Neutrino Town Meeting - Panel "Neutrinos and the Universe"

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Abstract

In this document we report about neutrinos and the universe.

Guiding questions

- What are the relevant questions (neutrino masses, number of neutrino species, leptogenesis/baryogenesis, origin of UHE neutrinos, ...)
- What are the relevant experiments, measurements, and observations now and in the future (CMB, BBN, Neutrino Telescopes, KATRIN, Project 8, ...)
- What is needed from the theory community?
- What is the complementarity between different approaches?
- What risks are involved (technological and physics-related)?

1 Introduction

In the Standard Model (SM) of particle physics interactions neutrinos are exactly massless and three different leptonic numbers, associated with e, μ and τ flavours are separately conserved. However, it is an experimental fact that neutrinos have tiny but non-zero masses and that neutrinos of different flavours mix with each other. This provides a solid experimental *laboratory* evidence (and the only one at present) in favour of physics beyond the SM. Is this a signal for existence of a new energy scale in particle physics, related to Grand Unification? Is this an indication that the SM has to be replaced by a new renormalizable low-energy theory? What kind of new particles (if any) are responsible for neutrino masses? How to search for these new particles experimentally? What could be the manifestations of new particles besides generating active neutrino masses?

We do not know yet the answers to these questions, and the input from cosmology may appear to be crucial in resolving these puzzles.

2 Cosmic probes of neutrino masses and properties

Neutrinos are among the most abundant particles in our Universe, and consequently they influence many cosmological observables such as Big Bang nucleosynthesis and the formation of structures (see e.g. [1, 2, 3, 4] for reviews). Big Bang nucleosynthesis is sensitive to the energy density in light neutrinos (or similar relativistic particles) because they affect the expansion rate during BBN. However, BBN is also sensitive to the flavour distribution of neutrinos because neutrinos directly enter the nuclear reaction network (primarily affecting the conversion of neutrons and protons). Given that BBN takes place at keV-MeV temperatures it is insensitive to the masses of light neutrinos. However, BBN can be used to constrain parameters such as the energy density in light neutrinos and possible non-zero chemical potentials of light neutrinos (see e.g. [5]).

Constraints from the CMB Cosmological structure formation, on the other hand, is exceedingly sensitive to even minute neutrino masses. Even though such neutrinos are almost completely relativistic around the epoch of CMB formation, the CMB is still quite sensitive to neutrino masses through their effect on the angular diameter distance to the last scattering surface, through the early ISW effect, and through the lensing of the primary CMB signal. Data from the Planck satellite [6] currently provides and upper bound on $\sum m_\nu$ of 0.54 eV (95% C.L.) from temperature and low-l polarisation alone, improving to 0.24 eV when high-l polarisation and lensing are included. Future CMB experiments such as the proposed LiteBIRD [7] or CORE [8] missions combined with the ground-based CMB-S4 [9] survey might bring the 1σ sensitivity down to the 0.05 eV or even 0.04 eV level, mainly via measurements of the CMB lensing potential (see e.g. [10]).

Constraints from CMB and BAO data CMB data can be used in combination with probes of the universe expansion at small redshift, like for instance measurements of the angular diameter distance through Baryon Acoustic Oscillations (BAOs) in the two-point statistics of the galaxy distribution. Such a combination reduces parameter degeneracies and brings the current Planck constraints down to $\sum m_\nu < 0.12$ eV [6], i.e. close to the point where cosmology is able to discern between the two mass orderings. The sensitivity of future CMB+BAO data sets is expected to be of order 0.02 eV (see e.g. [10]).

