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High-energy neutrino astronomy

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Abstract. Neutrinos constitute a unique probe since they escape from their sources, travel undisturbed on cosmological distances and are produced in high-energy (HE) hadronic processes. In particular they would allow a direct detection and unambiguous identification of the acceleration sites of HE baryonic cosmic rays (CR), which remain unknown. The latest results achieved with the current experiments are briefly reviewed, including the efforts towards a multi-messenger approach.

1 Scientific motivations

Neutrino astronomy has a key role to play towards a multi-messenger coverage of the HE sky. Unlike photons, neutrinos can escape from the core of the sources and cross with the speed of light magnetic fields and matter without being deflected or absorbed (while a 10^{15} eV photon would interact with the CMB and typically travel $\sim$10 kpc). The other alternative messengers like neutrons or charged CRs also suffer limitations. Neutrons pass undeflected through magnetic fields, but have a short lifetime. CRs suffer magnetic deflections, which might incidentally be the cause for the observed isotropy of their arrival directions. Above $\sim 10^{19}$ eV protons start to point back to the production site, but suffer an unknown delay with respect to neutral particles, preventing simultaneous detection with other messengers. In addition, because of the interaction with the relic radiation fields -GZK effect-, the window for large distance proton astronomy closes just above $\sim 10^{20}$ eV. Neutrinos therefore constitute a unique probe: they can deliver direct information about the processes taking place in the production sites and reveal the existence of undetected sources.

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High-energy neutrinos (HE ν) are produced in a beam dump scenario in dense matter via meson (mainly pion) decay, when the accelerated hadrons interact with ambient matter or dense photon fields:

$$A/p + A/\gamma \to \pi + X \to \mu + \nu_\mu \to e + \nu_e + 2\nu_\mu \quad (1)$$

In this so-called “bottom-up” scenario, the production of HE ν is associated with the acceleration of nuclei through Fermi-like mechanisms, and with the production of HE gamma-rays. Following this association, various authors have inferred benchmark fluxes of cosmic neutrinos based on the observed ultra HE CR (UHECR)-like the WB bound (Waxman and Bahcall, 1998)- or on the observed diffuse gamma-ray flux (Mannheim et al., 2001). These neutrino fluxes essentially set the size of neutrino telescopes (NT) to the kilometer scale. From the above relation, it is also expected that ultra HE ν (>PeV) would arise from the interaction of the UHECR with the relic radiation fields. These are called cosmogenic neutrinos (Berezinsky and Zatsepin, 1969).

Good candidates for HE ν production are active galactic nuclei (AGN) where the accretion of matter by a supermassive black hole may lead to relativistic ejecta (Halzen and Zas, 1997; Mannheim, 1995). Other potential sources of extra-galactic HE ν are transient sources like gamma ray bursters (GRB). The flux of HE ν from GRBs (Waxman and Bahcall, 1997) is lower than the one expected from AGNs, but the background can be dramatically reduced by requiring a directional and temporal coincidence with the direction and time of a GRB detected by a satellite.

TeV activity from our Galaxy has also been reported by ground based gamma-ray telescopes (Aharonian et al., 2004). Many of the observed galactic sources (Bednarek et al., 2005) are candidates of hadron acceleration and subsequent neutrino production. This includes among others supernovae remnants, pulsar wind nebulae or microquasars. As explained in Sect. 2, such TeV sources would be observed with better sensitivity by a northern NT.

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HE ν can also be produced by more exotic processes such as the decay of massive particles ("top down" scenarios) or the annihilation of dark matter gravitationally trapped inside massive objects like the Sun, the Earth or the Galactic centre (Hooper and Silk, 2004). A review of the current NT sensitivity to dark matter annihilation can be found in (Buckley et al., 2010).

