# Multimessenger Astronomy

**Imre Bartos** and **Marek Kowalski** exploring the universe by combining information from electromagnetic radiation, gravitational waves, neutrinos and cosmic rays.

**physics**world Discovery

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# Abstract

With the recent discovery of gravitational waves and high-energy cosmic neutrinos, we are witnessing the beginning of a new era in multimessenger astronomy. The exploration of the Universe through these new messengers, along with electromagnetic radiation and cosmic rays, gives us new insights into the most extreme energetic cosmic events, environments and particle accelerators. The objects of interest range from galaxies with accreting supermassive black holes in their centre to collapsing stars and coalescing stellar black holes. In this ebook we provide an introduction to the scientific questions surrounding these new messengers and the detectors and observational techniques used to study them, together with an overview of current and future directions in the field.

# Acknowledgments

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# Author biographies

## Imre Bartos

Dr Imre Bartos received his PhD from Columbia University, USA, where he is currently a research scientist. He studies extreme cosmic explosions related to the formation and evolution of black holes. He is a member of the LIGO Scientific Collaboration, which recently announced the discovery of gravitational waves, and an associate member of the IceCube Collaboration. He also works on the biological applications of optics to fight malaria in sub-Saharan Africa and to better understand neurological diseases.

Dr Bartos has been recognized as one of the top 30 under 30 Rising Stars of Science by Forbes magazine in 2012, and was part of a Grand Challenges Explorations Team supported by the Bill & Melinda Gates Foundation. He was the recipient of the Allan M Sachs Teaching Award, and was a finalist for Columbia's Presidential Teaching Award. As a member of LIGO, he was the co-recipient of the 2016 Special Breakthrough Prize and the 2016 Gruber Prize.

## Marek Kowalski

Dr Marek Kowalski's involvement in neutrino astronomy goes back to his graduate school days at Germany's Humboldt University, where he worked on IceCube's predecessor project, AMANDA. After a postdoc at the Lawrence Berkeley National Laboratory in the US, where he worked for a few years in supernova cosmology, he returned to Humboldt University to lead an Emmy Noether young investigator group. He became a full professor in experimental astroparticle physics at the University of Bonn in 2009, only to return to Berlin in 2014 through a joint appointment at Humboldt University and DESY. His current research interests include finding the sources of IceCube's cosmic neutrinos through multimessenger observations, R&D for the planed extension of IceCube and preparing for a new optical survey, the Zwicky Transient Facility.

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## 1 Introduction

Astronomers have long explored the Universe by taking advantage of an electromagnetic spectrum that spans more than 20 orders of magnitude. This spectrum extends from radio wavelengths, where the Universe is transparent—giving us a snapshot of its nature 380 000 years after the Big Bang—all the way to x-rays and gamma rays, which provide a glimpse of the violent, high-energy Universe. In between, the optical band reveals a most inspiring view of stars and galaxies.

Yet many facets of the Universe remain unobserved. Black holes, as their name implies, emit essentially no electromagnetic radiation and hence are notoriously difficult to observe. The absorption of the highest-energy gamma rays by the cosmic microwave background—radiation left over from the Big Bang—and other radiation fields renders the Universe opaque to these photons. Cosmic rays—energetic particles coming from the cosmos—reach Joule energies that are more than ten million times higher than those achieved at the Large Hadron Collider in Geneva, extending the observable spectrum by another six orders of magnitude in energy. However, as these charged particles are scrambled by magnetic fields, it is difficult to pinpoint their origins.

Two fundamental discoveries made in this decade have opened new windows onto the Universe. One is the observation—made by the Laser Interferometer Gravitational-wave Observatory (LIGO)—of gravitational waves from two merging black holes. The other is the detection of the first high-energy neutrinos of cosmic origin by IceCube, a gigantic cubic-kilometer-sized detector in the Antarctic ice at the South Pole.

These observations mark a new age of **multimessenger astronomy**: *the exploration of the Universe through combining information from a multitude of cosmic messengers: electromagnetic radiation, gravitational waves, neutrinos and cosmic rays.*

Each of these cosmic messengers is produced by distinct processes at its origin, and thus carries information about different mechanisms within its source. The messengers also differ widely in how they carry this information to the astronomer: for example, gravitational waves and neutrinos can pass through matter and intergalactic magnetic fields, providing an unobstructed view of the Universe at all wavelengths. Combining observations of different messengers will therefore let us see more and look further. Figure 1 summarizes the new and old windows on the Universe.

The questions that can be explored through multimessenger observations concern the formation and evolution of black holes; the dynamics of exploding stars; the

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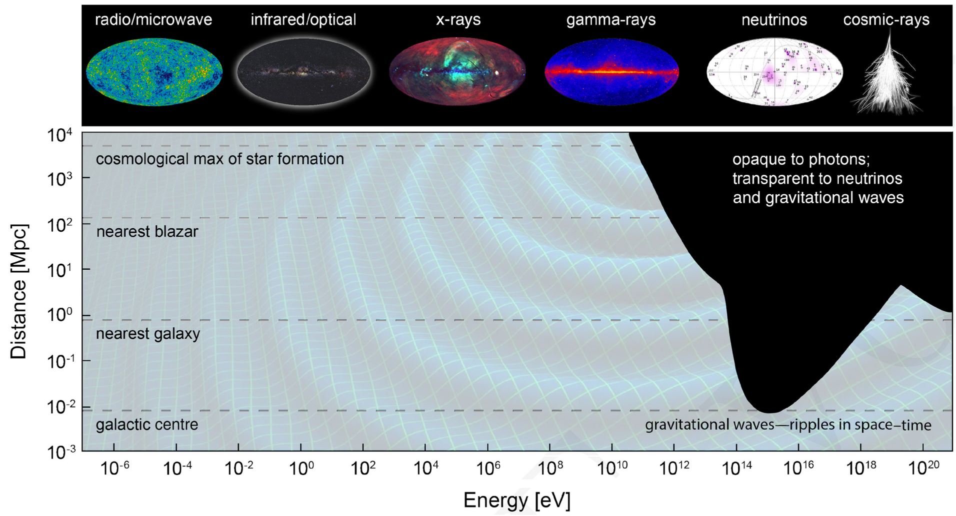


