Neutrino properties from cosmology

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Abstract. In the past few years there have been new developments in the effort of constraining neutrino properties with cosmology. The Cosmic Microwave Background has been measured with renewed and improved precision and large-scale structure surveys have mapped cosmological structures in the Universe over unprecedentedly large volumes. Future, massive large-scale structure surveys have been presented and approved. On the theory side, a significant effort has been devoted to achieve better modelling of small scale clustering and of cosmological non-linearities. As a result it has become clear that forthcoming cosmological data have, in principle, enough statistical power to detect the effect of non-zero neutrino mass (even at the lower mass scale limit imposed by oscillations) and to constrain the absolute neutrino mass scale. I will present some recent work on constraints on neutrino properties from cosmology, concentrating in particular on the work done by my group and my collaborators.

1. Introduction

Cosmology has witnessed an avalanche of data over the past decade or so which has marked the inception of "precision cosmology". A standard model for cosmology has been confirmed: this model with only few parameters describes well observations of the Universe over a wide range of scales and epochs. This model, however, is a model, which, we know, cannot be a complete description and, we know, it is incomplete. Thus by entering in the era of precision cosmology, the focus has shifted from measuring the parameters of the model, to looking for deviations for it and testing the physics on which it is based. Among the many areas of active research in this direction is the goal of studying neutrino properties with cosmology.

Experimental cosmology is however a completely different endeavour from other branches of experimental physics as we only have one observable Universe. We can only make observations (only of the observable Universe) and not controlled experiments; we then fit models (i.e., constrain cosmological parameters) to observations. Any statement or constraint is therefore model-dependent.

Moreover, while the physics of the early Universe is relatively simple and well understood, complicated non-linear physics and astrophysics drive observable quantities in the late-time Universe. Different observations are subject to different levels of trust and robustness because of the variety of poorly known astrophysical processes involved and other systematic effects. Any statement or constraint therefore depends also on the data set chosen. (A practical example will be discussed in §5).

This is what I call the "curse" of cosmology. It is also somewhat a blessing in the sense that in principle we can observe all there is to observe and therefore make "ultimate" experiments: taking more data will not improve the measurement for an "ultimate" experiment, there is a statistical error-floor. Observational cosmology is now getting to the point that for some observable quantities "ultimate" experiments are being made and the statistical error-floor is being reached.

These considerations are extremely important especially when trying to learn about neutrino properties from cosmological observations. In particular, all signals are indirect signals and must be interpreted in the framework of a cosmological model (with a watchful eye for residual systematic and astrophysical effects).

2. Neutrinos signatures in Cosmology

What is a neutrino for cosmology? It is something that behaves like radiation at $T \sim eV$ corresponding to the recombination and decoupling epoch, eventually (possibly, but possibly not) becomes non-relativistic, and behaves like matter. When this happens, it must have small interactions and therefore does not behave like a perfect fluid, and has a high velocity dispersion –it is "hot"–. Of course, neutrinos with masses below $\mathcal{O}(10)$ eV do fit the bill, but one can imagine other processes that also would.

Cosmologically relevant neutrinos are called relict neutrinos and belong to the Cosmic Neutrino Background, which is a relict of the big bang much like the Cosmic Microwave Background (CMB), but which decouples from matter some $2\ s$ after the big bang and not $380,000$ years. Neutrinos are in equilibrium with the primeval plasma through weak interactions, and decouple from it at a temperature $T \sim 1 \text{MeV}$. At decoupling neutrinos are still relativistic (if, not they would essentially behave like dark matter for cosmological observations and would not be distinguishable from it) and have large velocity dispersions.[1] The minimum total neutrino mass inferred by neutrino oscillations results indicates that neutrinos contribute at least to 0.5% of the total matter density. In the era of precision cosmology even this half % is non-negligible! As such neutrinos affect the growth of cosmic clustering so they can leave imprints on cosmological observables.

It is particularly interesting to resort to cosmology to constrain neutrino properties because cosmology is sensitive to the absolute neutrino mass scale, and current cosmological constraints on the sum of neutrino masses $\sum m_\nu$ are competitive with forecasted bounds from ambitious terrestrial experiments (see e.g., the Katrin experiment[2]).

