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*Review*

# Multimessenger Astronomy with Neutrinos

**Francisco Salesa Greus [1,2,†,‡,*] and Agustín Sánchez Losa [1,‡]**

1 IFIC-Instituto de Física Corpuscular (CSIC - Universitat de València) c/ Catedrático José Beltrán, 2 E-46980 Paterna, Valencia, Spain; Agustin.Sanchez@ific.uv.es (A.S.L.)
2 Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 IFJ-PAN, Krakow, Poland
* Correspondence: sagreus@ific.uv.es; Tel.: +34 963543538
† Current address: Affiliation 1
‡ These authors contributed equally to this work.

**Abstract:** Multimessenger astronomy is probably the branch of the astroparticle physics field that has seen more developments in recent years. In this manuscript we will review the state of the art, the recent observations, and the prospects and challenges for the near future. We will give special emphasis to the observation done with neutrino telescopes.

**Keywords:** multimessenger astronomy; astroparticle physics; neutrinos

## 1. Introduction

Astronomical observations have been traditionally done with visible light. From Galileo times until now we have been able to expand the observation range to all the electromagnetic spectrum, from radio to gamma rays. Apart from photons, the discovery of other particles has opened the possibility of using them as cosmic messengers to explore the Universe. For instance, cosmic rays (CRs) were first discovered in the early 1910s. We know that CRs are ionized nuclei of extraterrestrial origin, and that are produced and accelerated in a broad energy range, reaching energies above $10^{20}$ eV. Since they are charged, their directionality is lost due to the Galactic magnetic field. This is probably one of the main reasons why the origin of the most energetic CRs is still unknown. We have also detected neutrinos from extraterrestrial origin. First from the Sun [1], and then from a nearby supernova explosion in 1987 [2–4] which can be considered as the birth of neutrino astronomy. By that time the first project to construct a neutrino telescope was already ongoing [5]. However, only after decades of research and development, neutrino astronomy had its turning point in 2014 with the discovery of a high-energy cosmic neutrino flux by the IceCube collaboration [6]. The most recent cosmic messengers discovered are gravitational waves (GWs). The path to the first GW detection was also not easy, and it took a century from their theoretical prediction to the first confirmation in 2015 by the LIGO and VIRGO collaborations [7].

Multimessenger astronomy originates as a consequence of astrophysical neutrino and GW detection techniques reaching maturity. Multimessenger astronomy is based on the observation of four cosmic messengers, namely: photons, CRs, neutrinos, and GWs. The detection in coincidence of all, or some, of these messengers allows the study of a source in a similar fashion as it has been done with multiwavelengths electromagnetic observations. Moreover, the fact of involving different types of particles adds extra information coming from interactions involving all fundamental forces of nature.

We have divided this review into three sections. In Section 2, we will discuss the two events that marked the start of the multimessenger era, four years ago. In Section 3, we will review the most recent results and what we have learned from them. To conclude, in Section 4, we will discuss the future prospects and challenges in the field.

## 2. Multimessenger astronomy milestones

Excluding the solar neutrino detection, the observation by chance of neutrinos coming from the supernova explosion SN1987A, is the first astronomical event producing a multimessenger (photon-neutrino) coincidence. However, there are two main events, both happening in 2017, that really marked the birth of a new field in astrophysics, multimessenger astronomy.

The first event was the result of two neutron stars merging into a black hole. This produced a GW (GW170817) that was detected by the LIGO and Virgo [8] Scientific Collaborations. Less than 2 seconds after the event, a short gamma-ray burst (GRB) (GRB 170817A) was detected by the Fermi and INTEGRAL satellites. This coincidence triggered a campaign where several observatories followed-up the event in an unprecedented way [9]. Thanks to this coincident detection it was possible to determine the location and the type of sources involved, bringing the first experimental evidence of a kilonova [10], a type of transient event, theoretically predicted more than two decades ago [11], where nucleosynthesis of the heavy elements is produced.