**Figure 1.** Distance horizon at which the Universe becomes optically thick to electromagnetic radiation. While lower-energy photons can travel to us from the farthest corners of the Universe, the highest energy photons and cosmic rays are attenuated after short distances, obscuring our view of the most energetic cosmic events. In contrast, the Universe is transparent to gravitational waves and neutrinos, making them suitable probes of the high-energy sky. Radio/microwave image, credit: ESA/DLR/Ducris, CC BY-SA 3.0 IGO. Infrared/optical image, credit: Axel Mellinger, www.milkywaysky.com. X-rays image, credit: X-Ray Group at the Max-Planck-Institut für extraterrestrische Physik (MPE). Gamma-rays image, credit: NASA/DOE/Fermi LAT Collaboration. Neutrinos and cosmic-rays images, credit: IceCube.

origin of cosmic rays; relativistic jets; supermassive black holes in the hearts of galaxies; colliding black holes and neutron stars; and many others. Multimessenger astronomy also allows us to address the question of why we are here in the first place, by shedding light on the origin of heavy elements and the evolution of galaxies and the Universe.

In this book, we start by providing some introductory background, including a review of the existing cosmic messengers. This is followed by a discussion of current directions, focusing in particular on neutrinos and gravitational wave astronomy. Finally, we present an outlook and conclusions.

## 2 Background

### 2.1 What powers cosmic emission?

The most extreme events in the Universe are powered by gravity, a source of energy significantly more powerful than nuclear processes. The more compact matter can become, the more gravitational energy is released. Consequently, the most powerful cosmic processes involve so-called *compact objects:* black holes, neutron stars and white dwarfs.

For example, when a massive star with $M > 8M_{\odot}$, where $M_{\odot}$ is the mass of the Sun, builds up a dense core that collapses under its own gravity, it triggers arguably the most violent type of explosion the Universe has to offer: a core-collapse supernova. The gravitational energy liberated during the collapse is easily estimated:

$$E_{\rm SN} \approx G\frac{M^2}{R_{\rm NS}} \approx 2.7 \times 10^{46}\ {\rm J}\left(\frac{M}{M_\odot}\right)^2,$$

assuming $R_{\rm NS} = 10$ km for the radius of the neutron star that forms at the centre. This corresponds to 14% of the rest mass energy, much more than can be released through nuclear processes. If the collapse further proceeds to a black hole, the Schwarzschild radius of $2GM_{\rm BH}/c^2 \cong 3(M_{\rm BH}/M_\odot)$ km sets the dimensions relevant for the even greater energy release.

In the aftermath of such a gravitational collapse and explosion, some of the stellar material falls back onto the central black hole or neutron star. As the matter has too much angular momentum to settle onto the central compact object, it first forms a rotating disk around it, called an *accretion disk*. Matter in the disk spirals inwards due to gravity, compressing and heating up in the process due to its internal friction. Accretion disks are extremely efficient in converting their mass into energy as they fall to the centre. For black holes that grow by accretion, about 10–40% of their mass will be radiated away in the process.

Matter can also fall onto (or into) compact objects through events other than stellar death. Compact objects sometimes collide in the Universe, and the copious amount of gravitational energy released in the process is then radiated away. Such collisions are not as rare as one might think, based on how sparse the Universe is. Many compact objects reside in binaries—they are gravitationally bound to, and closely orbit, each other. Massive stars, which eventually collapse and form compact objects, are often born in binaries, naturally giving rise to binary black holes, binary neutron stars and other combinations. Alternatively, there are dense populations of stars and compact objects in the Universe, for example in the very centres of galaxies. In these dense environments, black holes and neutron stars occasionally get close enough to each other to merge.

Another key source of energy is single compact objects accreting matter from their environment. In the centre of essentially every galaxy (the galactic nucleus), there resides a so-called *supermassive black hole* that is millions or billions of times heavier than black holes formed in stellar collapse. These black holes can experience a large inflow of matter attracted towards the centre of the galaxy. Gas or tidally disrupted stars falling towards the central black hole can form a gigantic accretion disk, producing abundant radiation across the electromagnetic spectrum as the disk spirals inwards. Due to their brightness, galaxies that host a highly accreting supermassive black hole—which, in some cases, outshines the entire galaxy—are called *active galaxies*, and their centres *active galactic nuclei*.

## 2.2 Cosmic messengers

How is the energy released in cosmic events? In the case of stellar core collapse, most energy is emitted as thermal neutrinos at mega-electron volt (MeV) energies. The neutrinos are produced when matter is compressed to nuclear densities and electrons and protons combine to form neutrons through electron capture (hence the name neutron star). Some of the energy carried by the neutrinos is absorbed by the surrounding matter, giving rise to the powerful stellar explosion.

For black hole accretion disk systems, the energy outflow comes in the form of a beam of matter, typically perpendicular to the plane of the disk. The production mechanism of these outflows—called *relativistic jets*, as particles in them reach velocities close to the speed of light—is poorly understood, but is likely related to the magnetic fields generated by the accretion disk. Black holes driving relativistic jets are probably the most extreme particle accelerators in the cosmos, and protons and heavier atomic nuclei within the jets can be accelerated to ultra-high energies. For example, a proton, which has a mass of order $10^{-27}$ kg, can gain as much kinetic energy as a baseball thrown at 60 miles per hour—or, in more convenient units, $10^{20}$ eV.