Constraints from late-time structure formation Late time structure formation is more directly affected by light neutrinos because they act essentially as a matter contribution to the expansion rate, while having almost no structure, i.e. completely different from CDM. Adding such a smooth matter component leads to suppression of the fluctuation power of total matter on all scales below the free-streaming scale, approximately at the level $\Delta P/P \sim -8 f_\nu$. When combined with CMB experiments, future surveys such as EUCLID [11] will improve the neutrino mass constraint to $\sigma(\sum m_\nu) \sim 0.01$ eV (see e.g. [10, 12]) and can therefore be expected to provide a robust measurement of the sum of neutrino masses. However, it should be stressed here that cosmological structure formation is *not* sensitive to weak interaction physics, and that any any observed hot dark matter component cannot be unambiguously identified as due to neutrinos without help from auxiliary data. We also note that structure formation observations within the next decade will probe the effective energy density in light degrees of freedom to $\sigma(N_{\rm eff}) \sim 0.01 - 0.02$ (see e.g. [10, 13]). The standard model prediction for this number is approximately 3.05 [14, 15, 16], with the additional 0.05 coming from finite temperature QED and incomplete neutrino decoupling. While many calculations of the standard model prediction exist, there is to this date no definitive ab initio calculation, and given the precision of future data, priority should be given to firmly establishing the exact SM prediction.

Light sterile neutrinos The CMB and large scale structure are sensitive to any type of hot dark matter component, not just standard model neutrinos. Therefore, these observables can be used to constrain e.g. eV-mass axions and sterile neutrinos. Current cosmological bounds on such particles are seemingly at odds with the mass and mixing required for sterile neutrinos to explain the reactor and short baseline anomalies. Indeed, explaining these anomalies in terms of oscillations typically requires very large mixing which in turn would lead to complete equilibration of the sterile states in the early universe [17]. Data from Planck and other current surveys yield very stringent bounds on sterile neutrinos (see e.g. [6, 18]) so that an experimental verification of the existence of eV-mass sterile neutrinos would require dramatic changes to either neutrino physics or early universe cosmology [19, 20, 21, 22, 23].

Probing neutrino physics with high-energy neutrinos The Universe provides us with a flux of very high-energy cosmic neutrinos that are not just good for the investigation of extreme, astronomical sources, but also allows for probing fundamental properties of the neutrino themselves. Cosmic neutrinos have first been identified by IceCube in 2013 and today, these neutrinos have been detected with energies reaching several PeV in energy. Their cross-section can be probed indirectly through absorption (depending on energy and angle dependent matter column), allowing us to test SM predictions and constrain hypothesized BSM particles, including leptoquarks [24]. The flavor composition of cosmic neutrinos, predicted to lie in a narrow range for various source scenarios and standard neutrino oscillations, probes BSM physics and the cosmic fabric itself through propagation effects over cosmic baselines. A requirement is a large statistics of cosmic neutrinos, as only the next generation of detectors such as KM3NeT and IceCube-Gen2 can provide. Furthermore, the detection of neutrino interactions via radio techniques will provide an opportunity to increase the volume of the detectors by orders of magnitude and thus expanding the energy window for detecting neutrinos beyond 10^{18} eV.

At lower energies, e.g. below 100 TeV, the large statistics of atmospheric neutrino events observed by open water/ice detectors yields sensitivity to anomalous oscillation signatures, e.g. due to additional sterile neutrinos, Lorenz Invariance Violation, or previously unobserved neutrino production channels such as forward charm production in the atmosphere.

Finally, there are hypothesised exotic processes leaving distinct traces in the detectors, such as magnetic monopoles or charged SUSY particles, (e.g. [25], [26])

3 Direct laboratory probes of neutrino masses and properties

On the one hand, the tiny mass of the neutrino make it one of the most interesting particles, one that might hold the key to physics beyond the Standard Model. On the other hand this minute mass leads to great challenges in its laboratory-based experimental determination.

Absolute neutrino mass Generally, the absolute neutrino mass can be probed in two types of laboratory-based experiments based on 1) single-beta decay and 2) neutrino-less double beta decay [28]. The observation of the latter would require the existence of a Majorana neutrino mass term. The extraction of the neutrino mass depends on assumptions on the process that mediates the decay. The least model-dependent measurement of the absolute neutrino mass, is based solely on the kinematics of single-beta decay [29].

In the single-beta decay the imprint of a non-zero neutrino mass is a reduction of the maximum electron energy and a spectral distortion in the close vicinity of the spectrum's endpoint. In fact, the beta-decay spectrum is a superposition of spectra with different endpoints corresponding to the neutrino mass eigenstates, the neutrino flavor eigenstate (which is emitted in the beta decay) is composed of. However, as of today, no experiment can resolve this superposition and instead an effective electron neutrino mass, an incoherent sum of the neutrino mass eigenstates $m_\beta^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$ is measured.

