18 December 2018

A memorandum by the Global Neutrino Network as input to the update of the European Strategy for Particle Physics

U.F. Katz, Chair, Board of the Global Neutrino Network

Friedrich-Alexander University of Erlangen-Nürnberg
Erlangen Centre for Astroparticle Physics
Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
katz@physik.uni-erlangen.de

The Global Neutrino Network is an association of the neutrino telescope projects targeting the investigation of cosmic and atmospheric neutrinos in the energy range from GeV to beyond PeV. The main scientific objectives are the exploration of high-energy cosmic neutrinos from non-thermal astrophysical sources (neutrino astronomy), the investigation of fundamental questions of particle physics with atmospheric, but also cosmic neutrinos (neutrino physics), and further particle physics topics such as the search for dark matter. In this document we focus on the particle physics aspects and provide information that we consider useful in linking neutrino telescopes to the European Strategy for Particle Physics.

The Global Neutrino Network

The Global Neutrino Network (GNN) has been established in 2013 as an umbrella organisation of the neutrino telescope projects ANTARES, Baikal-GVD, IceCube and KM3NeT (in alphabetic order). It provides a forum for cross-coordination between the individual Collaborations and the development of common strategic objectives, as well as a basis for exchanges, common analyses and workshops, such as the VLVnT and MANTS series. GNN is governed by a Board encompassing the spokespersons of all four Collaborations and further key scientists of the field. The GNN Board has elaborated this document, which was endorsed by all collaborations involved, and welcomes its consideration in the CERN strategy process. We note that ANTARES, IceCube, and KM3NeT are CERN recognized experiments, demonstrating the mutual interest and synergy in cooperation.

The Neutrino telescope projects

The currently largest and most sensitive neutrino telescope is **IceCube**, instrumenting a cubic kilometre of deep glacial ice at the South Pole. Its construction has been completed in 2010 and it is continuously taking data since then. Two major breakthroughs in neutrino astronomy have been achieved by IceCube: The detection of a high-energy flux of cosmic neutrinos (2013) (1) and the first association of a high-energy neutrino to a specific astrophysical source (2018) (2) (3). IceCube comprises Deep Core, a densely instrumented infill in the clearest ice layer, allowing for the detection of neutrinos with energies down to 10 GeV. Recently, an upgrade with seven additional detector strings in the Deep Core region, improving both the low-energy capabilities and the investigation of optical ice properties, has been approved by NSF; it will receive additional funding from Europe and Japan. The deployment of these strings is expected for 2022/23. Subsequently, a major extension of IceCube, IceCube-Gen2, with a 10 km^3 deep-ice detector, a large surface array, a radio neutrino detection array and a densely instrumented low-energy detector (PINGU) is envisaged.

In the Northern hemisphere, neutrino telescope projects are pursued in the Mediterranean Sea and in Lake Baikal. **ANTARES**, completed in 2008 and taking data since then, was the first deep-sea neutrino telescope. Even though its instrumented volume is two orders of magnitude smaller than that of IceCube, it has provided important results due to its complementary sky view. In addition, it has demonstrated the feasibility of a deep-sea neutrino telescope. The next-generation neutrino telescope in the Mediterranean Sea, **KM3NeT** (4), will comprise a densely instrumented detector off the French shore (KM3NeT/ORCA: Oscillation Research with Cosmics in the Abyss) and a cubic-kilometre high-energy installation near Sicily (KM3NeT/ARCA: Astroparticle Research with Cosmics in the Abyss). KM3NeT is included in the ESFRI Roadmap. The technical design of KM3NeT is completed and construction has begun. It is expected that operation with a substantial part of the overall detector will start in 2021.

Many years of experience with smaller neutrino telescope installations in Lake Baikal in Siberia have led to the **GVD** project, aiming at a detector instrumenting a cubic-kilometre of water. GVD will primarily target neutrinos in the multi-TeV range. The GVD construction is ongoing and first results have recently been reported (5).

Neutrino physics with atmospheric neutrinos (GeV range)

In the context of neutrino telescopes, research in this field has first been established with ANTARES (6) and with IceCube/Deep Core. Recent IceCube results (7) obtained with Deep Core demonstrate a sensitivity to the neutrino oscillation parameters θ_{23} and Δm^2_{23} that is competitive with that of experiments employing accelerator neutrinos. The IceCube upgrade with seven additional detector strings in the Deep Core region will further lower the energy threshold and allow for a measurement of tau-neutrino appearance with unprecedented precision, and consequently of the element $U_{\tau 3}$ of the neutrino mixing matrix, which is currently the least constrained element of this matrix.

In the coming years, ORCA and somewhat later PINGU will be in the position to use oscillations of atmospheric neutrinos with energies between some GeV and some 10 GeV in the Earth to measure the neutrino mass ordering, i.e. to determine whether there are two light and one heavier or one light and two heavier neutrino mass eigenstates. Depending on the mass ordering and the octant of θ_{23}, a 3-5σ significance will be reached after a few years of data taking. It can be expected that a combination with results from the JUNO experiment – which employs a different approach to investigate the neutrino mass ordering, with completely different systematics – will surpass the 5σ threshold in less than three years of joint operation.

