Precision cosmology as a laboratory for particle physics

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Abstract. I review how precision data from observations of the cosmic microwave background anisotropies and the large scale structure distribution can be used to probe fundamental physics. Some examples are the absolute neutrino mass scale, sterile neutrinos, and non-standard neutrino interactions. I also discuss the sensitivities and discovery potential of future surveys.

1. Introduction: precision cosmological observations

The past twenty years have seen significant advances in the precision of astrophysical observations, a progress that has finally allowed physical cosmology to be studied as an exact science. Today, we have a large number of observations at our disposal that are specifically geared towards cosmological studies, with each type of observation probing a different aspect of the universe’s nature and history.

At the forefront are observations of the cosmic microwave background (CMB) temperature and polarisation anisotropies. These have been measured on large angular scales by satellite experiments such as COBE, WMAP, and the newly launched Planck, and on small angular scales by an array of balloon and ground-based instruments. Often called a snapshot of the universe when it was \(\sim 400,000\) years old, the CMB anisotropies in fact contain a great deal more information all the way down to the present time. Weak gravitational lensing of the CMB by foreground matter, for example, provides a way to determine the foreground matter distribution [1]. Extraction of this lensing signal has already been possible with the ACT [2] and will be one of the goals of the Planck mission.

A second type of cosmological observations are those that map out explicitly the large-scale structure (LSS) of matter in the universe. At present the best-known probe of this nature are the galaxy redshift surveys, with the Sloan Digital Sky Survey (SDSS) being the largest to date, observing some \(\sim 900,000\) galaxies over a 9,000 deg\(^2\) patch out to a redshift of \(\sim 0.5\) [3]. Other useful LSS probes include the Lyman-\(\alpha\) [4] (Ly\(\alpha\)) forest (absorption lines in the intergalactic low density gases along the line of sight to a distant quasar), weak gravitational lensing of galaxies by foreground matter [5], and cluster abundance as a function of the cluster mass [6].

Besides these probes of inhomogeneities, we also have measurements designed to establish the distance versus redshift relations. Standard candles, i.e., objects of known luminosities/energy

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1 For a list of CMB missions, see the website of NASA’s Legacy Archive for Microwave Background Data Analysis, http://lambda.gsfc.nasa.gov/.
emission such as the type Ia supernovae, allow us to establish the luminosity distances to the emitting objects by measuring their fluxes on Earth. Concomitant measurements of the objects’ redshifts then give us the luminosity distance versus redshift relation in the low-redshift universe. Similarly, standard rulers are objects of known physical sizes. Measurement of their angular sizes allows us to determine the angular diameter distances to the objects. The baryon acoustic oscillations (BAO) peak in the two-point correlation function of the matter density fluctuations is one such standard ruler [7].

In this article, I describe how the various aforementioned cosmological observations can be used to probe particle physics.

2. Particle content of the flat concordance ΛCDM model

The simplest cosmological model that accounts for all of the currently available observational data is the flat concordance ΛCDM model. Spacetime in this model is described by the Friedmann-Lemaître-Robertson-Walker metric with flat spatial geometry, and the initial conditions are those set by the simplest, single-field inflation models. The model’s energy/matter content is usually reported in terms of each component’s fractional contribution today, that is, 72% dark energy in the form of a cosmological constant, 23% cold dark matter (CDM), and 5% baryons (protons and electrons). For our purpose, however, it is more illuminating to consider the energy partition at the time of CMB decoupling (~ 400,000 years post-big bang, when the primary CMB anisotropies were “formed”); in this era, the dominant component is in fact CDM at 63%, followed by 15% photons, 12% baryons and 10% massless neutrinos. See, e.g., [8].

What enables the determination of the energy partition from astrophysical observations? To answer this question, it is useful to examine the schematic in figure 1, which shows the four particle components (or, loosely termed, fluids) in the ΛCDM model, their universal gravitational interaction with the spacetime metric, and, where appropriate, non-gravitational interaction amongst themselves. The photons are ultimately measurable as the CMB, while the baryons (protons/electrons) go on to become the galaxies and the hydrogen clouds we observe.

