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Multimessenger Astronomy with Neutrinos

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Abstract. The recent discovery of high-energy astrophysical neutrinos has opened a new window to the Universe. However, the sources of those neutrinos are still unknown. Among the plausible candidates are gamma-ray bursts, active galactic nuclei and supernovae. Combining neutrino data with electromagnetic measurements in a multimessenger approach will increase our ability to identify the neutrino sources and help to solve long-standing problems in astrophysics such as the origin of cosmic rays. Neutrino observations may also contribute to future detections of gravitational wave signals, and enable the study of their source progenitors. I will review the recent progress in multimessenger astronomy using neutrino data.

1. Introduction

The origin of high-energy cosmic rays (CR) is a more than 100 year old mystery, which neutrinos might help to resolve. Neutrinos are produced alongside high-energy CR in interactions with ambient matter or photon fields. In both, hadronuclear and photohadronic interactions, pions are produced, which in the case of neutral pions decay to two gamma rays and in the case of charged pions produce neutrinos in their decay chain. While gamma rays can also be produced in leptonic processes such as Inverse Compton scattering and Bremsstrahlung, neutrinos are the smoking gun signature for hadronic acceleration.

The first detection of high-energy extragalactic neutrinos by the IceCube neutrino observatory in 2013 [1] opens a new window to the high-energy Universe. No cluster in space and time was found in the neutrino data recorded by IceCube and the Mediterranean neutrino telescope ANTARES [2, 3, 4]. The most pressing question in this young field of neutrino astronomy is: where do the neutrinos come from? Neutrino data alone does not reveal their origin yet. However, if one would know where and when to search for neutrinos, it would become far easier to identify their sources. Electro-magnetic data can deliver information of where and when to expect a neutrino signal. In the same way neutrino data can tell us when and where to look for an electromagnetic counterpart, providing improved power to discriminate between proposed source models.

2. Multimessenger Approach

Combining neutrino data with electro-magnetic data is the key to identifying the neutrino sources. Several source classes are considered candidates for the production of high-energy neutrinos. The electro-magnetic signature varies for different source classes and determines the search strategy for a correlation with neutrinos. In the following the most promising source classes are discussed.

2.1. Star-Forming Galaxies

Star-forming galaxies host regions of increased star-formation, where cosmic rays are produced and efficiently accelerated. Neutrinos and gamma rays are produced when CR protons interact in pp-interactions. The neutrino energy spectrum is expected to follow the shape of the proton energy spectrum and so does the gamma-ray spectrum of the source. Star-forming galaxies are expected to be optically thin to gamma rays. However, due to interaction with the extra-galactic background light high-energy gamma rays cascade down to lower energies. The super-TeV electromagnetic energy gets shifted into the sub-TeV range. The gamma-ray flux corresponding to a predicted neutrino flux may not overshoot the measured extra-galactic gamma-ray background. The Fermi-LAT gamma-ray space telescope has measured the extra-galactic gamma-ray background in the energy range from 100 GeV to 820 GeV [5]. Blazars have been found to produce 86% of the gamma-ray flux [6]. The gamma-ray flux from starburst galaxies may thus not overshoot the remaining fraction of the gamma-ray background. From this consideration the authors of [7] conclude that star-forming galaxies can not produce more than 30% (at 100 TeV) of the diffuse neutrino flux. The same argument holds for other neutrino sources, that produce neutrinos in pp-interactions and are optically thin to gamma rays.

2.2. Blazars

Blazars are active galactic nuclei (AGN) with a jet pointing towards the observer. The relativistic outflow is powered by accretion onto a super-massive black hole. The electro-magnetic emission from blazars is typically highly variable. While blazars are the main sources of the gamma-ray background recent multimessenger studies exclude them as the main source of the diffuse neutrino flux. A correlation study of 862 gamma-ray blazars with 3 years of IceCube neutrino data found that less than 30% of the neutrino flux originates in blazars [8].

By correlating only a subclass of extreme high-frequency peaked blazars with a set of published high-energy neutrino candidates [9] found a hint for a correlation at significance level of 0.4-1.3%.