The second event (IC-170922A) was triggered by a high-energy neutrino, of about 300 TeV, detected by the IceCube observatory on September 22, 2017. Again, this event was extensively followed up by other observatories. In this case, observations from the Fermi-LAT satellite were able to point out a blazar (TXS0506+056) in active state which was in spatial and temporal coincidence with the neutrino event. The event was rejected to be produced by background fluctuations at $3\sigma$ level [12]. After this detection, archival analysis of IceCube data prior to the IceCube-170922A event unveiled a potential flare in neutrinos [13], between September 2014 and March 2015, with $3.5\sigma$ statistical significance and independent of the 2017 neutrino alert. In this case, no gamma-ray counterpart was observed. An extensive multiwavelength monitoring of TXS0506+056 started after the coincident event in Sep 2017 showed a low state emission except for December 1st and 3rd, 2018 with a flare comparable to the one in 2017 [14]. However, no neutrino excess was observed. It is also important to mention that TXS0506+056 came out as the second most significant source ($2.8\sigma$ pre-trial) in the point source search analysis done with the ANTARES neutrino telescope using a a pre-selected list of sources [15], which makes the case of TXS0506+056 stronger.

## 3. Recent results

Once it has been well established that a flux of high-energy neutrinos of cosmic origin exist [6], the new step is to disentangle it and identify which are the sources. The most recent all-sky searches performed by ANTARES [15] and IceCube [16] did not reveal any significant detection above the discovery threshold of $5\sigma$, being the excess near the galaxy NGC 1068 observed by IceCube the most interesting spot with a post-trial significance of $2.9\sigma$. This type of high-energy searches benefit from multimessenger astronomy thanks to including the sky coordinates and timing information from potential cosmic messenger counterparts. That was how the first evidence of a cosmic neutrino source, TXS0506+056, was found.

Understanding the multimessenger emission from TXS0506+056 has been challenging from the theoretical point of view, since it is difficult to get a good agreement between the observed neutrino signal and other wavelength observations. If one tries to explain it with a single-zone model, i.e., both gammas and neutrinos coming from the same region, one finds out that a leptonic scenario with a radiatively subdominant hadronic component provides the only physically consistent single-zone picture [17]. A higher neutrino flux would be expected if the source hosts two physically distinct emitting regions (see for instance [18]). However, current observations can not discriminate between single- or multi-zone emission models. Related to this, it has been recently discovered a compelling neutrino-radio correlation [19]. The authors proposed that neutrinos and gamma rays may be indeed produced in different regions [20]. If this is indeed the case, X-ray and radio may be better wavelengths when looking for

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photon-neutrino correlations. The correlation with radio blazars is also supported by ANTARES observations [21]. In this regard, ANTARES has recently reported the results from an untriggered search from radio blazars with an interesting association coming from J0242+1101 [22].

Thanks to the IceCube alert system [23], which is presently providing on the order of 10 (20) gold (bronze) alerts per year, more coincidences between neutrino and blazars have been found lately. For instance, PKS 1502+106 blazar was coincident with a 300 TeV neutrino [24]. In this case the blazar was in a quiescent state at the time of the neutrino alert. However, no more neutrinos were detected. Another example is 3HSP J095507.9 also coincident with a high-energy neutrino detected by IceCube [25,26]. However, for this event a lot of sources lay around the best position provided by IceCube, preventing the identification of a potential source candidate. This also underscores that sub-degree angular resolution, achievable by future neutrino observatories, will be key when looking for spatial coincidences. From Fermi-LAT observations we know that blazars are the most abundant extragalactic gamma-ray sources, constituting roughly 80% of the entire extragalactic source population [27]. However, current predictions based on stacking catalog searches performed with IceCube data estimate that neutrinos emitted by blazars, in the range between around 10 TeV and 2 PeV, can only contribute up to 27% to the total neutrino diffuse flux [28]. More multimessenger observations with next generation experiments are required to test current theoretical models, and therefore provide valuable information to understand the particle production and acceleration in blazars.

