Fundamental physics from astronomical observations

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Current and forthcoming astronomical observations are providing enough data as to address some of the fundamental questions in physics, such as: what is the mass of neutrinos, are neutrinos Majorana or Dirac and what is the nature of the dark matter particle? In this talk I will provide an overview of how these questions can be answered by astronomical observations.

1 Introduction

Astronomy is a peculiar science, as one does not do experiments, it simply observes the sky. The amount of information contained in the sky is finite, thus one can wonder if observations can extract all such information, and if so, what can be learned about fundamental physics. It turns out we already have one example where all information in the sky has been extracted. This is the case of the Planck satellite and the temperature of the cosmic microwave background. This satellite has performed a cosmic variance limited observation of the full sky; nobody ever will need to repeat it. Unfortunately, we have not reached the same status with other interesting probes, such as the polarization of the cosmic microwave background and the angular postions and redshifts of galaxies. However, it is not farfetched to think that at the end of this century we will have extracted all information in the sky at most wavelengths of the electromagnetic spectrum. In any event, even today, we have already obtained significant constraints on fundamental physics using astronomical observations. Here I will describe what our current robust limits are on the mass of neutrinos, how we can discover if they are Majorana or Dirac and what can be said about the nature of dark matter. Most of the material has been presented elsewhere [1, 2, 3] and I refer the interested reader to those papers for full details.

2 Robust neutrino masses

In [1] we have shown that probes of the cluster mass function and increased precision on the Hubble constant can break key degeneracies with CMB observations and yield excellent constraints on both the number of species and sum of the masses of cosmological neutrinos. When the expansion history is fixed to ΛCDM, current constraints on H_0 [4] and the cluster mass function [5] constrain $\sum m_\nu < 0.4$ eV at 95% confidence. This bound relaxes to 0.5 eV in the two extended models we considered: wCDM, and the dark coupling model of [6], which allowed curvature, w, and coupling strength ξ to vary. Probing the mass function using X-ray clusters, [7] combine their data with WMAP5+BAO+SN and find $\sum m_\nu < 0.33$ eV in a wCDM cosmology, though the systematic errors still must be clearly quantified. The optimistic upper bound available from current data, $\sum m_\nu \sim 0.3$ eV, almost excludes the scenario in which the neutrino masses are quasi-degenerate. The constraint on the number of relativistic species $N_{\rm rel}$ from probes of the cluster mass function has not been widely explored so far. We find that the combination of WMAP5, [4] H_0, and the maxBCG cluster mass function constraint provides an excellent constraint: $N_{\rm rel} = 3.76^{+0.63}_{-0.68}$. However, we point out that this constraint does not improve when BAO and SN data are also included; those data sets have been shown to have excellent constraining power on both Ω_k and w.

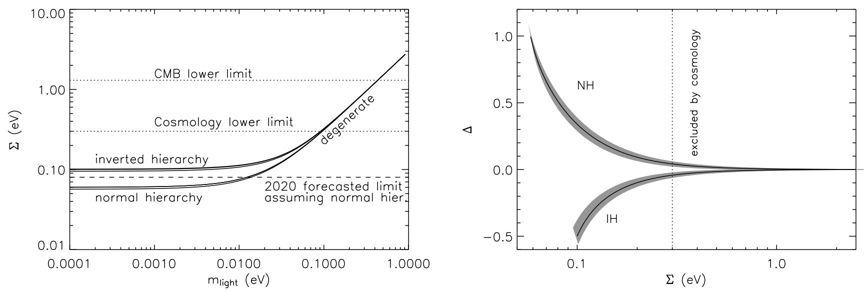

Figure 1: Left: constraints from neutrino oscillations and from cosmology in the m-Σ plane. Right: constraints from neutrino oscillations (shaded regions) and from cosmology in the Σ-Δ plane. In this parameterization the sign of Δ specifies the hierarchy.

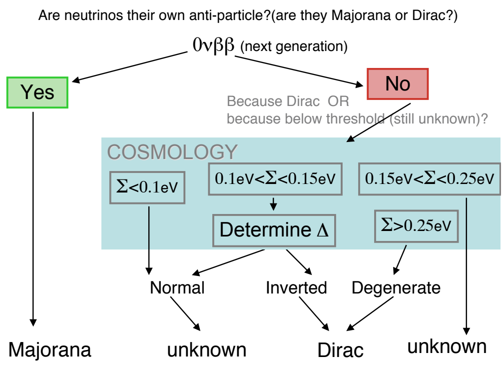

Figure 2: Future neutrinoless double beta decay ($0\nu\beta beta$) experiments and future cosmological surveys will be highly complementary in addressing the question of whether neutrinos are Dirac or Majorana particles. Next generation means near future experiments whose goal is to reach a sensitivity to the neutrinoless double beta decay effective mass of 0.01 eV. We can still find two small windows where this combination of experiments will not be able to give a definite answer, but this region is much reduced by combining $0\nu\beta beta$ and cosmological observations.

