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Rapporteur ICRC 2021: Neutrinos and Muons

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This contribution attempts to summarize the status of the field of neutrinos from the cosmos as presented at the ICRC 2021, the first online-only edition of this conference. This rapporteur report builds on 212 contributions with pre-recorded talks and posters, as well as 11 discussion sessions. Furthermore, many of the session conveners provided valuable input to this summary.

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The field of neutrino astronomy already provides exciting results, however,it is still dominated by very low statistics in astrophysical neutrino detections. The most transformative results have been discussed in the multi-messenger context [1] and clearly neutrinos are becoming a target of opportunity for all experiments with a potential sensitivity to them. The neutrino field itself is booming with new ideas for detectors and has reached a maturity in which detailed data analysis and systematic detector calibration are the order of business. To summarize the sentiment: the community is doing their homework to get ready for many more neutrinos, which the broader community is excited about.

1. Ideas

The field is driven by ideas, both in further developing experiments and theoretical models.

1.1 Established players, upgrading or under construction

10 years after its completion, IceCube is still only scratching the surface of neutrino astronomy [2]. The IceCube Upgrade, targeting lower energies and an improved detector calibration is funded and optical modules are currently being produced. IceCube-Gen2, an order of magnitude better in sensitivity across the energy range is proposed for construction after completion of the Upgrade. The IceCube-Gen2 collaboration published a comprehensive whitepaper that can be referred to for more details and an overview of the science case [3].

Baikal-GVD, exploiting the waters of lake Baikal, is still under construction. Currently 8 clusters are operational, corresponding to an effective volume of 0.4 km^3 in cascade mode. Completion of the detector with 14 clusters is scheduled for 2024 [4].

12 KM3NeT detection units are now operational in the Mediterranean sea. It is planned to complete the ORCA115 array (focusing on neutrino oscillations) in 2025 and ARCA230 (focusing on astrophysical neutrinos) in 2027 [5]. Antares data analysis is ongoing with 10 years of data.

1.2 New players under construction

With RNO-G (Radio Neutrino Observatory Greenland) the first large scale implementation of a radio neutrino array is currently being deployed at Summit Station in its first season. 35 stations are planned and fully-funded [6]. The radio in-ice techniques targets neutrino energies above 10 PeV. RNO-G will have to show the scalability of the radio detection technique from smaller pathfinder experiments.

A successor to ANITA, PUEO [7], has been selected as balloon mission to fly over Antarctica. It will improve on ANITA by lowering the energy threshold and increasing the sensitivity by a factor of 10. It is scheduled to fly in December 2024.

1.3 New players in pathfinder mode

The Pacific Ocean Neutrino Experiment Explorer (P-ONE) deployed the second pathfinder string [8]. The site off the coast of Vancouver has the potential to develop into a third large water array, as the infrastructure is already in place and first measurements of the attenuation length are promising [9] (see also Figure 2 right).

A demonstrator Cherenkov telescope for Trinity has been funded [10, 11], which will look at the rim of the Earth from a mountain top for upcoming τ stemming from ν_τ-interactions. The Cherenkov technique has the potential to bridge the energy gap between optical in air or water arrays and the radio technique.

The various EUSO missions combine the Cherenkov with the Fluorescence approach. EUSO-SPB2, scheduled to fly in 2023 on a super-pressure balloon, targets the observation of UHECRs and works as technology demonstrator for the proposed POEMMA mission targeting (also) transient neutrinos [12, 13].

There are various proposed radio air shower arrays in pathfinder mode aiming at the detection of ν_{tau} through τ-induced air showers. To this end, one can either blanket large areas with simple antennas as proposed for GRAND [14, 15] or one can set-up smaller arrays on mountain tops overlooking large areas, like proposed for BEACON [16, 17] or TAROGE [18]. Demonstrators for both approaches are currently operational.