Firstly, we note that what we call CDM, neutrinos, photons, and baryons can be classified and labelled more descriptively in terms of their kinematic properties and non-gravitational interactions (or lack thereof). At the homogeneous level, the kinematic properties (i.e., relativistic, nonrelativistic, or somewhere in between) of a cosmological fluid influence strongly the time evolution of the fluid’s energy density $\rho$. For example, a fully nonrelativistic fluid has $\rho(t) \propto a^{-3}(t)$, where $a(t)$ is the scale factor as a function of cosmic time $t$, while the energy density of a fully relativistic species evolves as $\rho \propto a^{-4}$. Because gravity couples universally
to all forms of energy, the exact admixture of relativistic and nonrelativistic (and other) fluids has a strong impact on the expansion history of the universe, as described by the Friedmann equation

$$\left( \frac{1}{a} \frac{da}{dt} \right)^2 = \frac{8 \pi G}{3} \sum_i \rho_i,$$

where the index $i$ counts all forms of energy in the universe.

On the level of the inhomogeneities, both the kinematic properties and the non-gravitational interactions of a fluid can affect its response to perturbations in the spacetime metric (or, loosely, gravitational potential). This can be understood in terms of the Boltzmann equation which governs the evolution of the fluid’s phase space density $f(x, p, t)$:

$$\frac{\partial f}{\partial t} + \frac{dx}{dt} \cdot \frac{\partial f}{\partial x} + \frac{dp}{dt} \cdot \frac{\partial f}{\partial p} = C[f].$$

Here, on the l.h.s., the $dx/dt$ term encodes the velocity of the fluid element at $\{x, p\} \rightarrow \{x + dx, p + dp\}$, while the $dp/dt$ term is linked to the metric perturbations via the geodesic equation. On the r.h.s., the quantity $C[f]$ is known as the collision integral, which incorporates the effects of non-gravitational particle scattering. Equation (2) therefore shows that the evolution of inhomogeneities in a fluid depends strongly on what kind of fluid it is. Furthermore, these fluid inhomogeneities feed back into the metric perturbations via the Einstein equation $G_{\mu\nu} = 8\pi GT_{\mu\nu}$, where $G_{\mu\nu}$ is the Einstein tensor and $T_{\mu\nu}$ is the stress-energy tensor encoding the matter/energy. This means that if we were to change the properties of one fluid, this change could in principle be felt in all fluids present in the universe. How the photons and the baryons feel this change is particularly important, because they are ultimately what we observe as the CMB and the galaxies.

The kinematics and interactions of baryons and photons are well-known. The same cannot be said about neutrinos and dark matter. The fact that they are assumed in the concordance $\Lambda$CDM model to be, respectively, fully relativistic and fully nonrelativistic non-interacting fluids is because we do not know any better and these are convenient limiting behaviours. Realistic particle physics models may not give rise to precisely these properties. If we were to change these assumptions, we could expect corresponding changes in the CMB anisotropies and the LSS distribution. It is in this sense that precision cosmology can be used as a “laboratory” for particle physics.

There are many examples of how this interplay between cosmological fluid dynamics and gravity can result in interesting constraints on particle physics. In the dark matter sector, for instance, constraints can be placed on the dark matter annihilation cross-section and decay width [9, 10]. Others have sought to place an upper limit on the lightest supersymmetric particle and hence an upper limit on the supersymmetry breaking scale [11]. Here, I want to give a few examples pertaining to neutrino physics.

3. Neutrino masses

Perhaps the most well-known particle physics extension to the concordance $\Lambda$CDM model is the inclusion of neutrino masses. The discovery of neutrino flavour oscillations implies that some neutrinos have a minimum mass of 0.05 eV. Compared with the expected neutrino temperature today ($T_{\nu} = 1.95 \text{ K} \sim 10^{-4} \text{ eV}$), we see that cosmological neutrinos, although born relativistic, can become nonrelativistic at late times when the universe has cooled down sufficiently, and hence can contribute to the matter content with an energy density $\Omega_\nu h^2 = \sum m_\nu/(94 \text{ eV})$ today. In other words, we already have laboratory proof that the fully relativistic approximation in the cosmological context is incomplete!
If the neutrino mass is of order 0.1–1 eV, then the relativistic-to-nonrelativistic transition occurs close to the epoch of CMB decoupling. This leaves an interesting imprint on the CMB temperature anisotropies via the early Integrated Sachs Wolfe effect. Furthermore, even after they have become nonrelativistic at low redshifts, the neutrinos still possess a large thermal velocity dispersion. This dispersion causes neutrino clustering to be very inefficient on small scales, specifically, on scales smaller than the free-streaming scale $\lambda_{FS}$. Expressed in terms of wavenumbers