Including timing information in addition to the source localization can further help to reduce the background in the search for correlations with neutrinos. The authors of [10] find a PeV neutrino event in spatial and temporal coincidence with a bright outburst of the flat spectrum radio quasar PKS B1424-418. However, the p-value for a chance coincidence lies at 5%. A point-source search with 406-days of ANTARES data at the position of PKS B1424-418 did not find an excess of neutrinos and allows the neutrino spectrum at the source to be constrained. Very steep neutrino spectra are excluded [11].

2.3. Gamma-Ray Bursts

Gamma-ray bursts (GRBs) have been the prime candidates for production of the highest-energy cosmic rays [12]. GRBs are short gamma-ray flashes lasting from fractions of a second to tens of minutes. During their prompt emission they are the brightest explosions in the Universe reaching an isotropic-equivalent energy of up to 10^{54} erg likely powered by the core-collapse of a very massive star or the merger of two compact objects. The central engine produces highly relativistic collimated jets, which are predicted to host internal shocks, where particles are efficiently accelerated to high energies. In hadronic scenarios accelerated protons interact with ambient synchrotron photons and produce high-energy neutrinos. The neutrino emission is expected to be collimated and in temporal coincidence with the prompt gamma-ray emission.

A search for high-energy neutrinos detected by IceCube (ANTARES) from the locations of 807 (296) GRBs in coincidence with their prompt gamma-ray emission did not find a significant excess compared to background expectations [13, 14]. These results set tight constraints on models of neutrino and ultra-high-energy cosmic-ray production in GRBs. Current models assuming cosmic-ray escape via protons [15] and models assuming cosmic-ray escape via

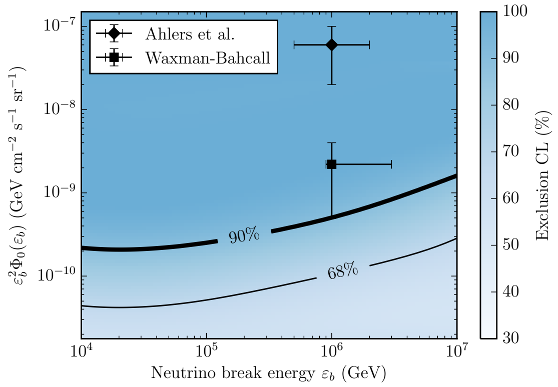

Figure 1. Limits on GRB model parameters from the search for IceCube neutrinos in coincidence with the prompt gamma-ray emission (from GRBs published by satellite detectors on the Gamma-ray Coordinates Network^2 and the Fermi GBM database [18, 19]), adopted from [13].

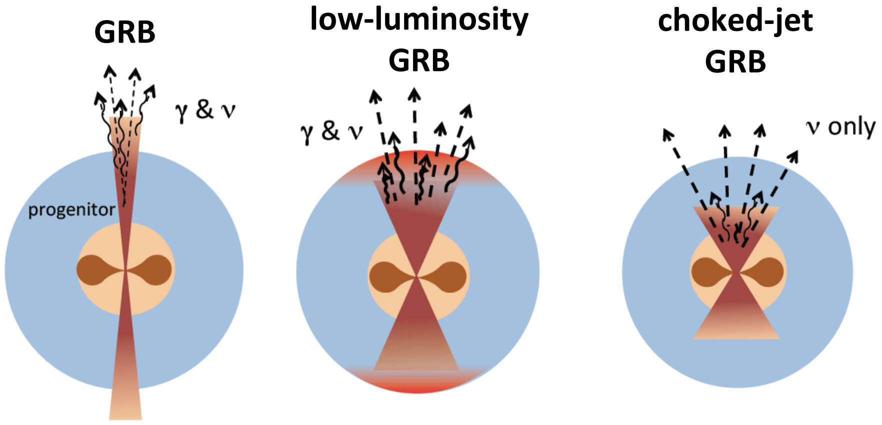

Figure 2. Neutrino and gamma-ray production in GRBs and SNe in a unified picture [21].

neutrons [16] are excluded at 90% confidence (see Figure 1). However, more complex models assuming multiple emission regions predict a neutrino flux below the current sensitivity [17].