2 Detection principles

If the weak interaction of neutrinos with matter is an asset for astronomy, it also makes the detection challenging. Huge volumes need to be monitored to compensate for the feeble signal expected from the cosmic neutrino sources. In this context, the water Cherenkov technique offers both a cheap and reliable option for the detection of neutrinos in the TeV-PeV range. At higher energies alternative options are being investigated such as radio and acoustic detections.In this paper we focus on the Cherenkov technique.

The method was first suggested by Greisen, Markov and Reines in the early 60's (Markov and Zheleznykh, 1961). It relies on the observation, using a 3D array of photodetectors, of the Cherenkov light emitted in a transparent medium by charged leptons induced by charged-current neutrino interactions in the matter surrounding the detector.

Due to the large muon path length, the effective detection volume in the muon channel is substantially higher than for other neutrino flavors. The deviation between the muon and the neutrino directions ($\Delta\theta \simeq 0.7^\circ \cdot (E_\nu(\mathrm{TeV}))^{-0.6}$) diminishes with the energy thus enabling to point back to the source with a precision close to the one of gamma-ray telescopes. Muon trajectories are reconstructed using the time and amplitude of the photodetector signals. The energy of the event can be estimated within a factor of 2–3. The muon background comes from cosmic particles penetrating the atmosphere producing a cascade of many secondary particles. To look above the horizon, energy cuts are mandatory to reduce the atmospheric background which is strongly suppressed (due to the steeply falling $dN/dE \propto E^{-3.7}$ spectrum) at HE (>PeV). Such a technique strongly reduces the sensitivity to astrophysical bodies in the TeV-PeV range. In this range the field of view is primarily restricted to one half of the celestial sky, below horizon. Even so, severe quality cuts are applied to the reconstruction to remove remaining misreconstructed atmospheric muons. Atmospheric neutrinos produced in the atmospheric cascades can travel through the Earth and interact in the detector vicinity. To claim for an extraterrestrial discovery, one has then to search for an excess of events above a certain energy (diffuse flux, Sect. 4.2) or in a given direction (point sources, Sect. 4.1). Another possible way to claim the discovery of cosmic neutrinos is to observe events in coincidence (in direction and/or time) with other messengers. This multi-messenger approach allows to strongly reduce the background by looking in a known direction for the reduced period of time, making the detection of a few events enough to claim a signal (see Sect. 4.3).

3 Detector construction status

A generic HE NT consists of a 3D grid of $\mathcal{O}(10^3)$ detection units called Optical Modules (OMs). These OMs basically comprise a photomultiplier with large photocathode area (8–15 inches) embedded in a pressure-proof glass sphere. They are arranged with a 10–30 m spacing on vertical cable strings typically distant of 60–100 m. This spacing has an impact on the energy threshold of the detector: the sparser the lines, the higher the threshold. The detector design is therefore a matter of trade-off between low energy physics such as dark matter searches (<TeV) and ultra HE physics like search for cosmogenic neutrinos (>PeV). NTs are usually optimized for the detection of astrophysical bodies (TeV–PeV).

The first attempt to build a NT was made by the DUMAND (Deep Underwater Muon And Neutrino Detector) collaboration (Badson et al., 1990), off the Hawaiian coast. New collaborations have arisen since then, some constructing in the ice (see Sect. 3.1), providing the detector with mechanical stability and avoiding leakage problems, while others have persevered with water (see Sect. 3.2). The principal layout features of all the projects are briefly summarized in Table 1.

3.1 In-ice detectors

The AMANDA (Antarctic Muon and Neutrino Detector Array) project started in the 90's. The collaboration chose the approximately 3 km thick antarctic ice cap at the South Pole to deploy the detector. The deployment technique was to lower OMs attached on cables into holes drilled by hot water. Once the structures are deployed, the water freezes, mechanically fixing the OMs. Deployment of the first four strings with 86 OMs took place in 1993/94 down to 900 m depth. At such a depth, the ice layer was found comprising many air bubbles, inducing a strong scattering of the light, detrimental to the reconstruction of the muon trajectories. The detector was subsequently extended deeper in the ice (less bubbles) with longer strings (AMANDA-II). The total amount of OMs was then 676 OMs spread over 19 strings commissioned in January 2000. After 7 years of data taking, 6595 neutrino candidates were cumulated with energies up to 100 TeV. This led to a limit on the diffuse flux of astrophysical neutrinos and to the rejection of some production models. Another analysis made use of showers induced by the interaction of all flavor neutrinos. The result is slightly higher but extends to higher energies. These results are shown in Fig. 3.