Apart from blazars other neutrino candidates have been already identified thanks to multimessenger observations. This is the case of Tidal Disruption Events (TDEs), which are the result of a star being ripped apart when passing next to a supermassive black hole. TDEs were already hypothesized as possible neutrino sources, e.g. [29]. However, it was not until 2019 when an IceCube neutrino, with 59% probability of being of astrophysical origin (IC-191001A), triggered an alert that was followed-up by the Zwicky Transient Facility [30]. In spatial coincidence with the neutrino alert a TDE (AT2019dsg) was observed. Given that TDEs are rare events, the change probability of finding this coincident event was estimated to be less than 0.5% [31]. After the first neutrino-TDE coincidence, more recently another possible association has been detected (IC200530A with AT2019fdr) which has been considered by some scientists as evidence of an emerging trend. The chance probability of finding this second event in coincidence was also small. Both events have been followed up by ANTARES, however did not produce any significant neutrino excess [15]. The non detection does not contradict the observation by IceCube, as the sensitivity of ANTARES was above the neutrino flux prediction. On the other hand, there are preliminary indications of an excess in GVD-Baikal data [32]. Current estimations predict that TDEs contribute at least 2% but not more than 40% of the total neutrino flux [33]. Again, more observations are needed to confirm TDEs as sources of high-energy neutrinos, and determine their precise contribution to the diffuse neutrino flux.

GRBs are other type of sources that have long been predicted as good candidates to emit high-energy neutrinos, see for instance [34]. However, so far, all the searches have been unsuccessful [35,36]. Recently, some studies have tried to infer what would be the relative contribution of the different neutrino candidate sources, e.g. [37]. However, it seems that there is no clear indication of a dominant type of source producing cosmic neutrinos. Interestingly enough, the same study suggest that there is room for unknown sources.

## 4. Future prospects and challenges

Regarding neutrino telescopes there are three major projects that will be operating in the near future. KM3NeT [38] is a research infrastructure being built in the Mediterranean sea. KM3NeT is composed of two detectors, first ARCA (Astroparticle Research with

Cosmics in the Abyss) which is designed to be sensitive to high-energy neutrinos in the TeV-PeV range, and therefore with astrophysics studies as the main goal. The second detector is called ORCA (Oscillation Research with Cosmics in the Abyss) and it is sensitive to GeV neutrinos. The ORCA detector will primarily be used to study of the neutrino properties. Both instruments will use the same technology and detection principle, i.e., array of photomultipliers tubes (PMTs) in sea water, being the main difference the volume covered, and therefore the PMT density. ARCA is expected to be fully operational in 2027 and ORCA in 2025.

Also in water there is the GVD-Baikal project that is also in construction in the Baikal lake in Russia. GVD-Baikal is currently operational with 2304 optical modules arranged in 8 clusters of 8 strings each. In the present configuration it has an effective volume of 0.4 $km^3$ for cascades with energy above 100 TeV [39]. Current plans are to deploy 6 additional clusters for the period from 2022 to 2024 which should provide an additional 0.3 $km^3$ effective volume.

The leading project in neutrino telescopes in the last decade has been IceCube [40] which is a neutrino telescope installed in the South Pole. After 10 years of successful operation there are plans for two major upgrades. One, called IceCube-Gen2 [41], expected to be completed by the early 2030s, will significantly increase IceCube effective volume and energy range sensitivity. The other, called IceCube-Upgrade [42], represents a fraction of a larger project called Precision IceCube Next Generation Upgrade (PINGU) [43], which aims to increase the sensitivity to lower energies even more than with IceCube-DeepCore, mostly to study neutrino properties.

We can also add to the list of future intended neutrino telescopes the Pacific Ocean Neutrino Experiment (P-ONE) [44]. The P-ONE project is presently in research and development phase. The goal of the collaboration is to install a multi-cubic-kilometre neutrino telescope in the Pacific Ocean, which is expected to be operational in the next decade.

There are also very exciting plans for next generation experiments aiming to detect other cosmic messengers. Just to mention a few of them, we have the Cherenkov Telescope Array (CTA) [45] with two planned sites (Northern and Southern Hemisphere), and LHAASO [46], fully operational since July 2021, detecting gamma rays. KAGRA [47] detecting GWs, which will join LIGO and Virgo for the next GW data taking run (O4) expected to start in late 2022. Finally, detecting ultra-high-energy CRs, there will be AugerPrime [48], the upgrade of the Pierre Auger Observatory. Such a network of observatories, distributed in different locations around the globe (see Figure 1), will provide a full multimessenger coverage of the sky.