1.4 The low energy regime

It has been 25 years since Super Kamiokande has started taking data. Gadolinium-sulfate is now being released for better neutrino anti-neutrino distinction and improving the performance [19]. Its successor Hyper-Kamiokande has been approved for construction in 2020, the tunnel construction has already begun, and operations are envisioned to begin in 2027 [20].

It was also reported about JUNO, a reactor neutrino experiment under construction in China [21], which is particularly intriguing for cosmic neutrinos in combination with sensitivities of ORCA or IceCube-Upgrade. Also, BAKSAN, a multi-purpose liquid scintillator detector targeting geo-neutrinos and neutrinos from the CNO cycle is currently in an R&D stage of 5 t with a target mass of 10 kt [22].

1.5 Other experimental endeavors

Valuable input for the neutrino and muon field is expected from two experiments at CERN. NA61/SHINE, a fixed-target experiment, has been and will be delivering input to cosmic-ray simulations. Planned are detector upgrades and the investigation of heavy particle fragmentation [23, 24]. FASERν will be placed in a service tunnel close to ATLAS, targeting the muon excess problems in air showers and predictions for prompt neutrinos (through forward charm meson production). It is scheduled to start data taking in 2022 [25, 26].

1.6 Ideas of what to target

In general the neutrino field tends to think in areas of fundamental physics and astrophysics, which has been reflected at this conference in two discussion sessions that are worth re-watching. Next to comprehensive summaries of on-going research and new theoretical developments, the discussion panels raised some provocative questions such as

- What is discovered first: new physics or secondary corrections to our models?
- Do we have too many fudge factors in our models, tuned to data?

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- Are we clear enough about assumptions (such as identical sources) when ruling out source classes?
- Are there enough precautions against over-interpreting correlations and bias?

It seems of utmost importance that the fields keeps critically questioning the advances and new results, so that bold claims that are being made in proposals or high-impact papers do not blend into reality without scrutiny. In particular when it comes to sources, we seem to be reaching a point where assumptions such as "all sources are the same" can no longer reasonably be defended.

2. Calibration and detector development

The larger ideas as presented in the first chapter, were complimented with reports about hands-on detector development and calibration. In particular calibration is gaining in importance to be able to better or more tightly interpret the signals detected.

2.1 Hardware development

Since many experiments rely on photo(n) detectors, a whole discussion session was reserved for this topic. The general trend seems to go towards more complex and segmented photodetectors like multi-PMT modules used in KM3NeT. These complex sensors, however, require optimized calibration plans. Also, given the increase also in size of the overall experiments, many discussions about the suitability for mass-production of more complex sensors, standardization needs and scalability were on the table, with one or the other voice arguing for simpler rather than more complex sensors.

Overall, there were rather few contributions dedicated to hardware only, with many from the radio domain, which is still more in the nuts and bolts phase, with the first large array only just now under construction. It can be concluded that fiber optics are here to stay and no longer controversial.

2.2 Detector calibration

The extended discussion session about detector calibration is indicative of the fact that the field has grown up. A point has been reached where studies are starting to be systematics limited, so a considerable effort is being made to reduce these systematic effects. It should be highlighted that despite not being put forward for a neutrino detector anymore, the acoustic detection has matured into being successfully used for positioning in all large arrays with strings [27–29] (see also Figure 1).

2.3 Media properties

Similarly, considerable effort is being undertaken to better model and understand the detection media ice and water. In many experiments the systematic uncertainties carried forward from attenuation length, scattering coefficients and media impurities are starting to dominate the progress. Also, given the long duration of calibration efforts presented (development of specialized measurement devices, dedicated measurement campaigns), it should not be underestimated that significant resource's are being allocated to this aspect. However, also interesting opportunities present themselves in this context. A new approach has been presented measuring the luminescence properties