A variety of other astrophysical messengers are also produced by cosmic events. Here, we discuss each of these messengers, and in particular how they are produced and detected.

### *2.2.1 Cosmic rays*

How do cosmic rays obtain their large energies? The acceleration of particles to high energies can happen through various mechanisms. However, Fermi shock acceleration—named after its discoverer, the physicist Enrico Fermi—one of the most frequently invoked. In a nutshell, particles scatter elastically (e.g. off magnetic fields) within a moving shock front or gas cloud. This can be visualized by imagining a table-tennis ball bouncing off a moving wall, and thereby picking up kinetic energy from the wall. If a particle's trajectory before and after the interaction is normal to the shock front (or moving wall), the fractional energy increase per encounter is $\xi = \frac{\Delta E}{E} \approx 2\frac{v}{c}$ for non-relativistic shock front velocities $v$. The process can be repeated if the particle is scattered back in the up-stream region. After $n$ encounters (imagine two walls, one still and one moving towards the other, with a table-tennis ball in-between), the energy will be $E_n = E_0(1 + \xi)^n$. If a particle can be confined inside such a system for a long time, it can be accelerated to rather high energies. Moreover, if the escape probability is constant for each encounter, one finds the number of particles reaching a certain energy $N(>E) \propto \frac{1}{P_{\rm esc}}\left(\frac{E}{E_0}\right)^{\gamma}$. This characteristic power law spectrum, predicted by Fermi's acceleration mechanism, is indeed what is observed in nature. The spectral index $\gamma$ is further predicted to be around 2 or larger, which is consistent with observations once propagation effects are taken into account.

The maximal energy of a source is reached when the particle's gyroradius, $r_g = E/QB$, which depends on the energy (E) and charge (Q) as well as the magnetic field strength (B), starts to exceed the dimensions of the source, i.e. the cosmic rays cannot be further confined. Through rearranging, one obtains Hillas' constraint on the maximal energy of a source, $E_{\rm max} = QBr_g$. For protons in the Large Hadron Collider (LHC) at CERN, with its 2.8 km bending radius and its magnets with a field strength of 8 Tesla, the maximum energy is 7 TeV, making it the most powerful human-built accelerator. Cosmic rays, however, have been observed at energies more than $10^7$ times higher than those available at the LHC, and correspondingly the magnetic fields or dimensions must be appropriately larger. Few astrophysical sources in the Universe satisfy Hillas' constraint.

Cosmic rays constantly reach the Earth's atmosphere, where they collide with atmospheric molecules to produce large numbers of energetic particles that then shower down towards the surface. These particle showers—and their accompanying fluorescence and Cherenkov radiation due to the particles crossing the atmosphere faster than the speed of light in air—provide the basis of cosmic ray detection.

Collisions between cosmic rays and atmospheric molecules are so frequent that hundreds of the energetic particles produced in such collisions cross a person's body every minute. However, the spectrum of cosmic rays arriving at the Earth's surface falls steeply with energy. To detect particle showers efficiently, therefore, cosmic ray observatories need to cover large areas. The biggest such detector, the Pierre Auger Observatory, has instruments distributed over 3000 km$^2$.

Cosmic rays are the highest-energy particles ever detected, making them an important messenger for learning about the abundance and properties of the most extreme particle accelerators. However, as they are charged particles, they are deflected by the magnetic fields found between and within galaxies. Therefore, we cannot trace them back to their origins. For this, we need to rely on other messengers.

### *2.2.2 High-energy neutrinos*

Relativistic particles that are produced in cosmic accelerators either escape their source as cosmic rays, or they collide with photons or slower particles. In the latter case, new particles are produced in the collisions and then decay, eventually producing energetic neutrinos, gamma rays and other types of particles. One possible such interaction looks like this:

$$p + \gamma \longrightarrow n + \pi^+ \longrightarrow n + \mu^+ + \nu_\mu \longrightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu, \qquad (1)$$

with $p$, $n$, $\pi^+$, $\mu^+$, $e^+$ and $\nu$, $\bar{\nu}$ denoting a proton, neutron, pion, muon, positron, neutrino and anti-neutrino, respectively. As neutrinos and anti-neutrinos stay far from each other compared to their interaction length, they will not annihilate.

If cosmic rays escape their source, they can still collide with interstellar gas particles, additionally producing neutrinos. At the same time, the highest-energy cosmic rays will interact with photons from the cosmic microwave background, losing energy to neutrino production.

However they are produced, all neutrinos interact only weakly with matter, and this makes it difficult to detect them. Very large detectors are needed to have a chance of catching neutrino interactions. The largest such detector, the IceCube Neutrino Observatory, has an instrumented volume of 1 km$^3$ and is located deep in the ice under the South Pole in Antarctica. It detects Cherenkov light from muons and other relativistic charged particles that are created when a high-energy neutrino interacts with the ice. Cherenkov radiation is produced when a particle is moving through a medium, in this case ice, with a speed greater than the speed of light in the medium.