We have essentially three windows to study relict neutrinos: at primordial nucleosynthesis $T \sim \text{MeV}$, neutrinos behave like radiation, any deviation from the standard 3 neutrino families would change the Universe expansion rate[3], changing the abundances of primordial light elements. This window probes the number of neutrino species (or effective number of species). Here I will concentrate on the other two windows: the CMB and the Large-scale clustering. These observables can be used to probe both number of species and masses.

3. Constraining or measuring neutrino masses

Neutrinos with total masses $\overset{\sim}{>} 1$ eV become non-relativistic before recombination and therefore their effects can be seen in the (primary) CMB. Neutrinos with $\sum m_\nu \lesssim 1$ eV still alter matter

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[1] There are about 100 relict neutrinos per cubic centimetre, to be compared with 60 Billion solar neutrinos per second per square cm. Relict neutrinos are of much lower energy but are distributed throughout the entire Universe.
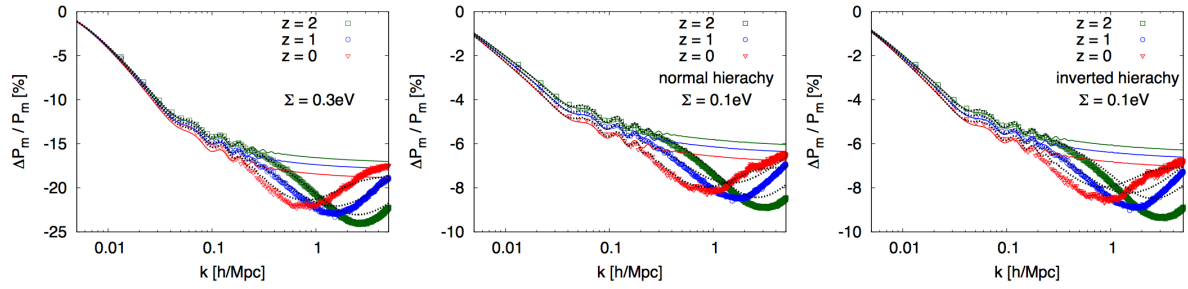
[2] https://www.katrin.kit.edu/68.php

[3] Recall that while matter density scales with redshift, z, as $(1+z)^3$, radiation and relativistic particles density scale like $(1+z)^4$. The radiation content is extremely well known because the CMB temperature is exquisitely measured.

radiation equality but this effect on the CMB can be "cancelled" through degeneracies with other cosmological parameters. On the other hand, due to their high velocity dispersion neutrinos free stream. Therefore finite neutrino masses suppress the matter power spectrum on scales smaller than the free streaming length. In linear theory (for the growth of cosmological perturbations) the suppression flattens out at scales $k > 0.1h/\text{Mpc}$: it is a 50% effect for $\sum m_\nu = 1$ eV a 15% for $\sum m_\nu = 0.3$ eV and a 6% effect for $\sum m_\nu = 0.3$ eV (this can be seen in the solid line of Fig. **??** (from [3]) showing the fractional change in the matter power spectrum as function of wave-number k. In addition different masses become non-relativistic at slightly different times affecting the shape of the matter power spectrum (more in §6).

The recently announced results from the Planck satellite place constraints at $\sum m_\nu < 0.66$ eV at the 95% confidence from CMB only and at $\sum m_\nu < 0.25$ eV when also considering constraints on the lower redshift expansion history coming from the Baryon Acoustic Oscillation (BAO) measurements which help break cosmological parameters degeneracies [1]. This constraint is interesting as it disfavours the degenerate hierarchy. It also puts cosmological (95% confidence) constraints on the sum of neutrino masses at a value just below the Katrin experiment window for detection–90% limit. Needless to say that it will be very interesting to compare the constraints from the two approaches when available.

