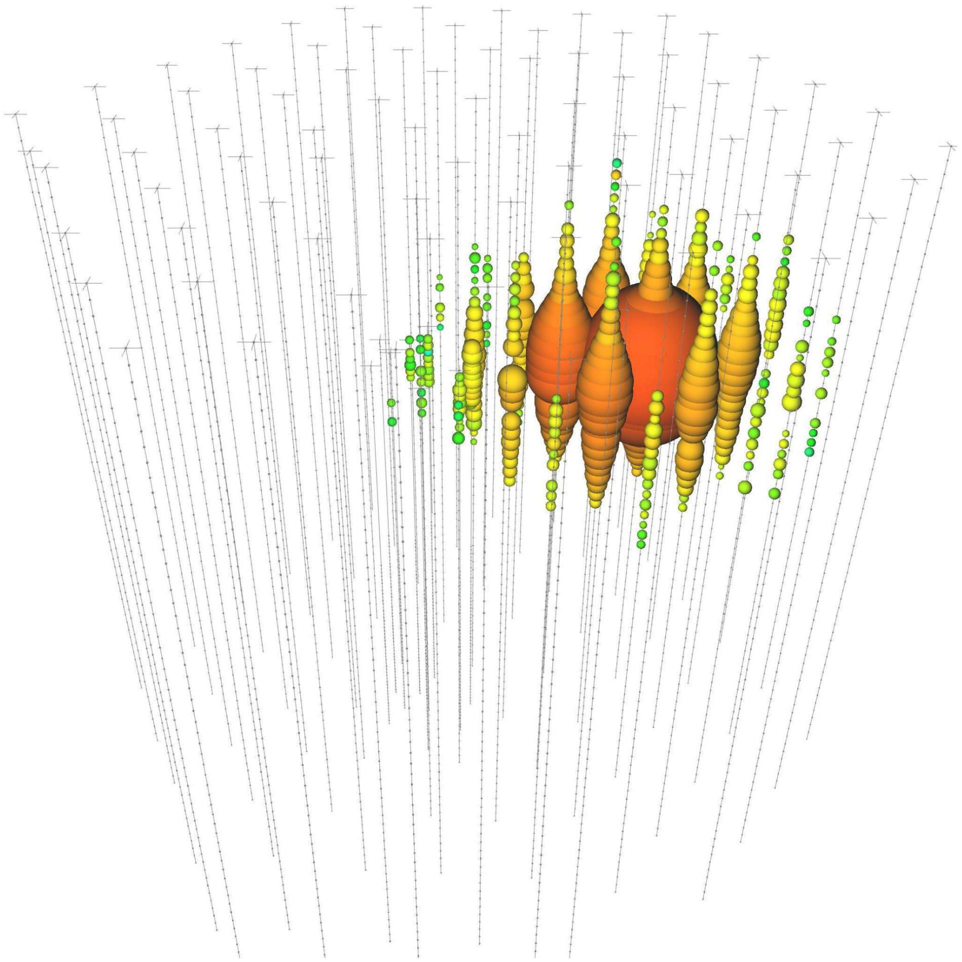
MULTIMESSENGER ASTRONOMY

Interstellar Texting

When the Cosmos Sends LOLs and Neutrinos



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SEDS Report

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Abstract

Multimessenger astronomy is the branch of the astroparticle physics field that has seen the most significant developments in recent years. In this report, we will review the state-of-the-art, the recent observations, and the prospects and challenges for the near future of this powerful discipline.

Introduction

WHAT? Multimessenger astronomy, born from decades of research conducted by scientists worldwide, is a new technique for exploring the universe that relies on **studying the same cosmic phenomenon through different channels**. These channels collect data from four different cosmic messengers, allowing for a more comprehensive and detailed view of the cosmos:

1. Photons. Revealed at various wavelengths, each capable of providing information about different physical processes that produce them. They are important because, being neutral, they are not deviated by magnetic fields and thus retain the direction of the source.
2. Cosmic Rays. High-energy particles and atomic nuclei moving at almost the speed of light, striking the Earth from all directions, losing all information about the source that produced them.
3. Neutrinos. Like photons, neutrinos are neutral, so their arrival direction indicates the position of the production sites. They provide fundamental information about the most distant astrophysical sources and the most powerful mechanisms of particle acceleration.
4. Gravitational Waves. They traverse celestial bodies' matter with almost no disturbance or energy loss, unlike electromagnetic waves. Interacting so little with cosmic objects, they can travel enormous distances without losing information about the sources that generated them.