$$k_{FS} = \frac{2\pi}{\lambda_{FS}} \approx 2.4 \sqrt{\frac{\Omega_m}{1 + z} \left(\frac{m_\nu}{\text{eV}}\right)} h \text{ Mpc}^{-1},$$

where $\Omega_m$ is the total matter (neutrino+dark matter+baryon) density fraction today, and $z$ is the redshift parameter. This inefficiency in neutrino clustering feeds back into the evolution of the metric perturbations and hence the growth of the dark matter and the baryon density perturbations. Thus, if we replace part of the CDM energy density with massive neutrinos, the end result is that the present-day matter power spectrum will show a suppression at wavenumbers larger than roughly

$$k_{FS,\text{min}} \equiv k_{FS}(z_{nr}) \approx 0.03 \Omega_m^{1/2} \left(\frac{m_\nu}{\text{eV}}\right)^{1/2} h \text{ Mpc}^{-1},$$

where $z_{nr}$ is the redshift at which the neutrinos first become nonrelativistic. The fractional suppression is asymptotically $\Delta P/P \simeq -8f_\nu$, where $f_\nu = \Omega_\nu/\Omega_m$.\(^2\) Note that this relation implies that the suppression is sensitive primarily to the sum of the neutrino masses $\sum m_\nu$, less so to the individual masses themselves.

Using a combination of CMB, LSS, and distance versus redshift data, we can already constrain the sum of neutrino masses via these effects down to $\sum m_\nu < 0.44$ eV (95\%C.I.) \(^\text{[15]}\), if we extend the $\Lambda$CDM model only with neutrino masses. However, even if we simultaneously allow for more exotic ideas such as phantom energy, extra species of neutrinos, and a running spectral index for the primordial fluctuation spectrum, the constraint does not deteriorate by much, $\sum m_\nu < 0.76$ eV \(^\text{[16]}\). In the future, we expect Planck alone to be able to achieve the same sensitivity to $\sum m_\nu$ \(^\text{[17]}\). This is interesting, because while present constraints rely on combining different types of probes—some of which (e.g., the galaxy redshift surveys) probing length scales verging on the nonlinear regime, CMB physics is by and large well-understood, linear physics. Further down the road, we expect probes of weak gravitational lensing of galaxies with, e.g., the Large Synoptic Survey Telescope (LSST) to be able to push the 95\% sensitivity to $\sum m_\nu$ down to below the 0.1 eV level \(^\text{[18]}\).

4. An extra neutrino species (or other light particles)?

A number of neutrino oscillations experiments have produced results that are inconsistent with the standard three-neutrino interpretation of the global neutrino oscillation data. First amongst them is the LSND anomaly which saw the appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam. This is followed by the more recent MiniBooNE $\bar{\nu}_e$ excess, and the re-evaluation of the reactor neutrino fluxes which points to the disappearance of $\bar{\nu}_e$ on a distance of tens to hundreds of metres. If these anomalies are to be explained in terms of neutrino oscillations, then a fourth (or possibly more) sterile neutrino state must be introduced, which mix with the standard model neutrinos with mixing parameters in the ballpark $\Delta m^2 \sim O(1)$ eV\(^2\) and $\sin^2 2\theta > 10^{-3}$. See, e.g., \(^\text{[19]}\) and references therein.

The existence of such sterile neutrino states have important consequences for cosmology. Within the standard cosmological setting, this mixing and the ensuing flavour oscillations
inevitably lead to thermalisation of the sterile neutrinos [20]. In other words, these sterile neutrinos are produced copiously in the early universe prior to neutrino decoupling, and contribute an excess of relativistic energy density which can impact on the primordial synthesis of light elements, as well as on the CMB and the LSS. Furthermore, if these sterile neutrinos are sufficiently massive, then their mass is also subject to the same sort of cosmological neutrino mass bound discussed in the previous section.

Surprisingly, it turns out that current cosmological data do in fact prefer an excess relativistic energy density. This excess is usually parameterised in terms of the effective number of thermalised relativistic neutrino species, i.e.,

$$\rho_{\text{rel}} = N_{\text{eff}} \left( \frac{7 \pi^2}{15} T_\nu^4 \right) = (3.046 + \Delta N_{\text{eff}}) \left( \frac{7 \pi^2}{15} T_\nu^4 \right),$$

(5)

where $N_{\text{eff}} = 3.046$ is the standard value for three standard model neutrinos [21]. If the $\Lambda$CDM model is extended with $\Delta N_{\text{eff}}$ massless neutrino-equivalent particles, then the preferred values of $N_{\text{eff}}$ are $3.06 < N_{\text{eff}} < 6.06$ (95% C.I.) [22] and $3.02 < N_{\text{eff}} < 4.7$ [23] from WMAP+ACT+BAO+H0 and WMAP+SPT+BAO+H0 respectively. If primordial elemental abundances are included in the analysis, then the evidence for $N_{\text{eff}}$ is even stronger: $3.34 < N_{\text{eff}} < 4.29$ (95% C.I.) [24].