To improve on the CMB constraint we must look at the shape of the matter power spectrum and thus at the clustering of large-scale structure. It is important to note that the effect of non-zero neutrino masses on the matter power spectrum is not small. A few % amplitude localised features in the power spectrum (the Baryon Acoustic Oscillations, or BAO) have been measured with high confidence! However the neutrino signature is a broadband feature and thus more prone to systematic errors. Statistical errors on the measurement of the power spectrum scale like the square root of the volume surveyed and planned surveys aim at covering a large fraction of the observable Universe. Forecasts for the Euclid satellite based on linear theory for the growth of cosmological perturbations [2] show that such survey should be able to see the signature of neutrino masses in the sky even for $\sum m_\nu$ at the lower limit imposed by oscillations. The main limitation to reach this goal is systematics: the power spectrum of the dark matter cannot be directly measured, in addition at small scales (where there is a lot of signal-to-noise) poorly known astrophysical and baryonic effects kick in. It would be great to have an internal consistency check in case of a detection of $\sum m_\nu > 0$. I will return to this later. The main limitation of linear theory predictions are the effects of non-linearities: non-linear scales enclose a lot of signal-to-noise (noise is scaling like the maximum wavenumber to the 3/2 power). Over the past three years a lot of advances have been made in modelling non-linear gravitational evolution in the presence of massive neutrinos. Approaches that have been considered include analytic/perturbation theory modelling, N-body simulations which also model neutrinos in a fully non-linear way, and an intermediated approach where neutrinos are evolved linearly and therefore analytically but the dark matter is simulated via N-body. Approaches to simulate both dark matter and neutrino masses include using particles to follow neutrinos, using grids or using an hybrid approach. Our group has simulated also the effects of mass hierarchy. Each of the approaches has of course its own advantages and disadvantages, but, encouragingly, the different approaches are in good agreement. The overall conclusion is that non-linearities enhance the signal compared to linear theory predictions both for the effect of neutrino masses and the effect of the hierarchy (to be discussed in §6). Figure 1 show the effects non-zero neutrino masses on the matter power spectrum at non-linear scales (figure from [3]). Here and hereafter NH denotes the normal mass hierarchy and IH denotes the inverted mass hierarchy.

However these predictions are for dark matter only and there are a lot of real-world effects that might make these scales and these gains not reachable. These effects are baryonic physics (which affects all probes including weak gravitational lensing), bias and redshift space distortions (both of which affect galaxy surveys). This is an active research area and no consensus has been

Figure 1. Fractional difference in the total matter power spectrum of the N-body runs with massive neutrinos and the masses neutrino run. Data points show the simulation results, the solid line linear theory predictions and black dotted lines show the estimated effect including non-linearities using the extended HALOFIT formula [4]. Note the typical shape of the effect in the non-linear case: non-linearities enhance the effect and lead to a maximum in the suppression located at mildly non-linear scales.

reached.

On the other hand a lot of these limitations could be bypassed by resorting to the imprint of the growth of clustering on the CMB radiation via gravitational lensing of the CMB. Gravitational lensing by large scale structure of the CMB light, modifies coherently not just the CMB temperature pattern but also the polarisation. This signal was undetected until few years ago, but since then enormous advances have been made. From the first detection in 2007 ([5]) exploiting the cross correlation of the NVSS survey (a large scale structure tracer) and the CMB temperature, to a $> 20\,\sigma$ detection from the Planck temperature maps alone via the the imprint lensing leaves in the temperature four point function, see [6] and refs therein. In the past few months we have seen detection of the signal also in polarisation [7]. CMB lensing is quite sensitive to neutrino masses and given how rapidly this field is evolving we might expect powerful new constraints soon.

Since the publication of the Planck results and constraints in March 2013, many papers have appeared claiming detection of non-standard neutrino properties, $\sum m_\nu > 0$ and/or more than three neutrino species [8, 9, 10, 11, 12]. Before the publication of the Planck results there were few claims for extra neutrinos e.g., [13] and the compilation by [14]. These findings are all somewhat related and will be discussed below, §5.