WHEN? Its birth dates back to September 14, 2015, following the first observation of a gravitational wave generated by the merger of two neutron stars. For the first time, a gravitational wave was observed in association with electromagnetic events by over 70 different detectors! In the days following that event, gamma-ray bursts, luminous explosions, and emissions of infrared and X-ray radiation were observed from the same source that had emitted gravitational waves. It was clear that a new and exciting era in observing the cosmos had begun, announced on February 11, 2016, by physicists from the international LIGO-VIRGO collaboration, namely Multimessenger Astronomy.

HOW? The possibilities offered by the ensemble of cosmic messengers are diverse and extend beyond cosmology and astrophysics. Ongoing verification of the theory of General Relativity and research that could impact the understanding of the intimate structure of matter (such as the identification of the nature of dark matter) and nuclear physics studies are examples.

Photons

A photon is a particle of light defined as a discrete bundle of electromagnetic energy (i.e. a small “package” of light). Photons were first described in 1900 by the German physicist Max Planck, who understood that energy is absorbed and re-emitted only in **discrete amounts of energy**, quanta. Planck’s results were used in 1905 by Einstein to explain the photoelectric effect and demonstrate that each light particle, or photon, contains a fixed amount of energy.

Photons are an essential component in multimessenger astronomy. Their range of emission from celestial bodies varies greatly, but most of the emissions are detected in the X-ray and γ-ray spectrum.

X-ray photons interact in the Earth’s atmosphere and are not able to directly reach the ground level. Thus, telescopes observing in the X-ray band have to be deployed outside the atmosphere. X-rays telescopes are focused with a technique known as “grazing incidence” optics. These telescopes are made of a series of concentric mirrors, each one being oriented almost parallel to the direction of arrival of X-ray photons, in order to reflect them without generating a significant deflection.
New technologies for the high-resolution X-ray spectroscopy are developing, such as that of “transition edge sensors”, with camera pixels made from superconducting material. This technology was used for the first time by the space telescope HITOMI in 2016.
The universe observed by X-ray telescopes includes both thermal and non-thermal sources. The thermal sources visible in the X-ray band have temperature of about $10^7 K$, which can be found, for example, in the corona of the Sun, in neutron stars and in white dwarfs. The nonthermal sources visible in the X-ray band include the same source classes as observed by the radio telescopes: AGN[1], pulsars, supernovae[2].

γ-rays emissions are produced by high-energy charged particles, which emit photons with great energy (up to 1 GeV). The high-energy γ-ray sources are all “non-thermal” (i.e. again, pulsars, supernovae, AGN). Gamma rays photons emissions are mostly observed with a Fermi/LAT telescope, which consists of a series of layers, each one being a “sandwich” of foils made of materials with a high atomic number, below which thin strips of silicon are layered in two perpendicular directions. These strips register the current and determine the coordinates of the photon through each layer of the tracker. The information is then sent to a calorimeter, which provides information about the direction of initial photons and their energy.

Cosmic Rays

In August 1912, the Austrian physicist Victor Hess made a historic balloon flight that opened a new window on matter in the universe: as he ascended to 5300 metres, he measured the rate of ionisation in the atmosphere and found that it increased to some three times that at sea level. He concluded that penetrating

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[1] A class of galaxies which spew massive amounts of energy from their centers, far more than ordinary galaxies. Many astronomers believe supermassive black holes may lie at the center of these galaxies.

[2] The death explosion of a massive star, resulting in a sharp increase in brightness followed by a gradual fading. The outer layers of the exploding star are blasted out in a radioactive cloud. This expanding cloud forms a supernova remnant.

radiation was entering the atmosphere from above. He had discovered cosmic rays.

Cosmic rays (CRs) provide one of our few direct samples of **matter from outside the solar system**. They are high energy particles that move through space at nearly the speed of light.

Since CRs are **charged**—positively charged protons or nuclei, or negatively charged electrons—their paths through space can be deflected by magnetic fields. On their journey to Earth, the magnetic fields of the galaxy, the solar system, and the Earth scramble their flight paths so much that we can no longer know exactly where they came from.