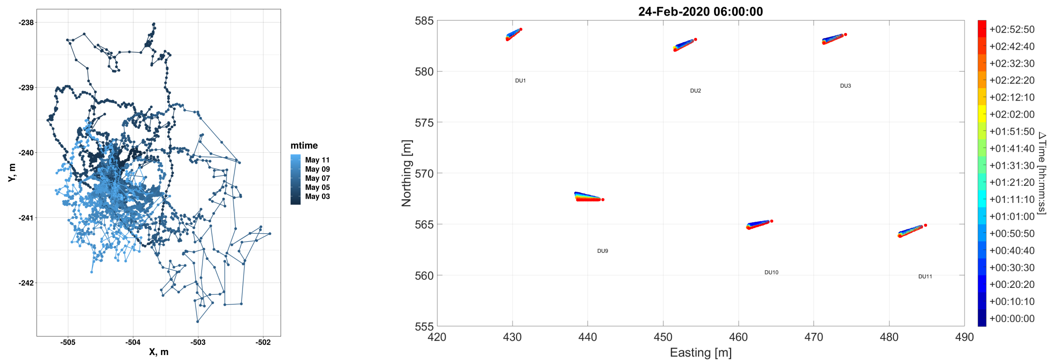

Figure 1: Top view of string positions as reconstructed through acoustic modules. Left: Baikal-GVD Beacon No. 306 drift between May 1 and May 12 2020, during a regular drift period [29]. Right: KM3NeT Detection Unit Line Fit position reconstruction with top-view for each line with respect to their position on the sea bed [28].

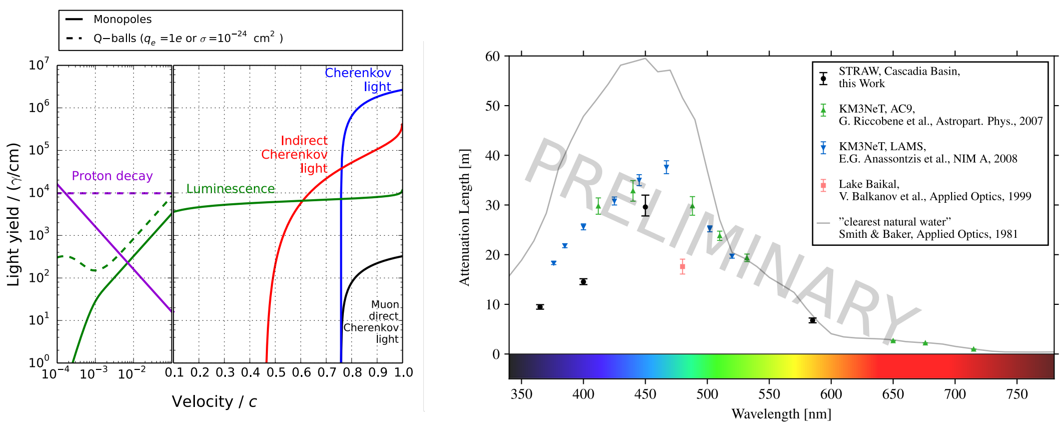

Figure 2: Left: Light yield of different emissions for magnetic monopoles carrying one Dirac charge and Q-balls with a charge of 1020 in comparison to a bare muon passing through ice [30]. Right: Attenuation length vs. wavelength from the simultaneous multi-wavelength fit obtained at the P-ONE site [9].

of ice and water resulting from moving charges, a potential new detection channel for exotic “slow” particles in neutrino telescopes [30] (see also Figure 2).

3. Reconstruction and simulations

An overall highlight of a conference like this is to see all the hands behind the scenes involved in getting the best out of the data of the detectors. Regrettably, the online format did not provide the usual chance to shine in person, but the discussion sessions did at least try to attempt to highlight this important work. A flurry of studies and new developments in reconstruction and simulations have been presented that future measurements and science results will benefit from. Only a tiny fraction can be highlighted here.