4. Number of neutrino species

In the standard model there are three neutrino families but in principle there could be more (sterile neutrinos). Free-streaming relativistic particles affect the CMB in two ways *1)* through their relativistic energy density, which alters the epoch of matter-radiation equality, boosting the expansion rate, and *2)* through their anisotropic stress. The first effect however can be mimicked by any other process that alters the expansion rate. For this reason the relevant parameter is called effective number of neutrino species, N_{eff}. The fiducial N_{eff} value for three neutrino families is slightly higher (3.046) to account for a small neutrino heating during $e^+ e^-$ annihilation. Assuming we keep fixed that angular size distance to the CMB (i.e., the position of the first peak), the redshift of matter-radiation equality and the physical baryon density the change of expansion rate due to N_{eff} affects both the distance acoustic waves travel $\propto t \propto H^{-1}$ and the distance photons diffuse $\propto t \propto H^{-1/2}$ giving a net overall effect of increasing Silk damping on small CMB scale. An increase in N_{eff} increases the expansion rate of the Universe at all redshifts affecting the Hubble constant H_0 and age of the Universe. Moreover, by affecting

matter radiation equality and radiation drag, $N_{\text{eff}} \neq 3.046$ affects the baryon acoustic scale and the interpretation of BAO measurements.

While the first effect gives a degeneracy between $\Omega_m h^2$ and N_{eff} and H_0 and N_{eff}, the second effect can break this degeneracy somewhat and affects the CMB damping tail. Neutrino perturbations cut effectively the degeneracy at low N_{eff} (some neutrinos are needed to explain the peaks height and location) but the degeneracy extends to high N_{eff}.

5. Claims of detection of non-standard neutrino properties.

Before the advent of Planck data, the CMB degeneracy in N_{eff}-H_0 plane extended to high values of N_{eff} and H_0. The fact that local H_0 measurements cut this degeneracy at $N_{\text{eff}} \gtrsim 3$ was driving all pre-Planck claims of sterile neutrinos from cosmology. This is discussed in details in [15].

With Planck data and a much improved measurement of the CMB damping tail the CMB-only constraint became $N_{\text{eff}} = 3.36^{+0.68}_{-0.64}$ (95% CL), including BAO measurements which break some parameters degeneracies, this improves to $N_{\text{eff}} = 3.30^{+0.54}_{-0.51}$ (95% CL). However in the ΛCDM model, the Planck inferred value for the Hubble constant is in tension with the local measurements, exacerbating the effect seen with pre-Planck data. The high value of local H_0 determinations could be reconciled with the CMB by going beyond the ΛCDM model and converging on values of N_{eff} close to 4. A detailed discussion can be found in e.g., [16].

The Planck data, within the ΛCDM framework are however also in tension with (some) measurements of the amplitude of clustering at linear-to-mildly non-linear scales. These are: the Planck Sunyaev-Zeldovich cluster abundances [17], some X-ray clusters abundances e.g., [18] and the (small scales) matter power spectrum as measured by weak lensing surveys [19, 20].

The clustering amplitude measured by these probes is lower than the one inferred from CMB data assuming a standard ($\sum m_\nu \gtrsim 0.06$ eV) ΛCDM model, a trend that would happen if neutrinos were actually massive. Note that increasing the neutrino mass above about 0.06 eV makes the tension between Planck data and local measurements of the Hubble parameter worst (which can be alleviated but at the cost of by introducing yet another parameter, i.e. allowing more than three neutrino families).

Several papers have appeared over the past few months claiming that a model where there are more than three neutrino species and neutrinos have a significantly non-zero mass, can reduce these tensions and accommodate all measurements [8, 9, 12]. Of course one cannot understate the extra-ordinary importance of the new physics that these results imply. However before interpreting this as evidence of new physics some extra care is needed.

One must first exclude the possibility that systematic biases in the measurements drive the result. New physics in the neutrino sector, therefore, is an acceptable solution if the extra parameters eliminate the tension between data sets that is present in the standard cosmological model. Moreover the trend should be seen consistently and robustly across a variety of data sets.

To be more precise, the fact that in an extended model the best fit values for extra parameters take non-standard values does not necessarily mean that the extended model provides a much improved fit to the data and that therefore should be favoured over the simpler one. This becomes an issue of model selection rather than simple parameters fitting. In the Bayesian framework (which is what is normally adopted in cosmology) model selection the Evidence ratio (or Bayes factor), gives the relative odds of two models correctly describing the observations, under the assumption of equal a priori model probabilities.