Major experimental requirements for a direct neutrino mass measurement are an excellent energy resolution of about 2 eV, high signal rates, and low background levels, in order to resolve the small spectral distortion close to the kinematic endpoint, where the signal rate is small, but the neutrino mass signal is maximal. Istotopes under consideration at the moment are the super-allowed decay of tritium, with a short half-life of 12.3 years, and the electron-capture decay of 163-holmium with a half-life of 4500 years.

The Karlsruhe Tritium Neutrino (KATRIN) experiment, a large-scale tritium beta decay experiment [30], celebrated its inauguration in July 2018 and will start data taking in March 2019. KATRIN combines an ultra-luminous gaseous tritium source (10^{11} decays per second) with a high-resolution spectrometer (1 eV) of the so-called MAC-E (magnetic-adiabatic collimation and electrostatic filter) type [31, 32]. The design sensitivity of 200 meV (90% CL) will be reached after 5 calender years of data taking.

The experiments ECHo [33], Holmes [34], and NuMecs [35], exploit the electron-capture decay of ^{163}Ho. Here, the beta-decaying isotope is encapsulated into an absorber material. The energy released in each decay is detected via a highly sensitive temperature sensors (MMCs or TESs) attached to the absorber. Promising first results have been presented by all collaborations [36]. Currently, different techniques for the ^{163}Ho production and multiplexed read-out systems are being developed to scale up the experiment to reach the sub-eV sensitivity.

The tritium-based Project-8 experiment [37], explores a novel idea based on a cyclotron-frequency measurement of the beta-electron. In 2015 the first detection of single-electron cyclotron radiation was announced [38]. Now, the experiment is advancing in a staged approach, targeting an atomic tritium source (to avoid systematic related to molecular final states) to finally reach a sensitivity of 40 meV.

Sterile neutrinos Sterile neutrinos can leave a characteristic signature in single beta decay spectra. With a sterile neutrino mass smaller than the endpoint of the decay, an emission of a new neutrino mass eigenstate is energetically allowed. The endpoint of the corresponding spectral branch is reduced by the mass of the sterile neutrino and has a largely different shape. Consequently, the total beta-decay spectrum exhibits a characteristic kink-like signature. The amplitude of this signature is governed by the active-to-sterile mixing amplitude.

Thanks to its high source luminosity and spectroscopic quality the KATRIN experiment can extend its physics program to also probe the existence of sterile neutrinos in the eV to keV mass range [41, 40, 39]. In the framework of the TRISTAN project an extension of the KATRIN experiment by novel detector and read-out system is being explored to enable the detection of the entire phase-space of tritium beta decay [42]. Analogously, a sterile neutrino search is also considered for the ^{163}Ho-based experiments, and in the Project-8 collaboration [44, 43].

4 Neutrino astronomy

Low-energy neutrino astronomy A high-statistics detection of neutrinos from a galactic supernova (SN) will provide precious information: the neutrino-driven explosion mechanism itself, early warning of SN, SN location, SN nucleosynthesis, others [?], also absolute neutrino masses and neutrino mass ordering, neutrino "condensates", others, can hopefully be revised or addressed [?]. Most relevant information to measure experimentally is time evolution, energy spectra and flavor contents of the SN neutrinos.

For a 10 Kpc core collapse supernova, the Hyper-Kamiokande detector is expected to see $\sim$ 55.000 $\bar{\nu}_e$ from the inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$, IBD) events, $\sim$ 2.300 νe^- elastic scattering events with direction information, $\sim$ 2000 of both $\nu_e +^{18} O$ CC events and $\bar{\nu}_e +^{16} O$ CC events (this last figure has large uncertainty) [45]. Correspondingly a DUNE-type 40kt LArg detector expects $\sim$ 3000 $\nu_e +^{40} Ar \rightarrow e^- +^{40} K^*$, $\sim$ 190 for $\bar{\nu}_e +^{40} Ar \rightarrow e^+ +^{40} Cl^*$ and $\sim$ 290 νe^- elastic scattering [46]. For JUNE's liquid scintillator it is expected $\sim$ 5000 IBD events, $\sim$ 2000 elastic neutrino-proton scattering events, and $\sim$ 300 elastic neutrino-electron scattering [47]. All these numbers suffer of large uncertainties covering possible variations due to the neutrino oscillation scenario and the models used. Hyper-K can detect neutrinos with energy down to $\sim$3 MeV. JUNE can go lower, down to few tenths of MeV. The above figures apparently point to HK as the natural step after SuperK-Gd [48] and JUNE to provide the largest statistics of individual neutrino events. A complementary, very important measurement is made possible by neutrino telescopes like IceCube (and the future IceCube-Gen2). Through their size and low noise environment, they observe an increase in PMT hits due to the large number of neutrino interactions, thus providing a unique very precise measurement of the light curve equivalent to a low energy neutrino detector of several M-tons mass.