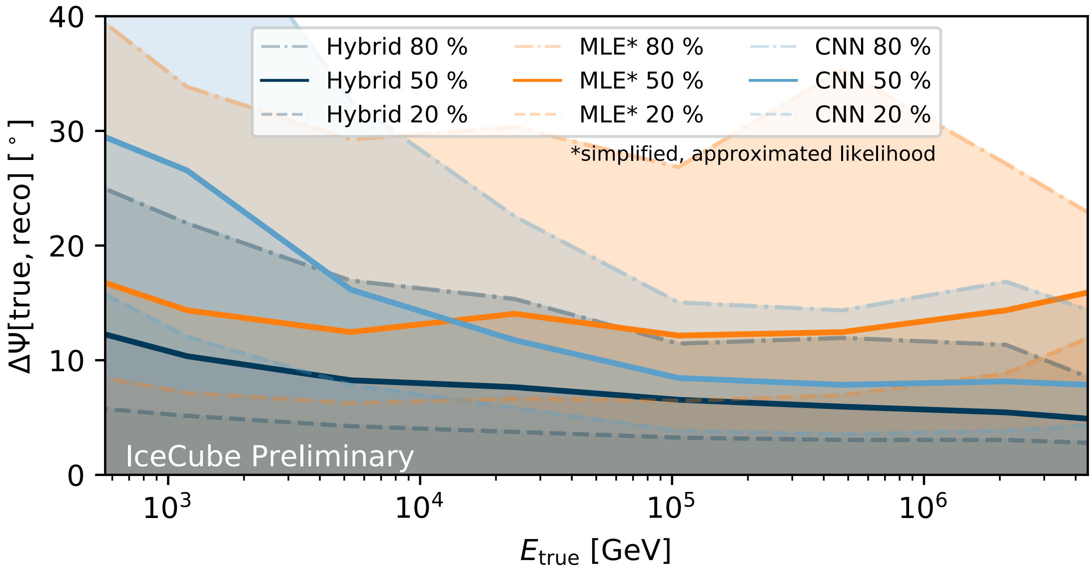

Figure 3: The angular resolution of charged-current ν_e interactions for a typical cascade event selection is compared between IceCube's default reconstruction (MLE), a CNN based method, and the presented hybrid method. The hybrid method leads to a significantly improved angular resolution over the whole energy range. The plateau towards higher energies is induced by systematic uncertainties [35].

3.1 Neutrino pointing

With the detection of the first likely neutrino sources, combined with the fact that event statistics are still very low, a significant effort is being made to better reconstruct arrival directions and to increase the fidelity of events, which are intrinsically harder to reconstruct a direction for such as cascade-like events.

KM3NeT will likely reach sub-degree resolution for single cascades [31], and IceCube has, for example, reported on checks of the pointing accuracy using the shadow of the moon, starting to resolve the rim of the moon [32]. While likely not competitive in angular pointing, predictions of the angular resolution of in-ice radio arrays are starting to be more concrete [33, 34] (see also Figure 4), which will be useful to evaluate physics cases of the upcoming and proposed in-ice radio arrays and get the theory community thinking of particular models to test in the highest energy range.

3.2 Event reconstruction

In the overall event reconstruction, a clear trend towards more modern machine learning techniques is observable, however, established are techniques still going strong; possibly with a little bit too much inertia in using the former techniques. By now, the characteristics and performance of machine learning tools are well understood and one could also consider to use them only for aspects in which they are good (the true pdf is unknown, too many parameters to efficiently be able to use parameterizations) and not for those where the physics modeling is solid and the analysis does not need to be trained, as for example shown in an analysis combing maximum likelihood estimation with a convolutional neural network [35] (see also Figure 3).