We have recently found that the extra parameters do not eliminate the tension between data sets that is present in the standard cosmological model [21].

First, models with total neutrino masses of about 0.4 eV, while may be preferred when performing a joint analysis with Planck Sunyaev-Zeldovich cluster and X-ray cluster abundances are disfavored by CMB +BAO data. Such large neutrino mass makes the tension between the

CMB-inferred H_0 and the locally measured one, very uncomfortable, pushing N_{eff} to high values. Therefore, the resulting constraints do not indicate a new concordance, but rather, a compromise solution between discrepant datasets.
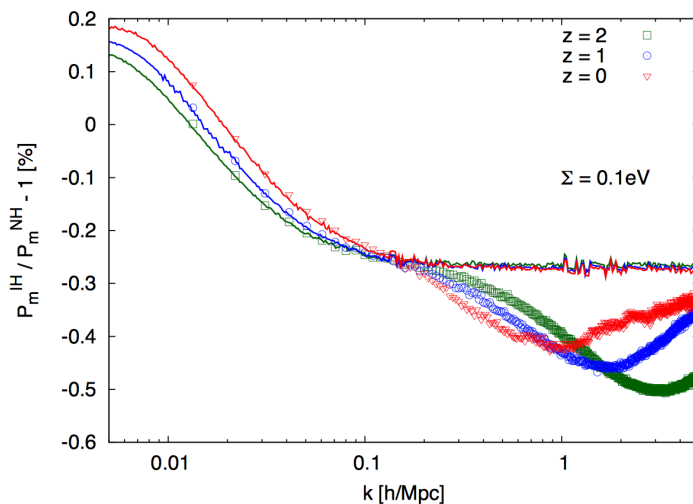
Second, not all datasets that measure the growth of structure e.g., cluster abundance or the clustering amplitude on mildly non-linear scales agree, and the evidence for non-standard neutrino physics is actually disfavoured by other data set combinations.

Finally the evidence calculation for no data combination prefers the extended model in any significant way and for most dataset combinations actually prefers the simpler standard ΛCDM model with standard neutrinos.

6. Outlook towards the future

In the future, planned or proposed surveys will map a sizeable fraction of the observable universe. Considering only statistical errors this will open the possibility not only to measure the absolute neutrino mass scale but also to attempt to determine the mass hirerachy [22]. Neutrino hierarchy affect the shape of the matter power spectrum: neutrinos of different masses have different transition redshifts from relativistic to non-relativistic behaviour, and their individual masses and their mass splitting change the details of the radiation-domination to matter- domination regime.

Figure 2 (from [3]), shows the effect of the hierarchy on the matter power spectrum (all another quantities are kept fixed including the total neutrino mass). Also here we see that non-linearities enhance the linear theory predictions. Note that the effect is small (below the %) and that at $k \sim 1$ baryonic effects that are not included in our simulations might be at play in the Cosmos. While in principle the statistical errors from future surveys might be small enough to measure this effect, the lesson learned from §5 indicate that limits will be set by the level of control of systematics. The hierarchy signal, however small, might actually offer a very useful systematic test.