A question then arises: can the sterile neutrino required to explain terrestrial neutrino experiments account for this excess $N_{\text{eff}}$? In short, it is not easy. The reason is that while flavour oscillations with the laboratory-preferred mixing parameters will almost certainly lead to sterile neutrino thermalisation to produce $\Delta N_{\text{eff}} = 1$, the sterile neutrino state is at the same time too heavy. A mass squared splitting of 1 eV implies that the heavier mass eigenstate has a mass of at least 1 eV. This is in violation of the cosmological neutrino mass bound. Looking at specific scenarios, if the $\Lambda$CDM model is extended with a fourth neutrino with a mass $m_s$, then the constraint on $m_s$ is $m_s < 0.48$ eV (95% C.I.) [25]. Similarly, if extended with a fourth

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\[\text{Note that } N_{\text{eff}} \text{ is defined at a time well before CMB decoupling, i.e., before the neutrinos become nonrelativistic (if they are massive), so that the definition applies in all situations irrespective of the neutrino mass.}\]
and a fifth neutrino with degenerate masses, then $m_s < 0.45$ eV [25]. These should be compared with the laboratory requirement of $m_s \sim 1$ eV [19]. Clearly, the laboratory-preferred sterile neutrinos, if they are indeed freely thermalised in the early universe, are in quite some conflict with precision cosmological data!

Is there a way out? Assuming that the sterile neutrino interpretation of the neutrino oscillation anomalies is correct, perhaps the easiest way out is to find a mechanism to suppress sterile neutrino thermalisation in the early universe. Some avenues appear to be promising, e.g., a large lepton asymmetry [26], although new physics is almost certainly required. This also leaves us with the problem that the observed excess relativistic energy density must be explained by some other physics. One well-motivated scenario might be an order 0.1–1 eV-mass QCD axion, which can also become thermalised in the early universe [27]. However, being a boson with only one internal degree of freedom and generally decoupling at an earlier time than do neutrinos, these axions tend not to be abundant or hot enough to make up even half a neutrino-equivalent species. Many exotic scenarios can also produce the required $N_{\text{eff}}$ excess, e.g., [28, 29].

Failing to find a suppression mechanism, we might still hope to exploit the many (near) parameter degeneracies in the cosmological observables in order to “engineer” a good fit for thermalised massive sterile neutrinos. But this avenue only works at the expense of introducing even more exotic elements to the $\Lambda$CDM model, and even then the engineered fit is not great [24].

Accommodating light sterile neutrinos in cosmology therefore remains an unsolved problem.

Finally, it is prudent to note that although the statistical significance of the present evidence for $N_{\text{eff}} > 3$ owes much to the ACT and the SPT, as well as non-CMB observations, the preference for a large $N_{\text{eff}}$ is very much driven by WMAP, in the sense that it is not possible to obtain meaningful constraints from any cosmological data set unless it is analysed together with WMAP data in order to break parameter degeneracies. Thus, it will be enormously interesting to see what Planck will find. Planck has a 68% sensitivity to $N_{\text{eff}}$ of $\sim 0.2$ after one year of observation [17, 30]. So if there really are four neutrinos, we will know very soon!

## 5. Neutrino interactions

In more exotic scenarios, one could even ponder the possibility that neutrinos have “hidden” interactions. Such possibilities include interactions between neutrinos and dark matter (e.g., [31]) and between neutrinos and dynamical dark energy (e.g., [32, 33]). In fact, the latter kind of interaction has been exploited in the so-called mass-varying neutrino (MaVaN) models [32] to ameliorate certain pathologies in dynamical dark energy models based on scalar field dynamics. Yet another possibility is neutrino-neutrino interaction mediated by light scalar fields [34]. The exact phenomenology of these models vary greatly. Rather than summarising them here, I discuss some generic consequences of neutrino interaction for the evolution of inhomogeneities.