The neutrinos produced by all of the supernova since the beginning of the universe must fill the present universe (Diffuse Supernova Neutrino Background, DSNB). If observable, they could provide a steady stream of information about stellar collapse and nucleosynthesis, and on the evolving size, speed, and nature of the universe itself [27]. It is important to measure the DSNB spectrum down to $\sim$10 MeV in order to explore back to the epoch of relative large red shift (z) and, for instance, to allow extracting the contributions from extraordinary SN bursts on the DSNB, e.g. black hole formation.

The first observation of the DSNB could be made by SuperK-Gd [48] with a competitive program [47] by JUNO both with $\sim$ 30 candidate events in $\sim$ 10 years (this has large uncertainties). However, to measure its spectrum more massive, yet precise, detectors are needed. Hyper-K with no Gd could measure DSBN neutrinos at E = 16-30 MeV, while SuperK-Gd and HK loaded with Gd will access down to $\sim$ 10-eV. The expected number of DSNB events by HK after 10 years observation is $\sim 70 \pm 10$ $(16 \leq E \leq 30 MeV)$. If HK is loaded with Gd the number rises to $\sim$ 300 (10-30 MeV). DUNE's 40$-$kt LArTPC detector estimates 46 ± 10 events with $16 \leq E_e \leq 40$ MeV (E_e is that of the electron from $\nu_e +^{40} Ar \rightarrow e^- +^{40} K^*$).

High-energy neutrino astronomy Astronomy has explored the Universe through electromagnetic radiation over 20 orders of magnitude in energy, from radio wavelength all the way to X-rays and gamma rays.

Yet, at high energies many facets of the Universe remain unobserved as the absorption of the highest-energy gamma rays by the CMB and other radiation fields renders the Universe outside our Milky Way opaque to photons beyond 10^{14}eV. Cosmic rays reach energies beyond 10^{20}eV, and thus extend the observable spectrum by another six decades of energy. However, these charged particles are scrambled by magnetic fields and it is hence difficult to pinpoint their origin. Neutrinos on the other hand, produced when charged cosmic rays interact with ambient matter or photon fields inside or outside the sources, point directly to the cosmic accelerators. With the detection of the first high-energy neutrinos of cosmic origin with IceCube in 2013 [49] this window on the high-energy Universe has finally been opened. And the subsequent observation of a source through a neutrino pointing towards a bright, flaring Blazar [50, 51] constitutes another success of the exciting field of multi-messenger astronomy. In addition to energy and directional information, the neutrino flavor is currently emerging as an additional, powerful diagnostic. And yet, the current observations constitute only the tip of the iceberg, with many other well-motivated candidate sources within reach of detection and the neutrino production mechanisms still to be understood. Accordingly, a new generation of neutrino detectors are being planed or constructed, such as the Norther detectors KM3NeT (1.2km^3 instrumented volume) in the Mediterranean sea and the GVD-detector (0.4 km^3 instrumented volume) in lake Baikal, as well as the IceCube-Gen2 detector (8 km^3 instrumented volume) at the South Pole. KM3NeT-ORCA and the IceCube Upgrade, with their denser instrumentation, will allow to lower the energy threshold to a few GeV. On the other side of the spectrum, for energies beyond 10^{16}eV the detection of neutrino interactions via the radio signature offers to instrument hundreds of km^3. Several projects are planed or underway to explore this energy frontier (e.g. ARA/ARIANNA, GRAND). Together, these detectors provide full coverage of the neutrino sky (North and South) over a very large energy range, with enormously improved sensitivity compared to what is currently available.