Considering the amount of experiments currently being under construction and planned it seems clear that an efficient communication between collaborations is crucial. Moreover, for the case of pointing instruments, like CTA, this communication also needs to be fast. There are already ways to announce in real-time interesting events to the astrophysics community, e.g, the GammaRay Coordinates Network (GCN) [49]. In addition to this announcements, there are also sites, like the Astronomers Telegram (ATEL) [50], where a brief report about recent observations made by the experiments is posted online. Still in beta testing phase there is a project called Astro-COLIBRI [51] whose goal is to act as a central platform where a large set of information coming from different experiments is gathered. This can be accessed via web or smartphone interface. The data will be immediately available and will contain relevant information such as the visibility of the event for a given observatory, the false alarm rate, or the probability of the event to be of astrophysical origin.

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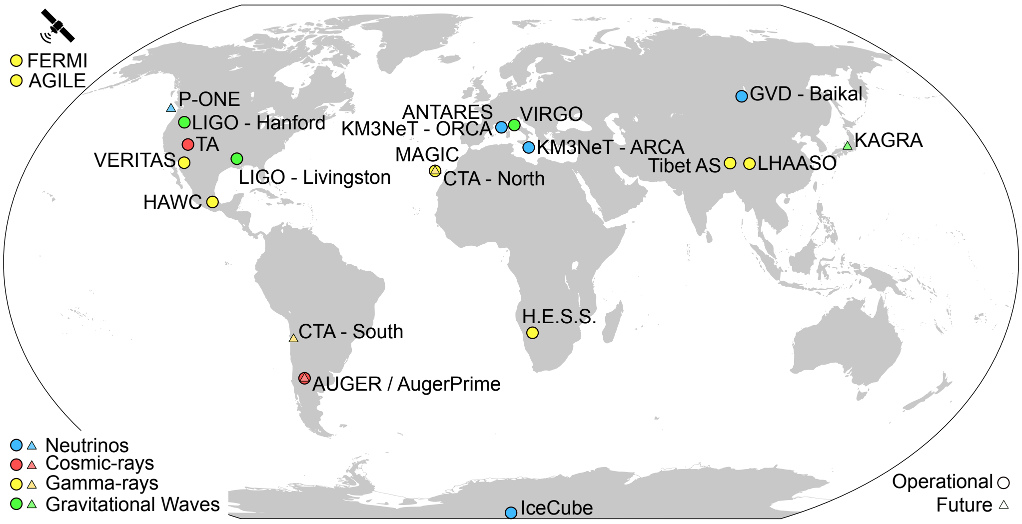


**Figure 1.** Earth map indicating the location of a selection of multimessenger observatories that are either currently operating (circles) or planned (triangles). Satellites are depicted outside to the map.

In addition to these prompt alert systems across collaborations, there are alert follow-up programs like TaToO [52], where the most promising ANTARES events trigger a prompt optical, radio and X-ray follow-up on the sky region where the neutrino candidate comes from, looking for any potential transient counterpart within hours, days and months since the event. This is done using a network of optical telescopes at different locations (at a rate of 25 alerts per year) and, for the most energetic ones (around 6 alerts per year), the XRT instrument aboard the Swift satellite and the Murchison Wide field Array radio telescope [53].

As another example of how data from different experiments is shared, we have the Astrophysical Multimessenger Observatory Network (AMON) [54]. One of the main ideas of AMON is to use sub-threshold data from different experiments to exploit the fact that a combined detection is expected to increase the significance of the event. Therefore, an event that by itself is not enough to claim a detection with a single experiment, and could have been rejected, can actually become significant when detected in coincidence with other observatories. An example of a recent analysis done through this network is [55], focused on gamma-ray and neutrino coincidences.

Concerning the multimessenger astronomy goals in the next few years, one thing that should be attainable very soon is a firm confirmation of a source of cosmic neutrinos above the discovery threshold of $5\sigma$. To this end, the selection of the most promising sources, to reduce the amount of trials in the search, thanks to multimessenger observations will be crucial. This is quite likely to be accomplished by more than one project which will provide an unbiased way of measuring the spectrum of the sources, bringing key information to understand the high-energy neutrino production and acceleration mechanisms in the source. Also combined analyses are possible, as has been already done in the past [56].