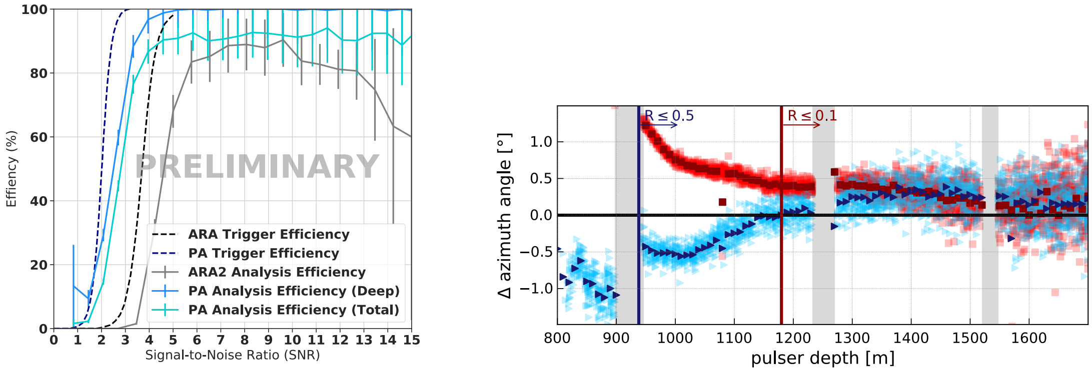

Figure 4: Left: Analysis efficiency resulting from an analysis of the phased array (PA) data compared to the most recent ARA Station 2 efficiency, scaled to have equal definitions. This most recent analysis shows a strong improvement at low signal-to-noise ratios, which was an outstanding issue to deliver on promised experiment sensitivities [36]. Right: Difference between measured and expected arrival directions from a pulser study with ARIANNA. Light blue triangles show the residuals using the four LPDAs along with a 10 m average shown in a darker blue color. Red squares show the residuals using the four dipoles along with a 10 m average shown in a darker red color. The gray shaded areas indicate communication periods [34]. Together with the resolution on polarization [39], this translates into a resolution on neutrinos arrival direction.

3.3 Radio reconstruction

It was encouraging to observe that the radio technique is slowly but surely moving towards the mainstream and contributions dealing with the event reconstruction were no longer exclusively grouped with other radio contributions. However, some discussions are still very unique to radio, given that radio is still a step behind optical methods in not having detected a neutrino yet. Progress has been reported on all fronts, most notably in being able to extract low-SNR neutrino signals, which is required to reach the proposed sensitivities [36] (see also Figure 4). This was complemented. among others, by studies showing the expected energy resolution [37] and first ideas of how to reconstruct flavor [38].

3.4 UHE tau-neutrinos

As already visible from the first section, the field of upward going ν_τ is booming. Clearly this development has also been fueled by the "ANITA mystery events", which experiments like PUEO, the Cherenkov camera of EUSO-SPB2, or ultimately POEMMA will have an excellent handle on. Without additional experimental evidence the discussion about the origin of these events have calmed down, while the ANITA collaboration naturally keeps investigating different scenarios [40].

The dedicated discussion session on ν_τ-related aspects did highlight the fact that currently 7 independent codes [41–43] are available to calculate the τ-propagation through the Earth, and raised the question whether this was sustainable for a smallish community. In particular, since other communities are using the codes and may be interested in using the most comprehensive of all codes. The overall opinion was that a consolidation has to take place for the sake of comparability, while not burdening all software developers with having to accommodate all experiments and all purposes.

3.5 Muons

Muons are grouped with the neutrinos in a track, but are likely to suffer from underexposure, despite being critical to understand for backgrounds and production mechanisms. Also, there is of course a large overlap with the air shower track.

The most pressing current issues are and have been for a long while that (1) too many muons are observed in air showers as compared to the predictions in air shower simulations and that (2) prompt neutrino production (and the related muon production) is rather uncertain, lacking solid quantitative predictions [44], while becoming more and more important at energies of the astrophysical flux. Both of these problems are likely to obtain fresh input from NA61/SHINE [23, 24] and FASERν measurements [25, 26]. Small flux differences to study prompt-production may also be observable for neutrino telescopes, but need a dedicated effort, not a by-product of neutrino analyses [45].