Neutrinos are massless non-interacting particles in the standard $\Lambda$CDM model. This means they should be free-streaming at all times. From a fluid point of view, free-streaming particles have anisotropic stress, i.e., the fluid elements suffer shear effects. For interacting particles, on the other hand, if the interactions are so frequent (i.e., interaction rate is larger than the Hubble expansion rate) that the particle species is in a state of thermal equilibrium, then the fluid has only isotropic stress or pressure. Indeed, it is this free-streaming property that sets neutrinos apart from photons prior to CMB decoupling. (Photons and electrons are “tightly coupled” before CMB decoupling.)

A second generic effect concerns the effective sound speed of the fluid. A relativistic fluid has a sound speed of $c_s^2 = 1/3$. But if the fluid should be tightly coupled to a heavy particle species, then the effective sound speed of the combined fluid will become lower. A ready example is the effective sound speed of the tightly coupled photon-baryon fluid prior to CMB decoupling, $c_{\text{eff}}^2 = 3\left(1 + \frac{3}{4}\left(\frac{\rho_b}{\rho}\right)\right)^{-1}$, where $\rho_b$ and $\rho$ are the mean baryon and photon energy densities respectively. Clearly, this number is lower than 1/3 because photons interact with electrons via
Thomson scattering, while Coulomb scattering couples the electrons to the protons. This chain of interactions ends up giving the tightly coupled photon-baryon fluid a lot of inertia.

A phenomenological parameterisation of these two effects is given in [35]. Using a sound speed parameter \( c_{\text{eff}}^2 \) and a viscosity parameter \( c_{\text{vis}}^2 \) that controls the anisotropic stress (standard value \( c_{\text{vis}}^2 = 1/3 \)), the evolution equations for a massless neutrino fluid can be written as

\[
\delta_\nu = \frac{\dot{a}}{a} (1 - 3c_{\text{eff}}^2) \left( \delta_\nu + 3\frac{\dot{q}_\nu}{a} \frac{\dot{q}_\nu}{a} - k \left( q_\nu + \frac{2}{3k} \dot{h} \right) \right),
\]

\[
\dot{q}_\nu = k c_{\text{eff}}^2 \left( \delta_\nu + 3\frac{\dot{q}_\nu}{a} \frac{\dot{q}_\nu}{a} \right) - \frac{\dot{a}}{a} q_\nu - \frac{2}{3} k \pi_\nu,
\]

\[
\dot{\pi}_\nu = 3c_{\text{vis}}^2 \left( \frac{2}{5} q_\nu + \frac{8}{15} \sigma \right) - \frac{3}{5} k F_{\nu,3},
\]

\[
\frac{2\ell + 1}{k} F_{\nu,\ell} = -F_{\nu,\ell-1} = -(\ell + 1) F_{\nu,\ell+1}, \quad \ell \geq 3,
\]

where \( \delta_\nu, q_\nu, \) and \( \pi_\nu \) are, respectively, the neutrino energy density perturbation, the peculiar velocity of the fluid, and the anisotropic stress, \( \sigma \) and \( h \) are two scalar degrees of freedom related to the metric perturbations in the synchronous gauge, and \( F_{\nu,\ell} \) is the \( \ell \)th moment in the neutrino Boltzmann hierarchy. If we were to substitute this set of equations for the standard set and make no further modifications to the standard ΛCDM model, then the main observable effect of a non-standard \( c_{\text{eff}}^2 \) and \( c_{\text{vis}}^2 \) is in the CMB anisotropies, at multipoles \( \ell > 200 \).

Using this description, two independent groups have recently derived constraints on the parameters \( c_{\text{eff}}^2 \) and \( c_{\text{vis}}^2 \) [36, 37], assuming the standard ΛCDM model extended with \( \{N_{\text{eff}}, c_{\text{eff}}^2, c_{\text{vis}}^2\} \). Both groups find \( c_{\text{vis}}^2 \) and \( c_{\text{vis}}^2 \) values that are compatible with standard expectations, indicating that the CMB anisotropies do indeed prefer free-streaming neutrinos over interacting ones.

6. Conclusions

There are many particle physics motivations for challenging the underlying assumptions of the flat concordance ΛCDM model, especially those assumptions we make in the dark matter and the neutrino sectors. In this article I have described three examples of how the ΛCDM model can be extended in the neutrino sector, and how these extensions can be probed using precision cosmological observations. Interesting constraints on neutrino masses and interactions have already arisen from the current generation of observations, and there is presently some indication of an excess of relativistic energy density, which might be interpreted as a thermal population of light particles in addition to the CMB photons and the standard model neutrinos. All these will be probed with much greater precision when Planck data become available.

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