One multimessenger observation that is most awaited, and can probably be achieved thanks to the improved sensitivity of the future experiments, is the coincident detection of a GW event with high-energy neutrinos. Thanks to recent GW observations, we have a better understanding of the link between neutron star mergers and short GRBs, and the physics involved. We already discussed the particular case of the binary neutron star merger GW170817, which led to the GRB170817A coincidence. This type of event should produce a GW signature together with gamma rays and neutrinos. However, at present, the only confirmed coincident detection is the GW-gamma correlation, while no evidence of neutrino emission was found [57,58]. The theoretical estimations of neutrino production [60] from GW170817 show that the expected flux should be already detectable, with current neutrino telescopes, under favourable circumstances, see Figure 2.

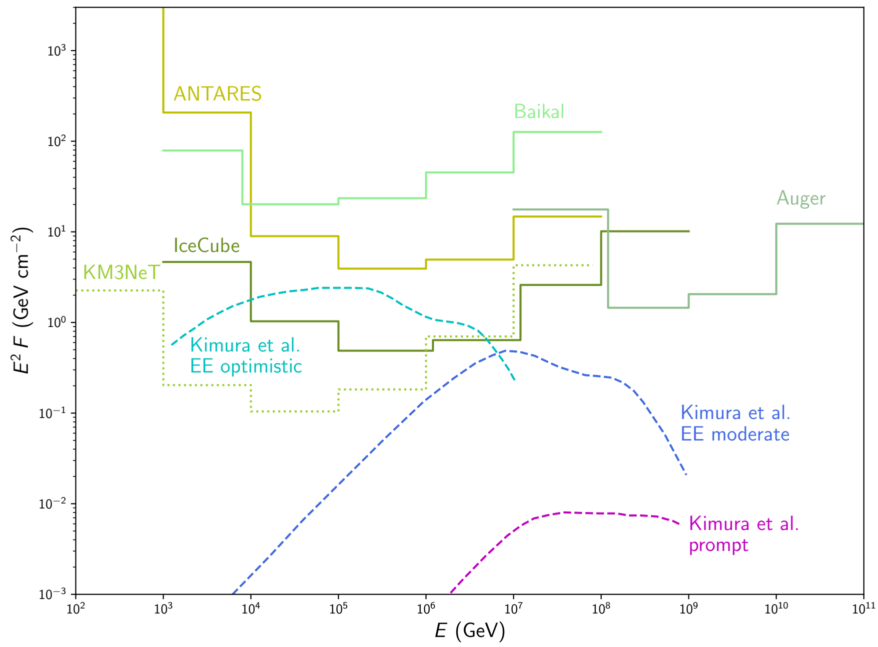


**Figure 2.** Fluence upper limits, per flavor, on the high-energy neutrino emission from experimental data assuming a $\pm$ 500s time window around the GW170817 event [57]. Baikal limits are from [58]. KM3NeT preliminary sensitivity, computed for an optimal zenith angle, is from [59]. Theoretical models for comparison are from [60]. Figure adapted from [57].

Apart from the detection of high-energy neutrinos, the detection of the prompt emission in gamma-rays by observatories like HAWC or LHAASO will be essential to understand how these energetic explosions work.

Another open question to be addressed by multimessenger observations is the connection between ultra-high-energy CRs, gamma-rays, and high-energy neutrinos. Intensity of gamma-rays, neutrinos and UHECRs has been shown to be comparable (see Figure 3), suggesting that they may be powered by the same sources. Since blazars are the most abundant extragalactic sources, they are by default the most promising candidates. However, blazars do not seem to fit the bill as they are subdominant in the HE neutrino flux [64].

Apart from the usual suspects (e.g. GRBs, TDEs), the case for star forming galaxies as common sources have recently grown in popularity thanks to [65] where the authors claim that the diffuse gamma-ray flux detected by Fermi-LAT [61] is actually dominated by star-forming galaxies. At the same time, the data collected in the Pierre Auger Observatory showed an indication of anisotropy at $4.0\sigma$ level in the arrival direction of CRs with E > 39 EeV showing an excess from the direction of nearby starburst galaxies [66]. Claiming that this type of high rate of star formation galaxies can be the cause of $\sim$ 10% of the ultra-high-energy CR flux. It has been also shown that the contribution of the starburst galaxies to the neutrino diffuse flux is sub-dominant and constrained to be at the level of $\sim$ 10% [67]. Therefore, it remains unanswered for now whether there is a dominant type of source accelerating all cosmic messengers.