On the simulation sides, a couple of codes has established themselves as dominant players, such as MCEq, which is widely used for the muon flux predictions e.g. [46], and PROPOSAL a lepton-propagator [47]. The arrival of CORSIKA 8 [48] is also eagerly awaited by the neutrino community.

3.6 Global and combined analysis

In the light of the still small event statistics, the discussion session about future neutrino telescopes resulted in the admittedly provocative question: *Should we be like particle physics and have ONE BIG telescope only?* While no one was willing to answer this question with "Yes" there was rising consensus that collaboration and cooperation between experiments has to be increased. Joint-analyses are currently rather cumbersome, as likelihoods and assumptions are baked deep into single-experiment analyses and are both hard to extract and to generalize. Also, the efficiency gain was pointed out, if not every experiment used for example their own source correlation tool, but forces were joined. This would also lead to more sustainable code development, as service tasks would be shared. This, in turn, almost immediately resulted in the well-known, but highly controversial statement: *We are physicists and not software developers*. While there was consensus that education in software development is lacking from ALL physics curricula and younger colleagues find themselves ill-prepared for the task of simulation or data analysis in astroparticle physics, opinions diverged on whether encouraging people to focus on programming is recommendable. The (broader) community still undervalues contributions to software frameworks in career decisions. This is despite the fact no result at this conference would have been possible without software, good software speeds up results, improves everyone's work satisfaction, and simplifies cross-instrument verification and collaboration.

4. Cosmic Physics

This conference series covers the newest results about all known types of neutrinos from the cosmos from solar neutrinos to astrophysical neutrinos, as well as exotic particles showing a signal

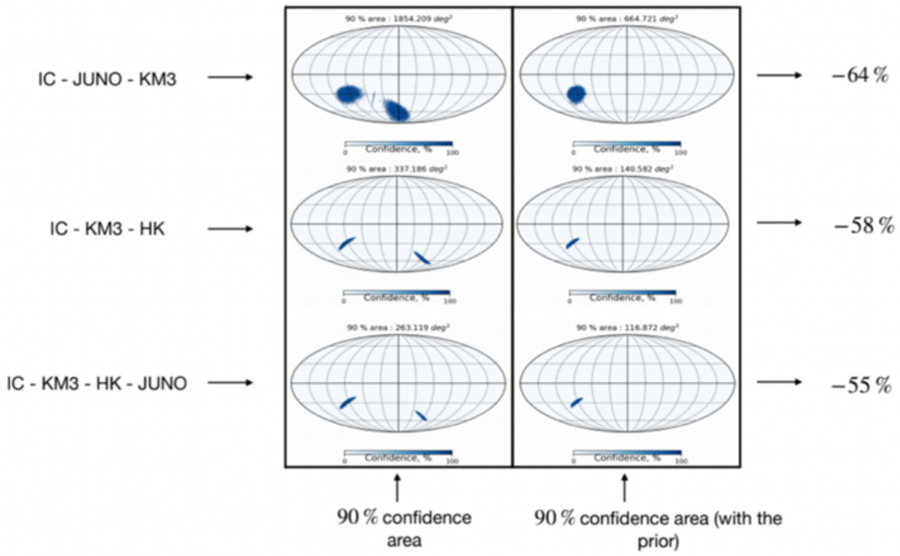

Figure 5: Illustrating the power of a multi-detector experiment for the determination of the location of a supernova. Comparison of the confidence areas obtained by the core-collapse supernova triangulation method with and without using the prior for a location at the Galactic Center [60].

in neutrino detectors. It is of course almost impossible to do justice to all experimental results shown.

4.1 Solar neutrinos

Per definition solar neutrinos reside on the border between the solar physics track and the neutrino track. It has been reported that Borexino sees the first evidence of neutrinos from the CNO cycle [49]. All other searches for solar neutrinos, including those from solar flares, remain consistent with background at this point [50–53]. For the future, JUNO is expected to be able to resolve B^8 neutrinos [54].