In general, the broad energy/baseline range covered by our experiments provides unique sensitivity to new physics in the neutrino sector, one example being non-standard interactions (NSI) of neutrinos.

On a longer timescale, the investigation of CP violation in the neutrino sector with neutrino telescopes may be in reach, using even more densely instrumented detectors (Super-ORCA or Super-PINGU) and/or an accelerator beam pointed from Protvino/Russia to ORCA (P2O initiative) (8).

We note that these science prospects complement those of the DUNE project, at a comparatively moderate price tag.

Particle physics with high-energy neutrinos (sub-TeV to PeV range)

In addition to the core objective of neutrino astronomy, the measurement of both atmospheric and cosmic neutrinos with energies between some 100 GeV and some PeV addresses a number of fundamental particle physics issues, for which accelerator experiments are not sensitive, or sensitive in different parameter regions:

- Neutrinos from the annihilation of dark matter particles – e.g. weakly interacting massive particles (WIMPs) or other hypothesised dark matter candidate particles – may signal the presence, location and characteristic properties of dark matter.
- The existence of sterile neutrinos of eV mass can be explored using the oscillation pattern of TeV-scale atmospheric muon neutrinos (9).
- At even higher energies, violation of Lorentz invariance may induce an oscillation-like pattern.
- The flavour composition of cosmic neutrinos is restricted to a narrow region in the "flavour triangle" for Standard-Model production processes and oscillations. Deviations from this expectation would signal new physics.
- Absorption of high energy neutrinos in the Earth provides a measure of the neutrino-nucleus cross section up to energies not accessible at accelerators and thus probes new physics both in the Standard Model (e.g. low-x QCD dynamics, electroweak sphalerons) and beyond it (e.g. leptoquarks, new dimensions) (10). Radio detection of neutrinos may provide opportunities to investigate particle physics at even higher energies up to the EeV range.
- The atmospheric neutrino flux in the 10-100 TeV region is sensitive to the production of charmed mesons in cosmic ray interactions in a kinematic region also probed by LHCb.
- Neutrino telescopes provide unique sensitivity to hypothesised exotic particles, such as magnetic monopoles (11) (12), strangelets or nuclearites.

Conclusions

Given the particle and in particular neutrino physics capabilities of the current and upcoming neutrino telescopes, we suggest to consider these instruments as an element of the future European Particle Physics Strategy and to exploit synergies both on the scientific and instrumental level. In particular, a mutually beneficial cooperation between the neutrino telescope projects and the CERN neutrino platform might be an option to explore. We note that the neutrino telescope community is deeply involved in technology, computing and data science developments which are also relevant for accelerator-based experiments – examples are photo-detection, GPU-based scientific computing and open data provision.

References

1. *Evidence for high-energy extraterrestrial neutrinos at the IceCube detector.* **IceCube Coll., M.G. Aartsen et al.** Science 342 (2013) 1242856.

2. *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A.* **IceCube and Fermi-LAT and MAGIC and AGILE and ASAS-SN and HAWC and H.E.S.S. and INTEGRAL and Kanata and Kiso and Kapteyn and Liverpool Telescope and Subaru and Swift NuSTAR and VERITAS and VLA/17B-403 Collaborations, M.G. Aartsen et al.** Science 361 (2018) eaat1378.

3. *Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert.* **IceCube Coll., M.G. Aartsen et al.** Science 361 (2018) 147.

4. *Letter of intent for KM3NeT 2.0.* **KM3NeT Coll., S. Adrián-Martínez et al.** J. Phys. G43 (2016) 084001.

5. **Z. Dzhilkibaev, for the Baikal-GVD Coll.** Baikal-GVD - the next-generation neutrino telescope in Lake Baikal. http://zenodo.org/record/1302982.

6. *Measurement of atmospheric neutrino oscillations with the ANTARES neutrino telescope.* **ANTARES Coll., S. Adrián-Martínez et al.** Phys. Lett. B714 (2012) 224.

7. *Measurement of atmospheric neutrino oscillations at 6–56 GeV with IceCube DeepCore.* **IceCube Coll., M.G. Aartsen et al.** Phys. Rev. Lett. 120 (2018) 071801.

8. **D. Zaborov for the KM3NeT Coll.** The KM3NeT Neutrino Telescope and the potential of a neutrino beam from Russia to the Mediterranean Sea. http://arxiv.org/abs/arXiv:1803.08017.

9. *Searches for sterile neutrinos with the IceCube detector.* **IceCube Coll., M.G. Aartsen et al.** Phys. Rev. Lett. 117 (2016) 071801.

10. *Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption.* **IceCube Coll., M.G. Aartsen et al.** Nature 551 (2017) 596.

11. *Searches for relativistic magnetic monopoles in IceCube.* **IceCube Coll., M.G. Aartsen et al.** Eur. Phys. J. C76 (2016) 133.

12. *Search for relativistic magnetic monopoles with five years of the ANTARES detector data.* **ANTARES Coll., A. Albert et al.** JHEP 1707 (2017) 054.