Most galactic CRs are accelerated in the the remnants of supernovae explosions—expanding clouds of gas and magnetic field that can last for thousands of years. Bouncing back and forth in the magnetic field of the remnant randomly lets some of the particles gain energy, and become CRs. Eventually they build up enough speed to escape into the galaxy. But here comes the trap: CRs accelerated in supernovae remnants can only reach a certain maximum energy; however, they have been observed at much higher energies than supernovae remnants can generate—where these ultra-high-energies come from is an open big question in astronomy. Perhaps they come from outside the galaxy, from active galactic nuclei (AGN), quasars[3] or gamma-ray bursts. Or perhaps they are the signature of some exotic new physics, for instance dark matter[4]. Questions like these tie cosmic-ray astrophysics to basic particle physics and the fundamental nature of the universe.

Studies of CRs opened the door to a world of particles beyond the confines of the atom: the first particle of antimatter, the positron (the anti-electron) was discovered in 1932, followed by several more, all of which are produced when CRs arrive at Earth and collide with the atoms in the upper atmosphere. Until the advent of **high-energy particle accelerators** in the early 1950s, this natural radiation provided the only way to investigate the growing particle "zoo."

Now, a weird yet fascinating question: could there be a link between galactic CRs and **cloud formation**? Clouds exert a strong influence on the Earth's energy balance and are fundamental for climate; nevertheless, their formation is poorly understood. In the CLOUD experiment, the Proton Synchrotron (a particle accelerator) provides an artificial source of "CRs" that simulates natural conditions of the atmosphere. A beam of particles is passed through the cloud chamber and its effects on clouds production inside the chamber are recorded and analysed.

Neutrinos

Neutrinos are elementary subatomic particles with no electrical charge and very little mass. They were first discovered by Enrico Fermi in 1934, but they were not detected experimentally for 20 years because of their

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[3] An enormously bright object which emits massive amounts of energy. In an optical telescope, they appear point-like, similar to stars, from which they derive their name (quasar = quasi-stellar).

[4] Name given to the amount of mass whose existence is deduced from the analysis of galaxy rotation curves but which until now, has escaped all detection.

extremely weak interactivity with matter.
Since neutrinos have no electrical charge and react with matter only through weak based interactions (the ones from which radioactive decay originates), they are **extremely penetrating particles**. Moreover, neutrinos are the only elementary subatomic particles that have the same electrical charge as their antiparticle, the antineutrinos[5].

Neutrinos are useful messengers because they travel in a straight, traceable line from their origin, passing through nearly every obstacle in their path. This allows scientists to see into locales that radiation cannot penetrate—but it also makes them difficult to detect.
Neutrinos provide information to probe the most violent astrophysical sources: events like exploding stars, gamma-ray bursts, and cataclysmic phenomena involving black holes and neutron stars. However, despite progress having been made, researchers have not managed to identify a dominant type of source producing cosmic neutrinos yet.

One of the largest centres of neutrinos detection is the **IceCube Neutrino Observer**. A series of observations carried with the IceCube between 2010 and 2012 provided the first evidence for a high-energy neutrino flux of extraterrestrial origin.

Looking to the future of multimessenger astronomy observation, at the moment there is one major project of neutrino telescopes building: KM3NeT, which is composed of two detectors. The first one, ARCA (Astroparticle Research with Cosmics in the Abyss), which is designed to detect neutrinos in the TeV-PeV range and that will be used for astrophysics studies. The second one, ORCA (Oscillation Research with Cosmics in the Abyss) is sensitive to GeV neutrinos, which will be used to study the particles' properties themselves. ARCA is expected to be fully operational in 2027 and ORCA in 2025.
Another interesting project is P-ONE, or Pacific Ocean Neutrino Experiment. The P-ONE project is presently in research and development phase. The goal of the collaboration is to install a multi-cubic-kilometer neutrino telescope in the Pacific Ocean. It is expected to be operational in the next decade.

Gravitational Waves

Gravitational waves are **infinitesimal vibrations of spacetime produced by the accelerated movement of masses**. According to General Relativity, our universe is characterized by a four-dimensional structure called spacetime, where the three spatial dimensions merge with time. Bodies define the geometry, giving indications of the shape it must assume, while space, curving under the mass of bodies, provides them with guidance on how to move. In this environment, masses in accelerated motion produce vibrations, infinitesimal ripples that propagate in the universe at the speed of light. Unlike electromagnetic radiation, gravitational waves are not waves traveling through space; instead, they are the very fabric of space and

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[5] Antiparticles have the same mass of a subatomic particle but opposite electric or magnetic properties. In the case of neutrinos, the opposite charge of zero is still zero. This raises unanswered questions on the role of neutrinos in the formation of the universe, when matter and antimatter annihilated each other.

time oscillating.