Limits on the neutrino flux normalization allow us to constrain the contribution of gamma-ray bright GRBs to less than 1% of the observed diffuse neutrino flux [20]. However, a possibly large population of choked-jet GRBs with low gamma-ray luminosity might contribute a larger fraction of the diffuse flux. Choked jets may explain transrelativistic supernovae (SNe) and low-luminosity GRBs, giving a unified picture of GRBs and GRB-SNe [21] (see Fig. 2). This scenario can be tested by correlating high-energy neutrinos with SNe.

2.4. Supernovae

Analogous to GRBs, high-energy neutrino production is predicted from SNe hosting mildy relativistic jets, which get choked in the envelope of the star [22, 23, 24]. Preferred candidates for choked-jet SNe are Type Ic SNe [25]. The neutrino emission is expected to start at the time of the SN explosion and to last $\mathcal{O}(10\,\mathrm{s})$, comparable to the typical GRB duration. Other models predict neutrino emission from SNe exploding in a dense circum-stellar medium (CSM) [26, 27]. Candidates for CSM interaction supernovae are Type IIn supernovae. Neutrinos are expected to be produced in the interactions of the SN ejecta with the dense medium on time scales of months to years.

3. Target of Opportunity Programs

Supernovae are best discovered in optical wavelength. However, current optical surveys cover only limited regions of the sky or do not go very deep. To overcome this limitation the IceCube and ANTARES collaborations set up an optical and X-ray follow-up program for interesting neutrino events in 2008 and 2009 respectively [28, 29] (see Fig. 3). The neutrino data is processed in real-time and the most interesting neutrino events are selected to trigger observations with optical and X-ray telescopes aiming for the detection of an electro-magnetic counterpart such as a GRB afterglow or a rising SN light curve. The program is capable of triggering follow-up observations in less than a minute.

The Palomar Transient Factory (PTF) [30] found the Type IIn SN PTF12csy from the direction of a neutrino doublet consisting of two track events detected by IceCube, which arrived within 1.6 s [31]. However it turned out that the SN was already 160 days old at the time of the neutrino burst and hence is likely a chance coincidence. Swift detected a variable X-ray source in the follow-up of a 60 TeV neutrino recorded by ANTARES [32]. A notification was sent through an Astronomer's Telegram [32], which triggered several observations in multiple wavelengths. In optical data the X-ray source was identified as a star. The X-ray emission is therefore unrelated to the neutrino event.

Besides the optical follow-up program, follow-up observations in other wavelengths are performed ranging from radio to gamma rays [33, 34]. They expand the sensitivity to gamma-ray flares of e.g. AGNs.

The IceCube gamma-ray follow-up has been running since March 2012 [33] and triggers the Cherenkov telescopes MAGIC[1] and VERITAS[2]. This program aims for the detection of neutrinos in coincidence with gamma-ray flares from blazars. A predefined list of known variable gamma-ray sources is monitored by IceCube for an excess in neutrinos on time scales of up to three weeks. So far no gamma-ray flare was detected in coincidence with a neutrino excess. The most significant neutrino excess was recorded in November 2012. Six events arrived from the blazar SBS 1150+497 within 4.2 days. A follow-up with VERITAS did not discover a gamma-ray flare at the same time.

A sketch of the target of opportunity programs run by ANTARES and IceCube is shown in Fig. 3.

3.1. IceCube Public Events

A real-time event selection for high-energy single track events with high probability of being of astrophysical origin has been in place since beginning of 2016. Four high-energy starting track events (HESE) and four extreme high-energy though-going track events (EHE) are selected per year and published in real-time through the Astrophysical Multimessenger Observatory Network (AMON) [35] via the Gamma-Ray Coordinate Network (GCN[3]). HESE events have an energy threshold of roughly 60 TeV and an angular resolution ranging from $0.4 - 1.6^\circ$ ($1.2 - 8.9^\circ$) at 50% (90%) confidence depending on the topology of the event. An improved resolution produced by more time consuming reconstruction algorithms is available after a few hours. EHE events do not have to start within the detector and thus usually produce longer tracks allowing a more accurate angular reconstruction of 0.2° (0.8°) at 50% (90%) confidence. Table 1 lists all public HESE and EHE from the start of the public notifications in April 2016 to end of September 2016. The first public neutrino alerts were followed up by various instruments in several wavelengths