The ICECUBE detector (Karg et al., 2011) is the successor of AMANDA extending the size to the kilometer scale. Most of the results already achieved with ICECUBE supersede the ones obtained with AMANDA. A selection of these results is mentioned in Sect. 4. The first detector string was deployed

Table 1. Summary of the principal characteristics of the past, present and future neutrino telescopes.

Experiment	**Dimensions**	**# PMTs**	**Medium**	**Angular resolution**	**Status**
AMANDA	Cylinder (R×H) 100 m ×500 m	677	Ice	$\sim 3^{o}$	Decommissioned
ICECUBE	Octagon 1 km^3	4800		$< 1^{o}$	Construction Operating
BAIKAL	Cylinder (R×H) 20 m ×72 m	192	Lake water	$\sim 3^{o}$	Operating
ANTARES	Octagon (l×H) 60-75 m × 350 m	875	Sea water	$< 0.5^{o}$	Operating
NESTOR	Cylinder (R×H) 16 m × 410 m	144/tower (design)			RandD Conception
NEMO KM3NET	1 km^3	$\sim$ 5000			

in January 2005, followed by 8 more in the austral summer 20005/2006, 13 in 2006/2007 (IC22 configuration) and 18 in 2007/2008 (IC40). The most recent results are established with the IC40. As of today the detector comprises 79 strings and the data of the 59 first lines are currently being analyzed. The completion of the detector is expected in 2011, with a total of 86 lines carrying 60 digital OMs each. Thanks to the long lever arm and the large amount of additional information the reconstruction will achieve a pointing accuracy better than 1°. On top of the telescope a large air-shower array named ICETOP has been developed. It is designed to detect the Cherenkov light of the charged particles reaching the Earth surface: it can be used for calibration purposes and for studies of mass composition of primary CRs up to 10^{17} eV (Kislat et al., 2011).

3.2 Deep underwater detectors

The operation of huge detectors like NTs in such a hostile environment as the water abysses is also a technical challenge which took a long time to be overcome. The main difficulties relate to the high pressure environment, the potential water leakages and the deployment and operation of a ∼500 m long structure. After the failure of the DUMAND project, the immersion of a detector deep in a lake appeared as a viable alternative (see Sect. 3.2.1). It took 20 years of efforts before the ANTARES collaboration finally managed to overcome the difficulties related to the deep sea (Sect. 3.3.1).

3.2.1 BAIKAL

The main advantage of the Russian lake Baikal is the ice shell covering the lake in winter providing a stable platform for the deployment. A first deployment was performed in the years 1984-1990 with the installation of a single string arrays of 36 OMs connected to shore. The second generation detector (NT-200) installed at 1.1 km depth, has grown while taking data from 36 OMs in 1993 till 192 OMs in 1998. The detector is running in permanent regime since 1998. An extension of the detector called NT-200+ has been proposed and put into operation in April 2005. It consists of 36 additional OMs on 3 further 140 m long strings. It is expected that a factor of 4 in sensitivity can be reached by this modest extension. The construction of NT200+ is a first step towards the deployment of a km-scale (Gton) neutrino telescope with a threshold around 50 TeV for muons and ∼100 TeV for cascades. Such an extension requires new RandD efforts. A prototype string meant to test the future technology (photomultipliers, electronics, acquisition system, trigger strategy, calibration elements) has been installed in April 2008 as part of the NT200+ array. A technical Design Report is foreseen by 2011.