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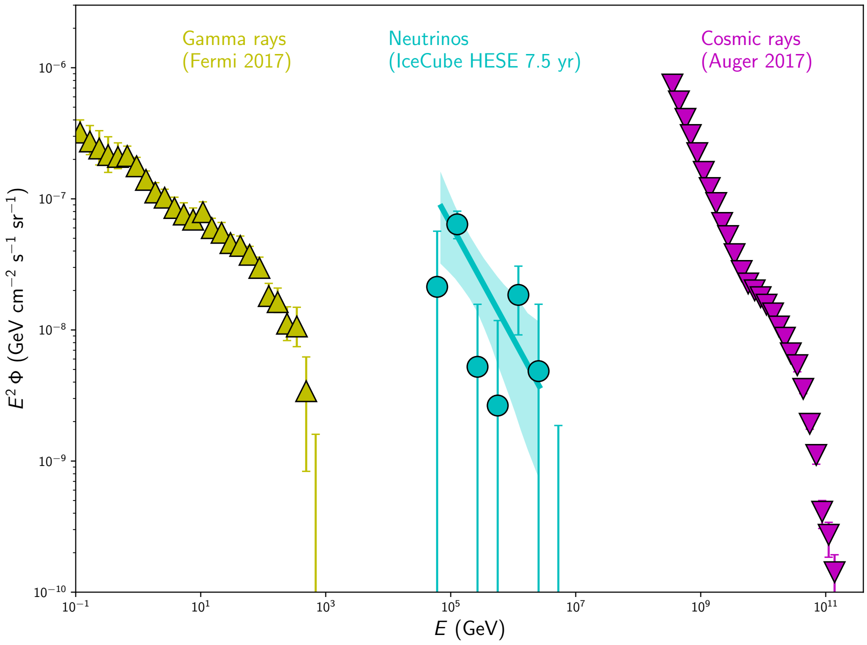


**Figure 3.** High-energy fluxes of gamma rays [61], neutrinos [62], and cosmic rays [63]. Figure adapted from [62].

Finally, if we restrict the search to our Galaxy, one of the questions that will be solved in the near future thanks to multimessenger observations is what are the Galactic CR sources and how those CR propagate through the Galaxy. Regarding this, it has been shown that a sub-PeV diffuse Galactic gamma-ray emission exists [68]. Based on this result in [69] the authors showed that the Galactic neutrino contribution should constitute roughly 5-10% of the IceCube diffuse flux and that, in the 10-100 TeV range, the expected Galactic neutrino flux should be comparable to the total neutrino diffuse flux. If so, the next generation neutrino telescopes should be sensitive enough to detect it. It is possible that part of the measured gamma-ray diffuse flux comes from individual sources, being the obvious candidates the very-high-energy sources detected by HAWC [70] and LHAASO [71]. Combined multimessenger observations should be able to confirm whether this is actually the case. In fact, there have been claimed already evidences for such joint production of high-energy neutrinos and gamma rays in the Cygnus Coocon region [72], based on the correlation of a high-energy IceCube neutrino and a high-energy (>300 TeV) photon flare.

## 5. Outlook

Multimessenger astronomy is a new branch of astroparticle physics, for which neutrinos are expected to play a key role. It took just a few events, detected in coincidence, to demonstrate that combining different messengers has a great potential for discoveries.

Questions like what is the origin of the ultra-high energy cosmic rays are likely to be answered thanks to multimessenger observations.

Considering the numerous facilities planned for the near future, or already taking data (KM3NeT, IceCube-Gen2, GVD-Baikal, P-ONE, CTA, LHAASO, KAGRA, Auger-Prime, etc), multimessenger astronomy has a bright future and is expected to revolutionize our understanding of the Universe in the next decade.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
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| GW | Gravitational Wave |
| CR | Cosmic Ray |
| GRB | Gamma-Ray Burst |
| TDE | Tidal Disruption Event |
| PMT | Photomultipliers tubes |

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