Figure 2. Fractional difference in the total matter power spectrum of the inverted hierarchy (IH) and normal hierarchy (NH) runs (we keep fixed $\sum m_\nu = 0.1$). Different colours correspond to different redshifts: green $z = 2$, blue $z = 1$, and red $z = 0$. Symbols denote the simulations results and solid lines correspond to linear theory predictions. Note that also in this case, non-linearities enhance the effect on mildly non-linear scales compared to linear theory predictions.
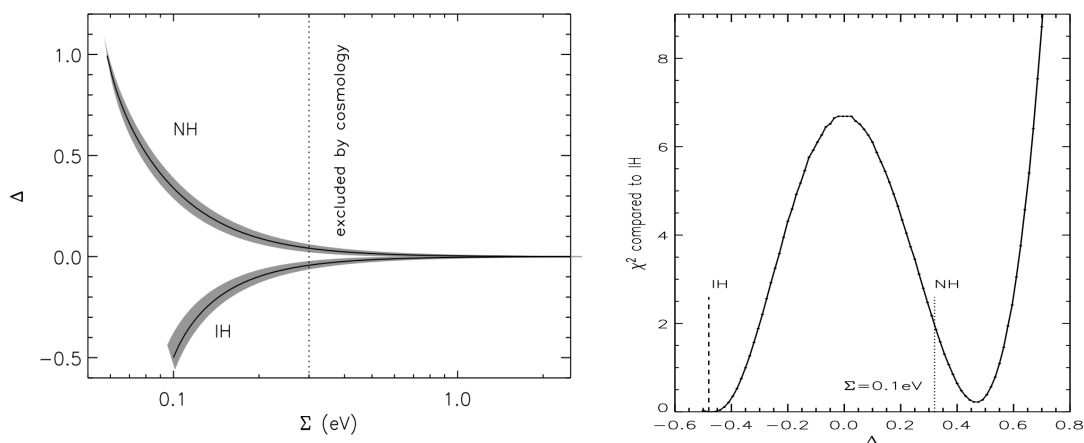
In order to understand this it is useful to introduce the following quantities. Let us ignore the small mass splitting and identify two mass states m the lower mass state and M the larger mass state. Then we have

$$\text{NH}: \quad \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma \tag{1}$$

$$\text{IH}: \quad \Sigma = m + 2M \quad \Delta = (m - M)/\Sigma\,. \tag{2}$$

$$\tag{3}$$

The left panel of Fig. 3 shows the regions in the Σ-Δ space that are allowed by oscillations experiments. Δ is positive for NH and negative for IH. The right panel shows the sensitivity of the matter power spectrum to Δ: clearly cosmology is mostly sensitive to the absolute value $|\Delta|$ and much less sensitive to its sign. Both figure panels are from Ref. [22]. Recall that cosmology is extremely sensitive to Σ, then to $|\Delta|$ and finally to a lesser extent to the sign of Δ. We estimate that a survey covering a sizeable part of the observable Universe and exquisite control of systematic errors could determine the hierarchy [22]; the requirements are much less stringent to constrain $|\Delta|$. Of course the sign is what gives the hierarchy but not all values of $|\Delta|$ are allowed for a given value of Σ. This offers a very powerful consistency check: when a survey measures to high statistical significance a non-zero total neutrino mass, the $|\Delta|$ value measured from the same survey should be consistent with that predicted by oscillations. Should this not be the case, then it would be a clear indication that the mass detection is affected by systematic errors.

Figure 3. Figure from [22]. Left panel: regions in the Σ-Δ space that are allowed by oscillations experiments. Current cosmology limits on the total neutrino mass are also reported. Right panel: cosmology sensitivity to Δ for an idealised survey that covers a sizeable fraction of the observable Universe. Note that cosmology is much more sensitive to $|\Delta|$ than to its sign and its sensitivity to the hierarchy is due to the fact that for a given Σ $|\Delta|$ for NH is not identical to that of the IH.

7. Conclusions

If cosmology could measure not only neutrino masses but also the hierarchy, in combination with neutrino-less double beta decay experiments, this would help answering the question of wether neutrinos are Majorana or Dirac particles. This is yet another example of how the deep connections and how powerful is the interplay between the infinitely big and the infinitely small.

Precision cosmology means that we can start (or prepare for) constraining interesting physical quantities by looking up at the Cosmos. Here I have concentrated on neutrino properties, absolute mass scale, number of species and possibly the mass hierarchy.

Recent contradictory statements have appeared in the literature: neutrino mass detections that are in tension with 95% upper limits and detection of extra species which are in tension with constraints on deviations from three families. My personal view is that once the dust has

settled, we will converge to a constrain of $\sum m_\nu \gtrsim 0.25$ eV (95% CL) and consistency with 3 families.

Large future surveys means that sub % effects become detectable, which brings in a whole new set of challenges but also of opportunities, examples that I have discussed are the absolute neutrino mass scale, the mass hierarchy. The (indirect) detection of neutrino masses from cosmology is within the reach of forthcoming experiments (even for the minimum mass allowed by oscillations). However systematic and real-world effects are the challenge. A lot of work is needed in this direction and there is a clear need for in-built consistency checks. There are exciting times ahead.

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