The BAIKAL collaboration has accumulated a total of 372 neutrino candidates after selection cuts (385 expected from simulations), for a live time of 1038 days. The sample has been used to search for clusters and correlation with gamma-ray bursts, leading to upper limits. Thanks to the low energy threshold, close to ∼10 GeV, the BAIKAL collaboration reports interesting limits on neutralinos as possible cold dark matter (Dzhilkibaev, 2004). Finally, studies of bright cascades mainly originating from electromagnetic showers induced by the interaction of ν_e were performed. A search for an excess above the expected background from atmospheric muons was conducted leading to the result presented in Sect. 4.2.

3.3 NESTOR and NEMO

The NESTOR project -the first in the Mediterranean sea- started in 1989 with the original goal to deploy an array of towers of 410 m height next to Pylos, on the Greek Ionian coast, at a depth of about 4000 m. The design of the tower consists of twelve 6 arm titanium stars of 16 m radius holding 144 PMTs. The first NESTOR floor prototype -a reduced star (5 m radius) with 12 OMs- was immersed in March 2003. The down-going muon flux was measured (Aggouras et al., 2006). According to the collaboration, the chosen techniques are validated, but the ability to deploy a full scale rigid tower is still to be demonstrated. This could be achieved with the recent construction of a dedicated vessel called "Delta-Bereniki", made of triangular ballasted platform of 275 tons equipped with engines and thrusters for positioning. The operation of the "Delta-Bereniki" is now part of the efforts undertaken by the KM3NeT consortium.

The NEMO collaboration was formed in 1998 with close ties to the ANTARES experiment. The collaboration prospected for suitable sites in Italy for the deployment of a km-scale NT. The best site appeared to be 80 km off Capo Passero, on the eastern coast of Sicily, at a depth of 3500 m, featuring low concentration of bioluminescent bacteria (Riccobene et al., 2007). In order to validate the technology proposed for a km-scale detector, a Phase-1 project was launched in 2002 and achieved, in December 2006 with the operation, in a test site (2100 m depth, 25 km off Catania port) of a prototype mini-tower equipped with all the critical components of a NT (Aiello et al., 2010). NEMO has now entered phase-2 which merges with the KM3NET project.

3.3.1 ANTARES

The ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) collaboration was formed in 1996 with the aim to deploy a large scale NT 40 km off La-Seyne-sur-Mer (Var, French Riviera), at a depth of 2475 m. The final deployment stage started in March 2006 with the connection of the first detection line and ended in May 2008. Since then, ANTARES is the largest NT constructed in the northern hemisphere, providing unprecedented sensitivity to the central region of our Galaxy. The full detector consists of an array of 12 flexible individual mooring lines. Its detailed configuration is described in (Margiotta et al., 2011) and summarized in Table 1. The an angular resolution is within design expectations ($<0.5°$) and allows to look for point sources with high sensitivity, as reported in Sect. 4.1.

3.3.2 KM3NeT

The three collaborations ANTARES, NEMO and NESTOR have formed the KM3NeT consortium with the goal to design and locate the future Mediterranean km-scale detector. Funding was granted by the EU. Minimum requirements are an instrumented volume $\geq 1\,\mathrm{km}^3$, sensitive to all neutrino flavors and an angular resolution for muon neutrinos of about 0.1° in the TeV range. These requirements are listed in detail in the "conceptual design report" published early 2008, as well as in the "technical design report" recently published (KM3NET, 2010). The goal is to built a NT able to detect events from galactic sources such as RXJ1713.7-3946 after a few years of operation, provided a hadronic origin of the observed electromagnetic TeV emission. Since March 2008, the consortium has moved to the preparatory phase meant to address political, governance and financial issues related to the KM3NeT detector, including the site selection. The construction of the detector should start in 2013. The overall cost is estimated to be $\sim$250 M€. KM3NeT is part of the ESFRI (European Strategic Forum on Research Infrastructures) road map for future large scale infrastructures. The project enlarges indeed the scope to an international and multidisciplinary endeavor. It is foreseen to instrument the detector with specialized equipment for seismology, gravimetry, radioactivity, geomagnetism, oceanography and geochemistry, making KM3NeT a complex laboratory for a large science community.