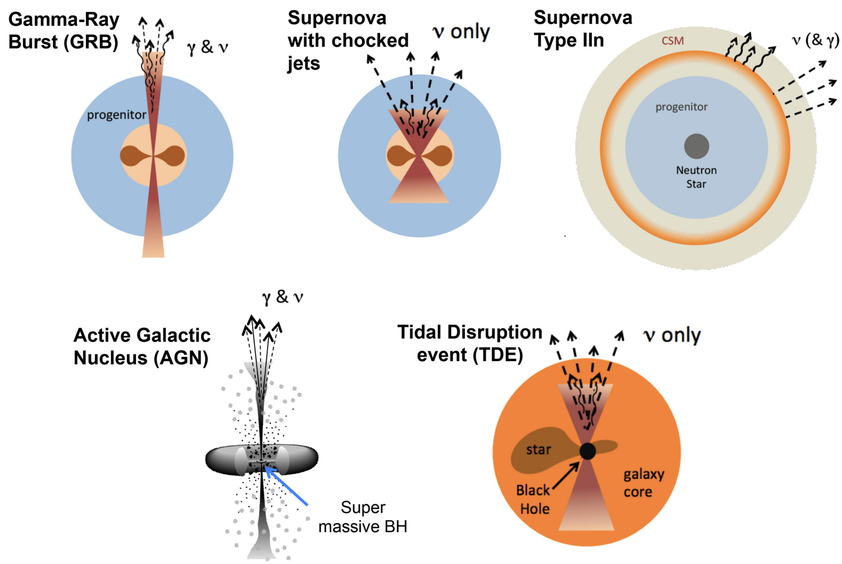


**Figure 2.** Scenarios for sources of neutrinos, with varying degrees of jet formation.

A variety of cosmic accelerators may produce neutrinos (see figure 2). The expected event rates can be estimated using supernovae as an example. The conditions provided in a supernova allow for shock acceleration, so a fraction of the kinetic energy of the explosion is expected to be transferred to high-energy protons and heavier nuclei. These will then result in neutrinos through the chain reaction shown in equation (1). Assuming that this process transfers $10^{44}$ J to neutrinos with tera-electron volt (TeV) energies (see section 2.1), it will yield a total of $6 \times 10^{50}$ neutrinos. The IceCube effective area—that is, its cross-section for neutrinos—corresponds to its geometric area of one square kilometer multiplied by its detection probability, which is notoriously small due to the fact that neutrinos only interact weakly. For muon neutrinos at 1 TeV the effective neutrino area—the number of detected neutrinos by the detector is equivalent to the flux of neutrinos crossing the effective area—is only $\sim$1 $m^2$ (and $\sim$10 $m^2$ for 10 TeV), hence one will detect on average only one TeV neutrino from a supernova at a distance of 100 Mpc (the most frequently used unit for extragalactic distance is the megaparsec, 1 Mpc = $3.26 \cdot 10^6$ light years). Fortunately, within such a distance, more than 1000 supernovae explode every year, including some very energetic ones with massive progenitors. Observing individual supernovae in connection with high-energy neutrinos hence appears within reach.

Neutrinos are the key to an unobstructed view of cosmic accelerators over a broad range of energies and distances. Their weak interaction with matter allows them to escape from dense environments that are opaque to photons. They can travel over essentially any distance in the Universe without being obstructed, making it possible for us to probe distant energetic sources outside the reach of electromagnetic observations at comparable energies. Neutrinos are also neutral, leaving their direction unaltered by magnetic fields; a detected neutrino will point back to its origin.

IceCube was the first (and is so far the only) detector to observe an astrophysical flux of high-energy neutrinos. The sources of these neutrinos are, nevertheless, currently unknown, since no individual source has produced sufficiently many events to be identified by itself. However, from current non-observations, strong constraints on the sources exist, as explained in section 3.2.

### *2.2.3 Electromagnetic emission from gamma rays to radio*

Electromagnetic observations taught us most of what we know about the Universe. There is a wealth of information in photons, with different wavelengths typically carrying the signatures of distinct processes. Below we organize and briefly explain some key signatures by wavelength.

**Gamma rays**—in addition to high-energy neutrinos, relativistic particles also produce energetic photons, called gamma rays, with energies of about 100 kilo-electron volts (keV) and above. Several strong gamma-ray emitters are observed regularly, including so-called *gamma-ray bursts* (GRBs), which are thought to be produced in the wake of stellar core collapse, or after the merger of either two neutron stars or a black hole and a neutron star. Nonetheless, the precise emission mechanism of gamma rays is not well understood.

Gamma rays are regularly detected up to giga-electron volt (GeV) energies. They are probably also produced at much higher energies, but we currently lack sensitive observatories, and the Universe also becomes opaque at these energies once we go much beyond our own galaxy (see figure 1). As they are unable to cross Earth's atmosphere, gamma rays are primarily observed using satellites.

Gamma-ray photons inform us of particle acceleration, and of the conversion of the energy of relativistic jets into non-thermal radiation. They are also the most abundant messengers we detect from the high-energy Universe. Nevertheless, understanding the processes involved in the production of gamma rays is made complicated by multiple plausible emission scenarios that are difficult to distinguish: gamma rays may be produced in the interaction of protons and heavier nuclei (so-called hadronic emission), or by lower energy photons undergoing inverse-Compton scattering on high energy electrons (leptonic emission).

**X-rays**—as a relativistic jet expands far out from its source, it thrusts into interstellar gas. This interaction launches shock waves into the gas, producing energetic x-rays. As the jet slows down as it accumulates more mass, the energy of the produced photons will also decrease, from x-rays to optical to radio. In the case of gamma-ray bursts, this emission is called *afterglow*, as it follows the initial burst of gamma rays and 'glows' much longer, gradually fading away with decreasing photon energy.

Besides afterglows, another important source of x-rays is accreting black holes. As accretion disks are heated to extremely high temperatures by friction, some of their thermal radiation will be in the form of X-rays.