An important characteristic that makes gravitational waves significant is their **transparency**—they can traverse the universe without being disturbed by other fields or particles. By interacting so little with cosmic objects, they become powerful tools for studying celestial events that might otherwise be obscured by cosmic dust or other optical obstacles. They can travel immense distances without losing information about the sources that generated them, providing insights into the remote both in space and time, revealing details about the universe's prehistory.

Albert Einstein predicted their existence in 1916 as a consequence of his General Theory of Relativity, published in 1915. After over 50 years of research, on **September 14, 2015**, at 9:50:45 Greenwich Mean Time, the confirmation arrived: our planet was hit by a gravitational wave related to an event that occurred a billion and three hundred million years ago, involving the rapid rotation of two black holes around each other in the phases of inspiral and merging. This first gravitational wave signal, named GW150914 (GW indicating "Gravitational Waves"), was intercepted by two instruments, called **LIGO** (Laser Interferometer Gravitational-Wave Observatory), located in the United States, one in Hanford and the other in Livingston. Based on the received signal and theoretical models calculated from General Relativity, physicists determined that the original black holes had masses of 29 and 36 solar masses, concentrated in two spheres with a diameter of less than 200 km. Moving at a surprising speed—half the speed of light—they joined to form a final black hole of 62 solar masses. The missing mass, 3 solar masses, was emitted as gravitational radiation energy. Since 2015, about fifty gravitational waves have been observed, opening a new chapter in physics and a new way of observing the Universe.

A Milestone in Multimessenger Astronomy

There is one big event, happening in 2017, that really marked the birth of multimessenger astronomy. It was the result of two neutron stars merging into a black hole. In the following years, many other observations have been made, the last one dating back to January 2023. Yet, we believe that, rather then making a list of all of those, it would be of higher interest to delve a bit into the particulars of that great event. To the readers, we say that they may feel free to skip the following part, if data and computations are not of interest!

The observation happened on 17 August 2017, when the gravitational-wave event GW170817 was observed at a short time interval from the gamma-ray burst GRB170817A. The probability of the near-simultaneous temporal and spatial observation of the two of them occurring by chance was 5.0×10^{-8}. Therefore, it could be confirmed with a high confidence level that merging binary neutron stars were the source of this phenomena. The recorded data provided extraordinary new insights into fundamental physics—indeed, using the observed time delay of (1.74 ± 0.05)s between the detection of γ-rays and gravitational waves, scientists could constrain the difference between the **speed of gravity** and the speed of light! Here's the math: assuming a difference in travel time Δt between GWs and photons, and knowing the travel distance D, the fractional speed difference during the trip can be written as

$$\frac{\Delta v}{c} \approx \frac{c \Delta t}{D},$$

where $\Delta v = v_{GW} - c$ is the difference between the speed of gravity v_{GW} and the well-known speed of light c. The distance can be set at $D = 26Mpc = 8.02276e + 20m$, while for Δt we can only give an upper and a lower bound, which lead to a resulting constraint of

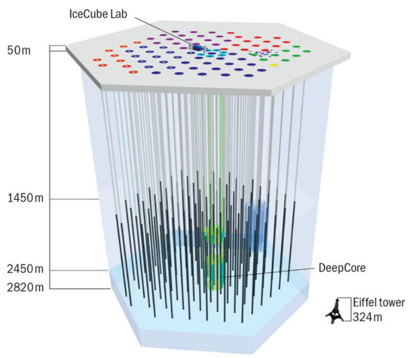
$$-3 \times 10^{-15} \leq \frac{\Delta v}{c} \leq +7 \times 10^{-16}.$$