4 Selected results

There are essentially 3 ways NT could claim for a discovery of cosmic neutrinos. One is to search for clusters of events distinguishable above the atmospheric background. Such clusters, if statistically significant, would either coincide with the position of a know astrophysical source, or indicate the existence of a new class of sources (see Sect. 4.1).

In case the sources could not be "resolved" individually, the sum of cosmic sources could create a detectable diffuse flux of neutrinos emerging from the background in the HE range (Sect. 4.2).

Another way to overcome the lack of statistics is to observe neutrino candidates in coicident in time or space with other messengers. Indeed, the knowledge of the time (and duration) and direction of a putative source can drastically reduce the background, making the observation of a single neutrino event an interesting signal. This so called "multi-messenger" approach is being actively pursued as discussed in Sect. 4.3.

4.1 Search for point sources of cosmic neutrinos

The search for point like source of HE ν requires a good pointing accuracy that can only be reached after applying severe quality cuts on the reconstructed data sample. The other objective of these cuts is to get rid of most of the down-going muons misreconstructed as up-going which would overwhelm by several orders of magnitude the flux of up-going neutrinos without special care. The cuts are generally optimized by means of Monte Carlo simulations or scrambled data (in order to ensure the usual blindness policy adopted by the community) and enable to achieve $\mathcal{O}(10\%)$ of contamination in the neutrino sample. After selection a clusterization algorithm is applied. For a given direction in the sky, a test statistic t is evaluated and compared to the expected value in case of no signal. A simple test statistic is

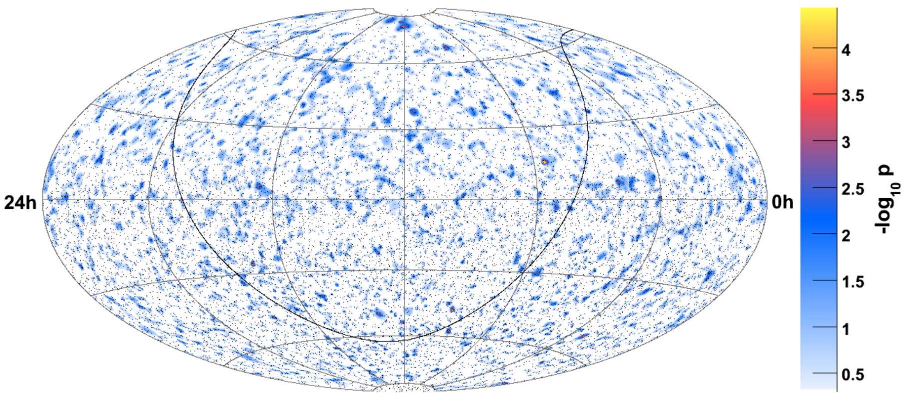

Fig. 1. Sky map (in equatorial coordinates) of reconstructed ν_μ events from ICECUBE in 40-lines configuration (Karle et al., 2009). The color scale corresponds to the p-value (as defined in Sect. 4.1) non corrected from trial effect.