There are very sensitive x-ray telescopes, all in space as x-rays cannot cross the atmosphere. These telescopes are, however, limited in how much of the sky they can see at once—their *field of view*. This is not critical for sources that emit x-rays continuously, as one can point a telescope towards them and integrate for a sufficiently long time. However, transient sources that last for only minutes to hours, as in the case of GRB x-ray afterglows, require a quick response and source localization through some other wavelength.

As x-ray afterglows are signatures of the interaction of relativistic jets with the surrounding gas, they provide information on the properties of the jet as well as the environment of the cosmic event. X-rays are also useful in finding and learning about accreting black holes.

**Visible**—visible light is the richest source of information about the Universe. Most cosmic events produce thermal radiation in or near the band visible to humans. This is not a coincidence. Our eyes evolved to see light from the Sun, which is a fairly typical cosmic object.

Most of the visible light we detect is thermal radiation. For instance, in a core collapse supernova, the interior is hidden in an optically thick environment and the energy is released, if not through neutrinos or gravitational waves, then through a photosphere of a temperature comparable to that of the Sun (although with different spectral properties). Beyond stars, accretion disks around black holes also radiate thermally, largely in the optical/near-infrared/ultraviolet spectrum. Importantly, the merger of neutron stars can also produce such radiation. During merger, one or both of the neutron stars get disrupted, and some of their matter is ejected away. This neutron-rich matter undergoes nucleosynthesis, during which heavier elements are formed. Some of these elements are radioactive, and their decay will produce observable transient radiation, called *kilonova*. A kilonova mainly emits in the near-infrared band, lasts for several days, and is observable from any direction around the merger.

**Radio**—thermal radiation does not produce appreciable amounts of radio emission, making radio observations an important probe of non-thermal processes. Radio emission is often the result of interaction between a particle outflow and the surrounding gas. This is the case in the late stages of gamma-ray burst afterglows, which are strong radio emitters for much longer than they are gamma-ray or optical emitters. In the mergers of compact objects, ejected matter that is also responsible for kilonova emission will interact with the surrounding medium, producing potentially detectable radio flares that can last for years.

### *2.2.4 Gravitational waves*

The most violent cosmic events produce a form of radiation that is distinct from those we discussed above, and is directly related to gravity. Massive objects create gravitational fields around them, which, according to Einstein's general theory of relativity, is a consequence of the curvature of space–time. As a massive object accelerates, it induces changes in the curvature of space–time around it. These changes will propagate away from the object as waves—called gravitational waves, travelling at the speed of light.

Since gravity is a very weak force, only very massive, rapidly accelerating objects can produce measurable gravitational waves. A primary source is colliding compact objects, mainly black holes and neutron stars, which are not only massive but can get very close to each other before they merge, reaching rapid accelerations. Two

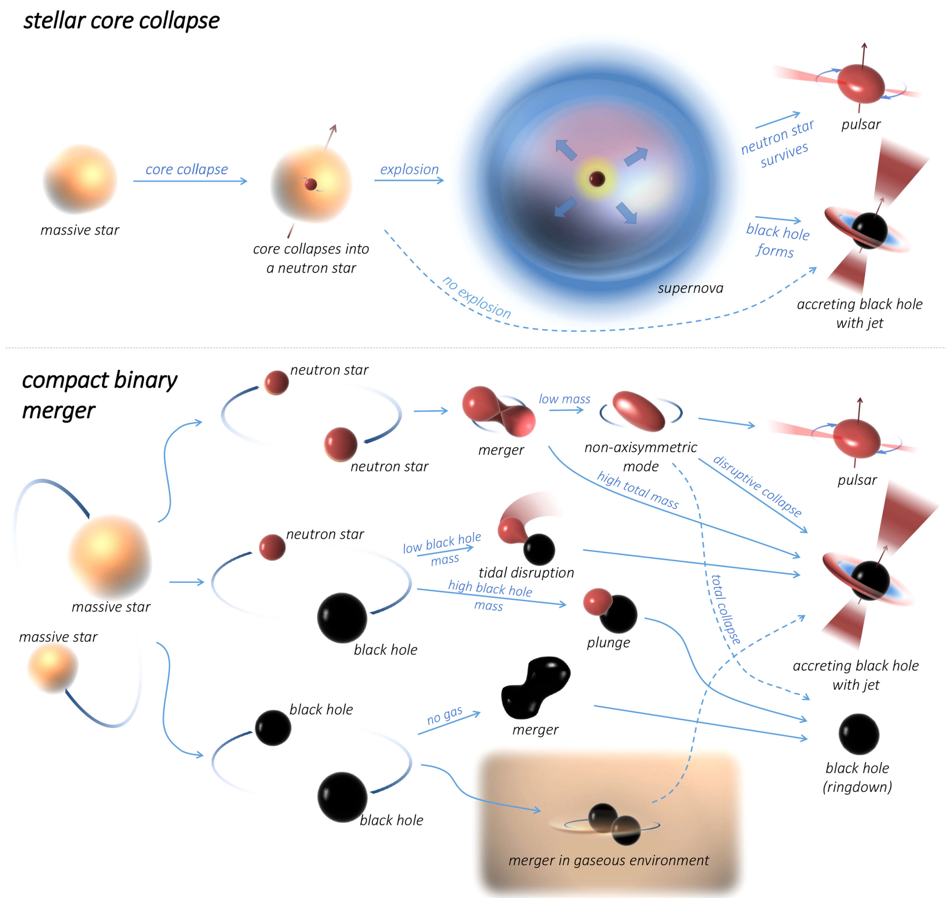


**Figure 3.** Gravitational wave emission.

compact objects that orbit each other—forming a so-called *compact binary*—will see their orbital radius decrease as their potential energy is radiated away as gravitational waves, and the two objects will spiral inwards, reaching high centripetal acceleration, and eventually merge (see figure 3). Right before merging, two orbiting black holes can circle each other up about a thousand times per second, reaching velocities of more than half the speed of light.