The goals of the next generation neutrino detectors include: 1) identify the sources of the highest energy cosmic rays, 2) resolve the complete populations of sources of IceCube's high energy astrophysical neutrinos, 3) decipher the production mechanisms of high energy cosmic particles, 4) obtain a unique multi-messenger view of active galaxies and the explosion of stars 5) observe the hadronic emission of supernova remnants and other galactic phenomena, 6) study of galactic and extra galactic propagation of cosmic rays with neutrinos as tracers and 7) test nuclear, neutrino and BSM physics (see also section 2).

Neutrinos constitute a unique messenger for exploring the high-energy Universe and in concert with other observatories, e.g. in gamma-rays or through gravitational waves, already a single high-energy neutrino can result in the identification of a cosmic hadron accelerator. Accordingly, the next generation of neutrino detectors are promising a rich harvest in the coming years and decades.

5 Leptogenesis/baryogenesis

One of the problems of the universe we live in – its baryon asymmetry – may be solved in the most natural way by existence of several heavy neutral leptons, HNLs for short (the names HNL, right-handed neutrino, sterile neutrino or Majorana lepton can be used as well) which do not carry the SM quantum numbers (for a comprehensive overview and references to the original works see [52, 53, 54, 55, 56, 57]). These particles may be superheavy, with the mass $\sim 10^{10}$ GeV. Their CP-violating decays may generate the lepton asymmetry, which is converted then into baryon asymmetry of the Universe by anomalous electroweak processes with fermion number non-conservation. The HNLs also could be in the reach of the LHC and future colliders such as FCC, with the masses in the tens of GeV - TeV region (see, e.g. [58, 59, 60]). Or, their mass can be as small as few GeV, in this case they can be searched for at high intensity experiments, such as SHiP [61], MATHUSLA [62], or NA62 [63]. There are intensive theory investigations aiming at elucidating the connection between leptogenesis, baryogenesis and neutrino physics, with an attempt to pin down the number of unknown yet of neutrino parameters (e.g. type of hierarchy and CP-violating phases) and properties of new particles responsible for neutrino masses and baryogenesis. These investigations are not limited by the simplest theory containing the HNLs only, and include other models based on ideas of left-right symmetry and different types of see-saw mechanism. In coming years we expect both the theoretical and experimental progress in this direction.

6 Sterile neutrino Dark Matter

Sterile neutrinos not only mediate neutrino oscillations and provide a mechanism of baryogenesis. In a family of sterile neutrinos there can be a viable dark-matter candidate (for a review and references to original papers see [64]). Sterile neutrino dark matter is (i) *decaying* (via small mixing with an active neutrino state); (ii) expected to be be *warm* (relativistic at its decoupling from the primordial plasma, cooling down later). This allows to efficiently test this model using astronomical data

Cosmological probes. Being warm and decaying dark matter, the sterile neutrino brings together predictions in a large range of observables:

1) Its decay products are searched in X-ray and gamma-ray astronomical observations.

2) Its primordial properties significantly affect galaxy formation and observable properties of the Milky Way and the Local Group.

3) It affects statistical properties of intergalactic medium probed for example by the Lyman-α forest data from cosmological surveys (BOSS) and deep spectroscopic observations HIRES.

A lot of work is being done along each of these directions. As these observables are not independent – they call for a holistic analysis of experimental data in order to decipher potential signature of sterile neutrino dark matter in astronomical and cosmological data. Two hints have emerged recently. First, an unidentified line was detected in spectra of DM-dominated objects by 4 different X-ray telescopes [65, 66]. Such a line would be compatible with a decay of 7 keV DM particle (in particular – sterile neutrino). Second, the same 7 keV sterile neutrino can also explain the observed cut-off in the Lyman-α power spectrum (as expected from warm DM) [67] and provide galactic structures (Milky Way and the Local group) consistent with current astronomical observations (for a recent review and references to original works see [68, 69, 70]).

The nature of these signals should be clarified by future X-ray missions, and we expect that a lot of work by theorists and observers will be carried out in this direction.

Laboratory probes. Even if the lightest member of the sterile-neutrino family cannot be easily detected in laboratories, the accelerators searches for the heavier members of the sterile-neutrino family, potentially responsible for neutrino masses and baryogenesis are largely motivated and directed by cosmological considerations. Properties of these sought-for sterile neutrino, may define initial conditions that strongly affect the production of sterile-neutrino dark matter.