the number of events in a cone whose size is optimized to set the best upper limit (Hill and Rawlins, 2003). A more sophisticated test statistic is the maximized likelihood ratio between a signal hypothesis and the background only hypothesis (Neunhöffer and Köpke, 2006). For a given direction in the sky, the p-value of the obtained test statistic t_0 is the probability to obtain at least t_0 just by a fluctuation of the background. Since several directions will be tested, one must account for the so called trial factor. This is done by generating $\mathcal{O}(10^4)$ random skies and evaluating the probability to obtain t_0 when searching in N directions. Results are usually presented in terms of post-trial or pre-trial p-values by the experiments, as shown for instance for IC40, in Fig. 1). This result corresponds to a total lifetime of 375.5 days and cumulate 32739 events. Interestingly the southern sky is visible thanks to a dedicated analysis that focuses on the highest energy range where the atmospheric background is strongly reduced. As a consequence the limits inferred essentially apply in PeV-EeV range and the sensitivity is reduced by $\sim$1 order of magnitude compared to the classical "through the Earth" approach as can be seen on Fig. 2. The ANTARES limits correspond to the 2007-2008 data set (equivalent live time of 295 days). The corresponding sky map of neutrino candidates can be seen in (Margiotta et al., 2011). The limits are competitive with the latest SUPERKAMIOKANDE results (Thrane et al., 2009) based on more than 7 years of data taking (with an energy threshold of $\sim$GeV). The plot also indicates the expected gain in sensitivity for the full ICECUBE detector and the future KM3NET detector after one year of data taking.

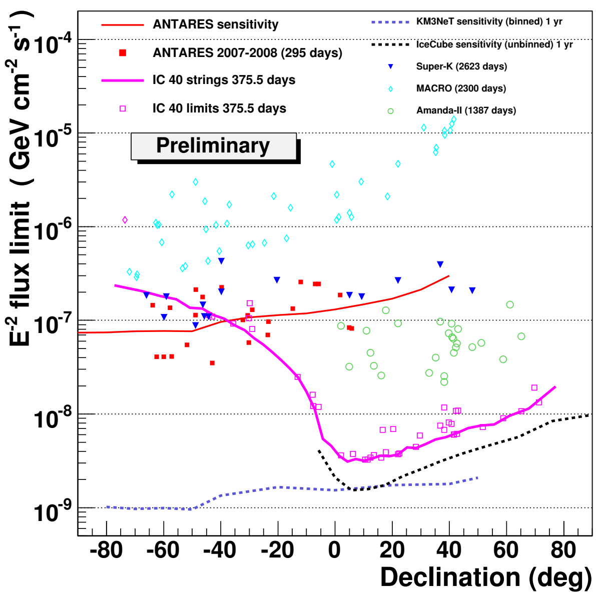

Fig. 2. The figure shows the latest limits inferred by NTs in the hypothesis of $dN/dE \propto E^{-2}$ cosmic neutrino spectrum emitted by a point-like source. The ANTARES results are preliminary.

4.2 Diffuse fluxes

The search for a diffuse flux of HE cosmic neutrinos mainly consists in looking for an excess of isotropically distributed HE events ($E > \mathcal{O}(10\,\text{TeV})$) on top of the expected atmospheric neutrino flux. The advantage of this search is that all signal contributions coming from individual sources sum up, increasing the signal. The analysis generally requires an energy estimator.

The ANTARES experiment has recently released a new limit of $dN/dE < 5.3 \cdot 10^{-8} E^{-2}\,\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ for a diffuse flux of cosmic muon neutrinos (see Fig. 3). This limit happens to be the best public limit in the world although it is anticipated that the IC40 sensitivity should supersede it by a factor of ~ 5, getting below the WB bound. The ANTARES analysis relies on the 2007–2009 data set (334 days live time) of reconstructed muon tracks. The energy estimator is based on the occurrence rate of secondary OM pulses after the electronic dead time of 250 ns (these late hits being more often generated by HE events).