Besides compact binary mergers, other interesting cosmic events can also produce gravitational waves, as figure 3 shows. In a stellar core collapse, infalling matter may emit gravitational waves if the fall is neither spherically nor axially symmetric; symmetric acceleration effectively cancels out any emission. A newly formed neutron star in the wake of a core collapse event is an even more promising source. It rotates rapidly at a frequency of up to a thousand times per second. It deforms into an elongated ellipse shape due to the centrifugal force, therefore losing axial symmetry, and begins to emit gravitational waves. For a typical neutron star radius of 10 km, the available rotational energy is $\sim 10^{45}$ J, or $10^{-2}\ M_{\odot}c^2$, where $M_{\odot}$ is the

**Figure 4.** Images of LIGO in Livingston, LA, USA (left) and Hanford, WA, USA (right). Credit: LIGO.

mass of the Sun, representing an abundant energy reservoir for gravitational wave radiation. Nor are newly born neutron stars the only ones of interest. Any rotating neutron star—especially one that continuously acquires rotational energy by accreting matter from a nearby star—is a potentially detectable gravitational wave source. Many of these rotating neutron stars are known as *pulsars*. They emit a beam of photons, typically X-rays or radio waves due to their internal magnetic field structure. As they rotate, we can observe this beam of light periodically as its direction rotates with the neutron star, functioning as a cosmic lighthouse.

The detection of gravitational waves is a particularly challenging enterprise. For decades, many (including Einstein) considered their observation to be impossible. Nevertheless, in 2015, about 100 years after Einstein's original publication proposing their existence, gravitational waves were finally detected by the Laser Interferometer Gravitational-wave Observatory (LIGO) (figure 4). LIGO uses laser interferometry, effectively sending laser beams in two perpendicular, 4 km-long tubes, in order to precisely measure any difference in the two path lengths. An incoming gravitational wave curves space, which in effect changes the lengths of the two paths. The periodic change of these lengths can therefore be reconstructed to be a gravitational wave signal. LIGO is able to detect a distance change of $10^{-18}$ m, which is much smaller than the size of a proton ($10^{-15}$ m), demonstrating the technological mastery needed for such measurements.

Gravitational waves represent a unique source of information on the dynamics of cosmic events, which are unobservable through other messengers. Most prominently, colliding black holes in empty space will not produce any other forms of radiation. Merging neutron stars will only emit photons and other particles following their merger. In stellar core collapse, only gravitational waves and thermal MeV neutrinos escape from the core. In general, gravitational waves reveal the formation and evolution of compact objects, as opposed to other messengers, which carry information about accretion, particle acceleration and interactions.

## 3 Current directions

Multimessenger studies have become a central theme in observational astronomy. A prime reason for this is the availability of new observatories for detecting alternative messengers, namely gravitational waves and high-energy neutrinos.

Additionally, the increasing size and sophistication of the global observatory network enables rapid information sharing and immediate follow-up observations. Further, as we interpret information from single messengers with increasing refinement, it is more and more valuable to leap forward by incorporating new information from other messengers.

Significant observational and theoretical resources are being directed towards the planning, execution and interpretation of multimessenger surveys. In this section, we review current directions for the two new messengers, gravitational waves and high-energy neutrinos, as well as current multimessenger efforts to probe the most extreme cosmic events.

### 3.1 Gravitational wave observations—LIGO

On 14 September 2015, shortly after their construction, the Advanced LIGO detectors recorded the first gravitational wave signal to be observed, from the merger of two black holes over a billion light years away. This detection concluded half a century of experimental work by thousands of scientists. The discovery was soon followed by a second observation in December 2015, again produced by two merging black holes. These detections marked the beginning of a new field: gravitational wave astronomy.

The first gravitational wave discoveries, at a rate of about one detection per two months, are only the beginning for a rapidly improving detector network. The LIGO detectors are scheduled to be turned on and off periodically, using the on-time for detection and the off-time to adjust the detectors and enhance their sensitivity. By around 2019, LIGO will reach its design sensitivity, at which gravitational wave detections are expected every few days.

Additional gravitational wave detectors are also being constructed. Virgo, an observatory near Pisa, Italy, is scheduled to turn on in 2017. KAGRA, located underground in Japan's Kamioka mine, will be completed by the end of the decade. LIGO is further planning to build a third detector in India, and this is also expected to be completed during the next decade.

Having multiple observatories around the globe has many key advantages. First, because of the large distances between the observatories, any 'noise' that the gravitational wave detectors pick up will only be present at individual observatories at a given time. By contrast, a gravitational wave signal coming from outer space at the speed of light will reach all of the detectors within milliseconds. This makes it easier to identify signals—they must appear almost simultaneously at all of the detectors. Additionally, having multiple detectors gives us a way to reconstruct the direction of origin of the gravitational wave signal. As an individual detector measures the local curvature of space, it obtains limited information on the direction of the incoming signal. Multiple detectors give us a way to compare the gravitational wave's relative times of arrival, which is informative about the direction the wave is coming from. This direction reconstruction is critical for searches for electromagnetic emission or neutrinos from the gravitational wave source (see below).

Both of the detected gravitational wave signals were emitted by the merger of black holes, making this the likely dominant source type for future observations. However, we expect to observe gravitational waves from other sources in the next few years. In particular, the prospects for observing the merger of two neutron stars, or a neutron star with a black hole, are promising. We can estimate the rate of neutron-star mergers from the gamma-ray emission we detect from them, and these rate estimates—several within a billion light years every year—imply that we should observe them soon. At design sensitivity, the LIGO detectors will discover neutron star mergers out to distances of about 650 million light years on average.