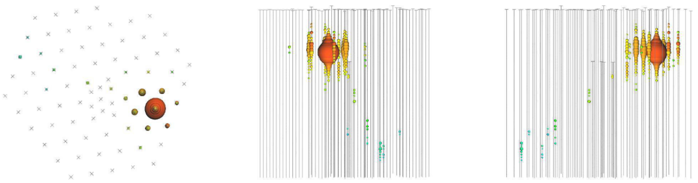
Observational Instruments

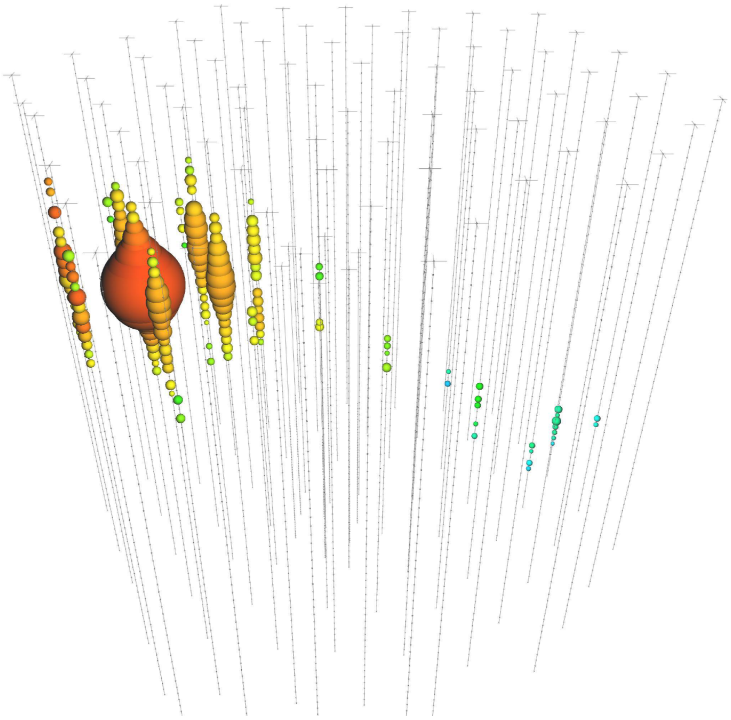
Multimessenger astronomy is a relative new field, which has given birth so far to some groundbreaking discoveries. Yet, the diversity in the nature of the messengers and the elusiveness of neutrinos require continuous advancement also for what regards instruments.
Considering the number of experiments currently being under construction and planned, it seems clear that an **efficient communication** between collaborations is crucial. Moreover, this communication also needs to be fast. Neutrinos are actually very good messengers to trigger alerts because they are able to easily escape from sources. These neutrino alerts can give an early warning to other observatories of an incoming event, allowing for a prompt follow-up of transient phenomena.

We shall focus on two already-mentioned instruments, both of which are some of the most astonishing observatories built so far.

The **IceCube** is a neutrino and cosmic-rays observatory, a cubic-kilometer particle detector made of Antarctic ice and located near the Amundsen-Scott South Pole Station. It is buried beneath the surface, extending to a depth of about 2,500 meters. A surface array, IceTop, and a denser inner sub-detector, DeepCore, significantly enhance the capabilities of the observatory, making it a multipurpose facility.
The in-ice component of IceCube consists of 5,160 spherical digital optical modules (DOMs) attached to vertical “strings” and arrayed over a cubic kilometer from 1,450 to 2,450 metres depth.
IceTop consists of 81 stations located on top of the same number of IceCube strings. Each station has two tanks, each equipped with two downward facing DOMs, which also detect air showers from cosmic rays. But how does IceCube work? Neutrinos are not observed directly, but when they happen to interact with the ice they produce electrically charged secondary particles that in turn emit **Cherenkov light**, which is the radiation emitted by charged particles traveling through the ice faster than light itself travels in ice (you probably know about the “sonic boom”—well, the principle here is the same). The IceCube sensors collect this light, which is subsequently digitized.