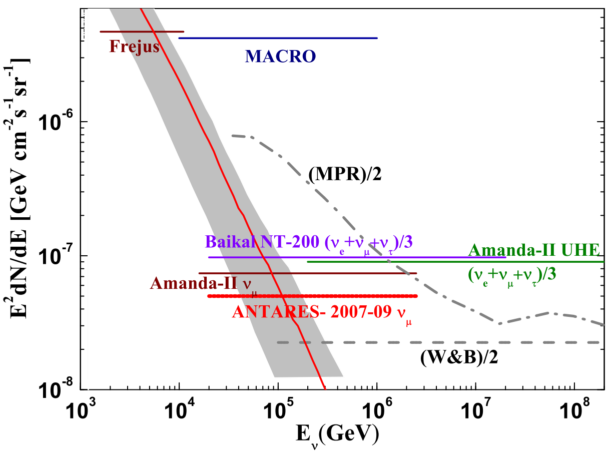

Fig. 3. Recent (single flavor) diffuse cosmic neutrino flux limits (and predictions) as a function of the neutrino energy.

The BAIKAL limit shown in Fig. 3 is a recent update (Avrorin et al., 2009). It is based on a data sample of 1038 live days. Unlike the ANTARES limit, it applies to all neutrino flavors. Indeed, since directional information is not of primary importance for diffuse fluxes, the signal expected is an upward moving light front induced by isolated cascades originated by any of the 3 flavored neutrinos. To increase the sensitivity no containment in the detector is required. The associated background is mainly bremsstrahlung showers initiated by HE downward atmospheric muons.

4.3 Multi-messenger approaches

Transient sources like gamma-ray bursts, microquasars or soft gamma-ray repeaters can be studied based on the observation of their electromagnetic component. Thus, HE ν can be searched for in a known direction and for a known duration, which helps reducing the background. Following this approach, ANTARES applies a specific data taking procedure based upon the reception of GCN (Gamma-ray burst Coordinate Network) alerts : whenever an alert is sent, the raw data which are continuously buffered for $\sim$2 min, are all written to disk, instead of being filtered. This allows a special treatment which enhances the sensitivity (Aguilar et al., 2007). Such a special treatment is not necessary for ICECUBE, the optical background being low compared to ANTARES (a few kHz only); the analysis is based on the reconstructed muon. It uses the absolute time of the alert to define an "on-time" window; the selection parameters are tuned in a blind way on data from the "off-time" region. A search for neutrinos emitted in coincidence with 117 GRBs was carried with IC40 (Resconi et al., 2010). No excess was found compared to background expectations, which strongly constrains generic production models of GRBs like (Waxman and Bahcall, 1997; Guetta et al., 2004).

Reversely, NT can also send alerts to other detectors for a counterpart follow-up in order to confirm a possible signal. Typical triggers are the observation of neutrino doublets in a short time and in roughly the same direction, or the observation of a very HE event. This method was first proposed in (Kowalski and Mohr, 2007). Since 2008 ICECUBE has developed a follow-up program with the ROTSE collaboration that operates 4 optical telescopes with a field of view of 1.85° each in the two hemispheres. The ANTARES collaboration applies a similar protocol with the ROTSE and TAROT optical telescopes. Recently the same sort of agreement has been conducted between ICECUBE and the MAGIC TeV telescopes.

Finally, coincident searches of HE ν (involving ANTARES and ICECUBE) and gravitational waves (GW) are performed. The network of GW detectors formed by the LIGO and VIRGO interferometers can determine the direction and time of GW bursts in connection with neutrino events observed in NTs. The consistency between two, independent, detection channels shall enable new searches for cosmic events arriving from potential common sources, among which putative "hidden sources" such as the failed or choked GRBs, which are opaque to photons and hadrons (Van Elewyck et al., 2009).

5 Conclusions

HE ν astronomy has now entered a new phase with several detectors continuously monitoring the entire sky with unprecedented sensitivity. At South Pole, ICECUBE is now probing a neutrino flux regime which is in the reach of theoretically motivated predictions. In the northern hemisphere ANTARES offers the best sensitivity to the TeV sources of the central region of our Galaxy, until it gets superseded by the next generation KM3NET detector. Possible common analyses are currently being discussed, as the different collaborations now start to form a synergetic community, as testified by the series of yearly common working group meetings organized since 2009.

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