The mergers of two black holes or two neutron stars are very well-understood gravitational wave sources. Due to their compact size, they behave essentially as point masses throughout their merger, making it straightforward to calculate the expected gravitational waveform. This allows for sensitive searches that seek to identify these precise waveforms in the data. Some other, more complex systems, such as the collapse and explosion of a massive star, will emit gravitational waves in a less systematic, and much less well-understood, fashion. For these cases, the strategy is to search for short, transient signals that perturb the curvature of space, but without more specific assumptions about the waveform. These broader searches also have the advantage of identifying other, less expected or unknown signals, truly opening up the Universe to surprises.

### 3.2 High-energy neutrino observations—IceCube

In 2012, the IceCube Collaboration announced that the IceCube Neutrino Observatory (see figure 5) detected two energetic neutrinos, both reaching energies of about $10^{15}$ electron volt (eV). At such energy levels—a hundred times higher than can be reached at the LHC—the measurement has essentially no background (that is, no signal from neutrinos produced by terrestrial processes), and the IceCube team concluded that these neutrinos must be originating from beyond the Solar System, in distant cosmic sources. High-energy neutrino astronomy had begun.

Subsequent IceCube searches found tens of additional energetic neutrinos, many of which also likely originate from cosmic sources. Because their distribution across the sky appears to be isotropic, without strongly correlating with the galactic plane, the sources must be of predominantly extragalactic origin—a first essential piece of information in the puzzle of their source.

Some potential neutrino source types will be easier to identify than others. If the observed neutrinos originate from a few bright sources, this will produce a clearer directional overlap; because the neutrinos are 'divided' between fewer sources, their identification will be straightforward. We can quantify this in terms of the density and luminosity of the source populations. Multiplying the luminosity per source by source density $L \cdot \rho$, we obtain the total emission per volume. This value can be estimated from the diffuse flux of neutrinos observed by IceCube. Similar to the solution of Olbert's paradox, one integrates the contributions of all the sources in the Universe, i.e. in a Euclidean universe without source evolution one obtains a flux per steradian of $\phi_{\text{diffuse}} = L \cdot \rho \cdot R_{\text{H}}/4\pi$, with a Hubble radius $R_{\text{H}} \approx 4000$ Mpc. For a

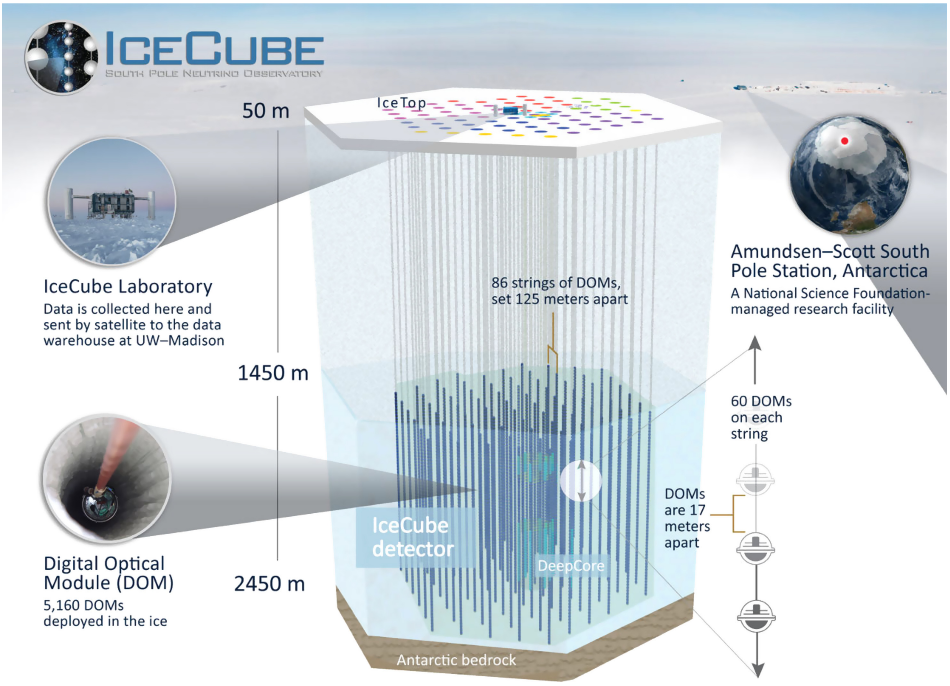


**Figure 5.** The IceCube Neutrino Observatory at the geographical South Pole. Credit: IceCube.

distance scale to the nearest source $d = (4\pi\rho)^{-1/3}$, along with the power density constraint $L \cdot \rho \sim 10^{36} \frac{\mathrm{J}}{\mathrm{Mpc}^3\,\mathrm{yr}}$ from the diffuse neutrino flux, one can estimate the neutrino (point source) flux of the nearest object within a population $\phi_{\mathrm{ps}} = L/d^2 \propto \rho^{-1/3}$. The expected flux increases with decreasing source density and the fact that point source searches, including the search for transient sources, have only resulted in upper limits, allows us to place constraints on possible populations and their associated source density. As a result, the nearest source of the population is expected to be within a distance of 100 Mpc. This already excludes many of the rare object classes.

Besides such general constraints, one can perform correlation studies between the direction of the neutrinos and known astrophysical sources to improve the sensitivity further. For instance, a search for neutrino emission from the direction of blazars—a subclass of active galactic nuclei where the jet points towards Earth—observed by the Fermi gamma-ray satellite has not led to a signal.