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[1] `http:magic.mppmu.mpg.de`

[2] `http://veritas.sao.arizona.edu`

[3] `http://gcn.gsfc.nasa.gov/`

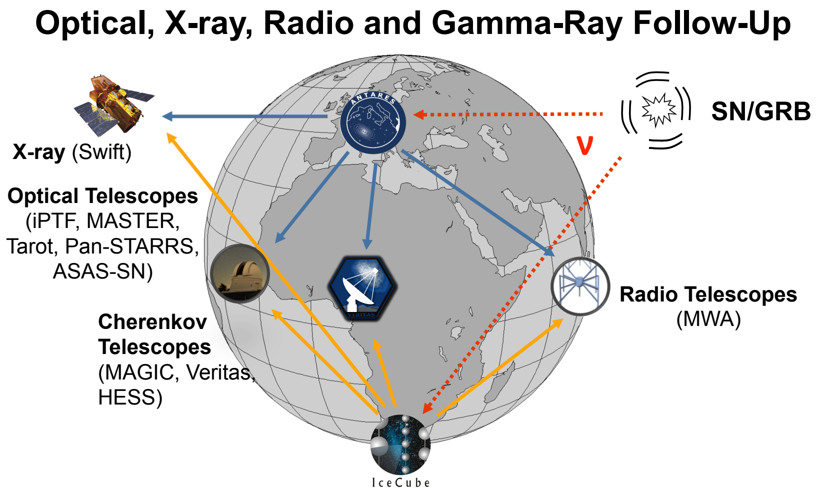

Figure 3. Sketch of the different target of opportunity programs operated by ANTARES and IceCube: High-energy neutrinos are detected in real-time and their direction is forwarded to follow-up observatories, which observe the corresponding region in the sky aiming for the detection of an electromagnetic counterpart.

ranging from optical to gamma-ray bands. A detailed overview of the different IceCube real-time channels can be found in [36].

Table 1. IceCube Public Alerts.

Date	Type	RA	Dec	50% Error	Delay
2016/04/27	HESE	240.6°	9.3°	0.6°	81 s
2016/07/31	EHE + HESE	214.5°	−0.3°	0.35°	41 s
2016/08/06	EHE	122.8°	−0.7°	0.11°	37 s
2016/08/14	HESE	200.3°	−32.4°	0.48°	42 s

4. Astrophysical Multimessenger Observatory Network (AMON)

The AMON program is currently under development at The Pennsylvania State University, in collaboration with multimessenger observatories. AMON provides a platform to perform real-time correlation analyses of high-energy signals across all known astronomical messengers - photons, neutrinos, cosmic rays, and gravitational waves. The goal is to enhance the combined sensitivity to astrophysical transients by searching for coincidences in sub-threshold data and to enable rapid follow-up imaging or archival analysis of the putative astrophysical sources [35].

5. Gravitational Wave Follow-Up

The detection of the first gravitational wave (GW) event by the advanced LIGO detectors in September 2015 was accompanied by a broad multimessenger follow-up program aiming for the detection of a counterpart to the GW signal. IceCube and ANTARES searched their data in a ±500 s time window centered on the GW event for high-energy neutrinos [37]. No event was detected by ANTARES while IceCube found three events in the time window, which is consistent with background expectations. However those events are not in spatial coincidence with the GW position. An upper limit on the total energy radiated by neutrinos of $5.4 \times 10^{51} - 1.3 \times 10^{54}$ erg was derived assuming an energy spectrum following $dN/dE \sim E^{-2}$. The range includes the two distinct localization regions of the sky.

6. Conclusion

Neutrinos are unique messengers from the high-energy Universe and provide crucial information for the origin of high-energy cosmic rays. IceCube has detected the first astrophysical high-energy neutrinos. However, their origin is still unknown. Naturally the most pressing question in this young field of neutrino astronomy is the question about the neutrino sources. Multimessenger studies are crucial to increase the sensitivity to find the sources and could already be applied to disfavor or even exclude major contributions of some source classes, while the remaining source classes are extensively studied by multimessener analyses. Many developments are pushing the real-time analysis of high-energy neutrino data forward to ensure rapid follow-up observations aiming for the detection of an electro-magnetic counterpart of the neutrino sources.

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