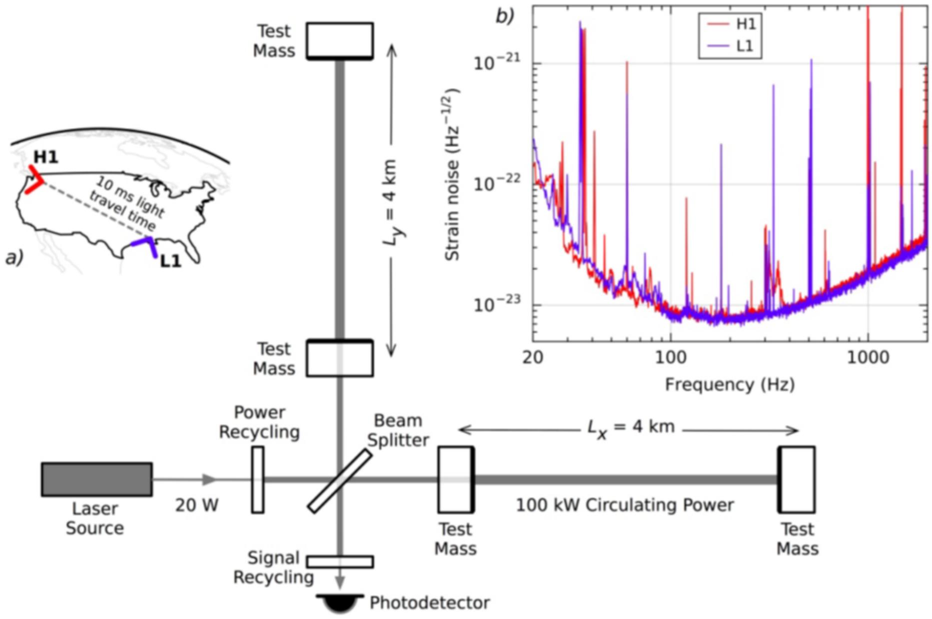
In the graphical rendering, each DOM is shown by a white dot. Colored spheres show sensors that have detected light. The size scales with the amount of recorded light and the color indicates arrival time (red first, green last, so in our case the neutrinos clearly traveled from the left to the right).

LIGO (Laser Interferometer Gravitational-Wave Observatory) is a gravitational wave observatory located in the United States, which can be accessed by the global scientific community, composed of two powerful interferometers that are able to perceive the slightest changes in the geometry of the space-time fabric. How? Using laser beams to detect the transit of gravitational waves.

The observatory is made up of two twin facilities about three thousand kilometers away from each other (one is located in Livingston, Louisiana, and the other in Hanford, Washington state). It is necessary that there are two detectors and that they are far enough apart, to avoid possible disturbances (such as micro-earthquakes, laser fluctuations, acoustic noise) that could occur in one of the two, and which could be mistakenly associated with a gravitational wave.

Each system (interferometer) is 4 kilometers long and has an “L” shape, that is, it is composed of two “arms” perpendicular to each other, each crossed by a laser beam which is reflected by a mirror (suspended as a tests mass) to the end.

The lasers travel back and forth inside high vacuum tubes (1.2 meter diameter) which allow to compute the distance of the events between the two mirrors on which these rays are reflected with maximum precision. These mirrors are very important because they are the real sensors: when they pass through the detectors, the gravitational waves disturb, even if very slightly, the travel of the beams, producing very small changes that can only be detected by isolating the test masses from all the disturbances coming from the outside, such as seismic vibrations or gas molecules present in the air (the two tunnels, however, which are entirely shielded with concrete, have an ultra-high vacuum inside). When slight **variations in the distances** of the masses are observed, we are faced with the passage of a gravitational wave.



The picture shows a simplified diagram of an Advanced LIGO interferometer. Inset (a), on the left, shows the position and orientation of the two LIGO observatories and indicates the time it takes for light to travel from one to the other. Inset (b) shows how the instrumental noise expressed in strain varied with frequency in each interferometer close to the time of the event.

Conclusion

The field of multimessenger astronomy has ushered in a new era of exploration, allowing us to study the universe through various cosmic messengers. The birth of this field in 2015, marked by the simultaneous observation of a gravitational wave and electromagnetic events, has opened doors to unprecedented discoveries. We have witnessed the merger of neutron stars, observed gamma-ray bursts, and delved into the intimate details of fundamental physics. The ability to study cosmic events through different channels has not only confirmed existing theories but has also provided unexpected insights, such as the constraints on the speed of gravity versus the speed of light, or even clouds formation!

Looking ahead, the development of new instruments and the collaboration between observatories will play a crucial role in advancing multimessenger astronomy. Projects like KM3NeT, IceCube, and LIGO promise exciting prospects on multimessenger observations.

In essence, multimessenger astronomy has become a cornerstone in our quest to comprehend the vast complexities of the cosmos, our world and fundamental physics. Pioneering discoveries have already been carried out, yet there is still much more to learn!

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