7 Proton decay; Grand Unification

A fundamental question in Science is the stability of matter. Experimentally it initially reduces to the search for proton (nucleon in general) decay reactions. From the view of a Grand Unified Theory, the current limits on the proton lifetime ($\sim 10^{34}$years, mostly by Super-Kamiokande) exceed by more than three orders of magnitude, the prediction of the first, simplest GUT proposed by Georgy and Glashow.

A key decay mode is $p \to e^+\pi^0$ since it is a nearly model independent reaction mediated by the exchange of a new heavy gauge boson with a mass at the GUT scale and it is dominant in a number of models. Other key channels involve kaons since final states containing second generation quarks are generic predictions of GUTs that include supersymmetry; particularly accessible experimentally is $p \to \bar{\nu}K^+$. In any case the two main experimental characteristics that any search for proton decay must fulfill are: enormous amount of active mass and enough resolution.

Hyper-Kamiokande, because of the water-cherenkov technique, will have by far the largest mass among the three next-generation detectors DUNE, HK and JUNO. As HK is rather good at reconstructing $p \to e^+\pi^0$, it will be exploring well above $\sim 10^{35}$years and a factor of ~ 5 better than the less massive DUNE (for this and the figures thereafter, the instrumental conditions of [45], [46] and [47] are taken for a 20 years period).

Charged particle tracking with DUNE's TPC provides large sensitivity to the $p \to \bar{\nu}K^+$ such that, despite of its significantly smaller mass, is expected to access to similar limits (or even slightly higher) than HK for this mode, $6\cdot \sim 10^{34}$ years. Also the JUNO experiment can explore it with high efficiency due to the large scintillation signal from the K^+; expectations give slightly poorer, yet competitive, limits for this mode .

Generally, nucleon decay may occur through multiple channels and ideally, experiments would reveal information about the underlying GUT by measuring branching ratios. It is found as a strength of Hyper-Kamiokande its sensitivity to a wider range of relevant nucleon decay channels.

8 Conclusions

Active neutrino masses - Cosmology will be able to measure the absolute mass scale of standard model neutrinos associated with hot dark matter within the coming decade through a combination of CMB and large scale structure measurements. However, cosmology lacks flavour sensitivity and cosmological measurements of neutrino properties are therefore done through inference, not direct measurement. A lot of progress is expected in direct measurements of single beta decay and electron capture experiments (KATRIN, ECHo, Holmes, NuMecs and Project-8) aiming to achieve the superior sensitivity in the absolute scale of neutrino mass.

Light sterile neutrinos - Cosmology is very sensitive to the presence of eV-mass sterile neutrinos and the presence of such neutrinos, if experimentally confirmed, would have wide-ranging implications for cosmology. The light sterile neutrinos can be searched for in experiments designed to reveal the absolute scale of neutrino masses, as well as through their oscillation signatures in atmospheric neutrino experiments.

Neutrino astronomy - whether at low or at high energies, the next generation of neutrino detectors will need to significantly increase in size to exploit the potential that neutrino astronomy has to offer. For MeV neutrinos, Hyper-Kamiokande offers an unprecedented statistics for galactic Supernovae as well as the diffuse SN neutrino background. At higher energies, a new generation of open water/ice neutrino detectors such as Km3NeT and IceCube-Gen2 will provide a novel window to the PeV Universe. In addition, these detectors will allow for unique studies of a number of neutrino properties and other BSM physics.

Leptogenesis, baryogenesis and proton decay - Non-zero neutrino masses most probably imply lepton number non-conservation, with strong arguments in favour of CP-violation in neutrino sector. These leads naturally to a possible explanation of the baryon asymmetry of the Universe. The testable predictions of different theoretical scenarios include existence of relatively light Majorana leptons which can be searched at high intensity experiments; the values of CP-violating phases in neutrino mixing; and the proton decay, to be tested best with the Hyper-Kamiokande.

KeV sterile neutrino is a viable DM candidate that has a number of distinct observational signatures. In the coming years a significant progress is expected in this direction with the data of new planed missions becoming available.

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