3 Measuring neutrino hierarchy

The shape of the matter power spectrum contains information, in order of decreasing sensitivity, about the sum of neutrino masses, the amplitude of the mass splitting and the hierarchy (i.e., the mass splitting order). In [2] we introduced a novel parameterization of the neutrino mass hierarchy, Δ, that has the advantage of changing continuously between normal, degenerate and inverted hierarchies and whose sign changes between normal and inverted. The absolute value of Δ describes the maximum mass difference between the eigenstates. We stress that, current constraints from neutrino oscillations have ruled out large part of the parameter space given by the sum of the masses and the Δ parameter, leaving two narrow regions: for a fixed value of the total mass, the value of Δ for the normal hierarchy is related to that of the inverted one and $\Delta_{\rm NH} \simeq -\Delta_{\rm IH}$. It is the allowed region that cosmology should explore.

We found that the information about Δ accessible from the power spectrum shape yields a degeneracy: parameters values Δ and $-\Delta$ yield nearly identical power spectra and therefore that the likelihood surface in Δ is bimodal. This was not noted in the literature before and not taking this into account when using the Fisher matrix-approach to forecast future surveys performance may lead to spurious indications of a surveys ability to determine the hierarchy.

Detecting the signature of the hierarchy in the sky is therefore extremely challenging, and therefore we asked: can cosmology in the cosmic-variance limit, and for an ideal experiment, distinguish the neutrino heirarchy? or in other words, is there enough information in the sky to measure the neutrino hierarchy? To address these questions we considered ideal, full-sky, cosmic variance-limited surveys and found that substantial Bayesian evidence can be achieved assuming a minimal LCDM base model. Increasing the parameter space by including e.g. effective number of neutrino species, non-inflationary motivated shape of the primordial power spectrum, etc. weakens the constraints and makes a determination of the hierarchy not possible, even though the constraint on the total neutrino mass are less affected and remain still at an interesting level. Are such surveys feasible in the next $5-10$ years? There are two candidates for such surveys: a full extragalactic survey in the optical/ infrared like Euclid[1] and a full 21cm survey by the SKA[2]. Euclid will make an all sky Hubble-quality map for weak lensing and will directly trace the dark matter using this technique. The 21cm surveys provide the most un-biased indirect tracer of the dark matter distribution in the Universe and have negligible shot noise.

For the degenerate and inverted mass spectra, the next generation neutrinoless double beta decay experiments can determine if neutrinos are their own anti-particle. For the normal hierarchy, the effective electron-neutrino mass may even vanish. However, if the large-scale structure cosmological data, improved data on the tritium beta decay, or the long-baseline neutrino oscillation experiments establish the degenerate or inverted mass spectrum, the null result from such double-beta decay experiments will lead to a definitive result pointing to the Dirac nature of the neutrino mass. This is summarized in Fig. 2. If the small mixing in the neutrino mixing matrix is negligible, cosmology might be the most promising arena to help in this puzzle. Our work shows that depending on the total neutrino mass, there might be substantial evidence by cosmological data to infer the neutrino hierarchy.

[1] sci.esa.int/euclid
[2] www.skatelescope.org

4 Constraining beyond the standard model physics

Cosmological observations provide constraints on different distance measures: luminosity distance (as provided e.g., by supernovae), angular diameter distance (as provided e.g., by baryon acoustic oscillations) and even on the expansion rate or the Hubble parameter as a function of redshift z. Both luminosity distance and angular diameter distance are functions of the Hubble parameter. While combining these measurements helps to break parameter degeneracies and constrain cosmological parameters, comparing them helps to constrain possible deviations from the assumptions underlying the standard cosmological model (e.g. isotropy), or to directly constrain physics beyond the standard model of particle physics (e.g. couplings of photons to scalar or pseudo-scalar matter). The Etherington relation implies that, in a cosmology based on a metric theory of gravity, distance measures are unique: the luminosity distance is $(1+z)^2$ times the angular diameter distance. This is valid in any cosmological background where photons travel on null geodesics and where, crucially, photon number is conserved.

More exotic sources of photon conservation violation involve a coupling of photons to particles beyond the standard model of particle physics. Such couplings would mean that, while passing through the intergalactic medium, a photon could disappear or even (re)appear! interacting with such exotic particles, modifying the apparent luminosity of sources. In [3] we considered the mixing of photons with scalars, known as axion-like particles, and the possibility of mini-charged particles which have a tiny, and unquantised electric charge. Photon-conservation can be violated by simple astrophysical effects which give uniform attenuation such as gray dust. We have reported updated constraints on this effect.

More exotic sources of photon-conservation violation involve a coupling of photons to particles beyond the standard model of particle physics. We have focused on axion-like particles, new scalar or pseudo scalar elds which couple to the kinetic terms of photons, and mini-charged particles which are hidden sector particles with a tiny electric charge. Photons passing through intergalactic magnetic fields may be lost by pair production of light mini-charged particles. If the mixing between axion-like particles and photons is signicant, then interactions in the intergalactic magnetic elds will also lead to a loss of photons due to conversion into ALPs. However if the coupling between photons and ALPs is sufficiently strong, one-third of any initial ux will be converted into ALPs, and two-thirds into photons, resulting in a redshift-independent dimming of supernovae which we cannot constrain or exclude with cosmic opacity bounds.

The improved measurement of the cosmic opacity found in [3] leads to improved bounds on these exotic physics scenarios which are summarised in Fig. 13 of [3]. Future measurements of baryon acoustic oscillations, and an increase in the number of observations of high redshift supernovae will lead to further improvements in the constraints on physics beyond the standard model.

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