-IV CMB polarization experiment CMB-S4, will achieve $\sigma(\Sigma m_\nu) = 16$ meV and $\sigma(N_{\rm eff}) = 0.020$. Such a mass measurement will produce a high significance detection of non-zero Σm_ν, whose lower bound derived from atmospheric and solar neutrino oscillation data is about 58 meV. If neutrinos have a normal mass hierarchy, this measurement will definitively rule out the inverted neutrino mass hierarchy, shedding light on one of the most puzzling aspects of the Standard Model of particle physics – the origin of mass.

This precise a measurement of $N_{\rm eff}$ will allow for a precision test of the standard cosmological model prediction that $N_{\rm eff} = 3.046$. The difference from three is due to the small amount of entropy from electron/positron annihilation that gets transferred to the neutrinos; $N_{\rm eff}$ is by design equal to three in the idealized case that all of this entropy is transferred to photons. Finding $N_{\rm eff}$ consistent with 3.046 would demonstrate that we understand very well the thermal conditions in the universe at just one second after the big bang. On the other hand, finding $N_{\rm eff}$ significantly different from 3.046 would be a signature of new physics. Possibilities include sterile neutrinos produced via oscillations in the early universe, a large matter/anti-matter asymmetry in the neutrino sector, or new particles that interact even more weakly than neutrinos but that were in thermal and chemical equilibrium deep in the radiation-dominated era (e.g. Weinberg, 2013 [2]).

The effects of neutrino properties on cosmology are precisely predicted from theory, appear in many observables in diverse ways, and are clearly observationally distinguishable from the effects of other cosmological parameters. For example, increasing $N_{\rm eff}$ not only suppresses small-scale fluctuation power in the CMB, but also leads to detectable changes in the temporal phase of the acoustic oscillations, e.g. Hou et al. [3]. Increasing Σm_ν in a manner that is consistent with the measured CMB power spectrum leads to very specific redshift- and scale-dependent changes to the power spectrum of both matter and the galaxy distribution