4.2 Supernova neutrinos

When it comes to supernova neutrinos, everyone is getting ready to see "the ONE". A supernova in our own Galaxy will certainly be a game changer for the field, so we better not miss it! The supernova Early Warning System (SNEWS) will alert the astronomical community to what is coming and all neutrino telescopes are (in the process of) joining forces through the network [55–59] (see also Figure 5).

Searches for the diffuse background of supernovae remain consistent with background at this point [61–63].

4.3 Atmospheric neutrinos

Atmospheric neutrinos are the background for some and the signal for others. The measured atmospheric spectra keep improving with increasing statistics and new players [64, 65], so a measurement of the prompt neutrino flux seems within reach, putting pressure on the models to increase precision as well [66–69].

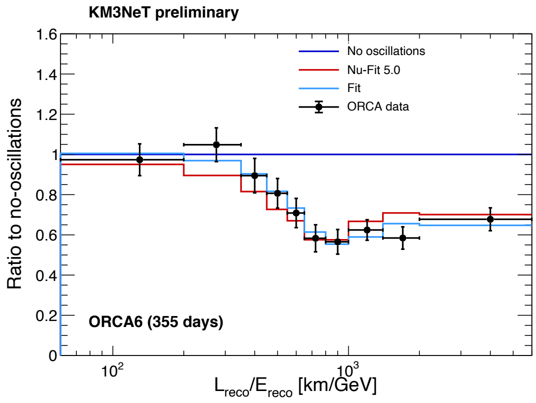

Figure 6: First oscillation results from KM3Net ORCA. L/E distribution for the ORCA6 data and expected number of events relative to the "no oscillation" hypothesis. The no oscillations and nu-fit curves in this figure do not include systematic uncertainties as modeled for the 'Fit' curve [70].

Using the improved measurements of the atmospheric neutrinos, results of oscillation physics [70, 71], mass ordering [72, 73] and other neutrino properties [74–76] keep in lock-step. In particular the arrival of the first data from ORCA shows the potential how soon new oscillation results may be available (see Figure 6).

4.4 Astrophysical neutrinos

In terms of an astrophysical neutrino flux, IceCube remains the only player in the field, albeit increasing evidence is tangible that KM3NeT [77, 78] or Baikal-GVD [79, 80] may report on a significant detection of an excess flux before the next ICRC. IceCube is increasing the effort to provide the community with one estimate of the astrophysical spectrum and consistent reporting [81–83], which is in particular valuable as the spectrum is needed/used as input for many estimates for studies of sources or new fundamental physics [84]. So far, no new global fit has been shown but with the new methods presented, it should also be clear soon whether there is a significant difference observed between different data sets (ν_μ vs. cascades, etc.).

Since last ICRC, IceCube has reported the observation of a first identifiable electron-anti-neutrino at the Glashow resonance [2], which leads to a very accurate flux point in the energy spectrum and will influence combined fits of the spectral index and flavor.

There was no shortage in terms for theoretical models [85–89], motivating different searches for neutrinos in correlation with astrophysical sources. Models are continuously being refined and data is combined from multiple observatories to predict interesting objects to look at (see also the multi-messenger track [1]). Similarly, various searches are conducted at experiments, looking for correlations, time-variability or other multi-messenger aspects, coming close to observing a detection or still hunting flukes [90–105]. However, it seems that in the absence of clear data, there is currently no "knock-it-out-of the-park" suggestion and one may have to content with the fact that the sources of astrophysical neutrinos are both variable and intrinsically different. As initially stated several interesting multi-messenger associations were reported on, such as Tidal disruption events [106], so the interested audience should pay attention to the rapporteur review of the multi-messenger track [1].

5. Conclusions

In conclusion, the field of neutrino astrophysics is maturing, but feeling the lack of event statistics: We need more neutrinos.

Experimental ideas are available and with a bit more patience, new doors may open soon. Certainly, new and maybe puzzling experimental evidence is expected at the next ICRC.

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