Another important factor is the duration of neutrino emission. The above examples are sources that emit neutrinos continuously, making the neutrinos' time of arrival irrelevant. Short-duration sources, on the other hand, are easier to identify, as overlaps in both direction and time can be used. Gamma-ray bursts, which typically last for only a few seconds, are an example of such sources.

IceCube is carrying out searches for all these source types, so far with no clear association. In fact, the source types that would be easier to pinpoint are also easier to rule out. Accordingly, gamma-ray bursts and blazars have already been ruled out by IceCube as the primary source of the observed astrophysical neutrinos. Of course, this does not mean that we should stop looking at these sources. Even if they are not responsible for the majority of astrophysical neutrinos, detecting even a few from them could be illuminating in our understanding of their inner mechanisms.

Identifying the primary source of the observed cosmic neutrinos will likely require multimessenger observations (see below). But advances in neutrino searches and detectors will also be critical. To continue improving IceCube's sensitivity, the collaboration is (i) developing advanced search algorithms; (ii) working on understanding the detector itself better, for example regarding the properties of the ice that surrounds the detector, as well as the properties of the atmospheric neutrinos and charged particles that represent the background in neutrino searches; (iii) adopting more accurate astrophysical models for neutrino production, which help to narrow down the searches to the most promising directions. This allows IceCube to filter out some of the neutrinos originating in the atmosphere, reducing the background.

## 3.3 Connecting the messengers—combined observations and interpretation

Perhaps the most surprising finding connected to the discovery of cosmic neutrinos is the fact that the corresponding power density (see section 3.2) injected in neutrinos matches those of the highest-energy cosmic rays, as well as the extra-galactic gamma rays (above a few GeV). This implies that the sources could very well be connected, representing a truly formidable cosmic puzzle.

It is clear that if we want to learn as much as we can about cosmic objects and events, we need to combine all of the information channels—all of the cosmic messengers—at our disposal. Light, gravitational waves, neutrinos and gamma rays inform us about different aspects and regions of cosmic events. In addition, using more messengers improves the search sensitivity and our confidence in detections, broadening our observational horizon.

Realizing the importance of multimessenger observations, the astronomy community is undertaking a large-scale project to coordinate multimessenger efforts. There are a number of scientific, technical and other challenges, but some collaborations are already proving highly successful.

Short-lived so-called *transient* cosmic events—mergers of black holes or neutron stars, supernovae, gamma-ray bursts, and many more—present special observational challenges. As most observatories are only able to see a small part of the sky at once, they need to be warned that something interesting is happening in some particular direction. They respond with a so-called *target-of-opportunity* observation. Warnings typically come from detectors that can see, or hear, the whole sky at once. These include gravitational-wave, neutrino and gamma-ray observatories, all of which have important roles in triggering *follow-up* observations by others.

### *3.3.1 Gravitational wave follow-up searches*

The gravitational-wave detectors LIGO and Virgo have developed close collaborations with a wide range of observatories. Over 80 instruments are involved, representing the full electromagnetic range, as well as thermal and high-energy neutrinos. Input from several of these observatories is used as an external trigger to initiate searches for gravitational-wave signals, while gravitational-wave signal candidates are used to trigger follow-up observations.

The task of finding the electromagnetic counterpart of a gravitational-wave signal is complicated by the fact that the direction of origin of gravitational waves is poorly reconstructed, with typical uncertainties of tens to hundreds of square degrees. This is significantly greater than the sky area most telescopes can observe at once. In order to find photons from gravitational-wave sources, telescopes need to scan through a large patch of the sky. This requires significant commitment of telescope time, and can take so long that an electromagnetic emission may have faded by the time the telescope turns in the right direction.

The amount of time available for searches in the wake of a gravitational wave signal is instructive. Take, for example, the merger of two neutron stars, the most anticipated candidate for electromagnetic follow-up observations. The highest-energy emissions, gamma rays and neutrinos, are typically emitted for about a second; this time frame is extremely short, but not critical, as gamma-ray satellites are essentially observing most of the sky at all times. At lower energies, the x-ray and optical afterglow emission may last for hours. This is a challenging time frame for scanning significant patches of the sky, particularly with x-ray satellites that currently have small fields of view (for example, the X-Ray Telescope on the Swift satellite has about a 0.1 square degree field of view). Another challenge with gamma-ray and afterglow emission is that it is *beamed*—it originates from relativistic jets, so it is only emitted in a relatively narrow direction. Thus, we will only be able to detect it if the emission points towards Earth, which will not be the case for most mergers. A later optical emission, a kilonova, has the benefit of being emitted in essentially all directions. It will last for about a week, giving observatories sufficient time to survey the sky for it. On the other hand, kilonova emission is likely weak, and will only be observable by the largest telescopes. The longest emission will be the one at the lowest energies. In the radio band, radiation will last for years, providing ample time for follow-up observations, albeit of signals that are expected to be weak.

LIGO's follow-up observatory network has already been put to the test after the first discovery of gravitational waves in 2015. After LIGO recorded a signal, it sent its electromagnetic and neutrino partners a warning, which included the time and sky location of the event. A large number of telescopes scanned through the sky, searching for a counterpart. As the signal was coming from two merging black holes, it was less likely that the source emitted anything besides gravitational waves, and accordingly most follow-up observatories came back empty-handed. The Fermi satellite, however, detected a weak burst of gamma rays 0.4 seconds after the LIGO signal. The extragalactic origin of this signal is, however, currently debatable.

### *3.3.2 Neutrino early warning*

Neutrino detectors, being able to observe the whole sky at all times, are also well suited to drive multimessenger observations. The importance of follow-up searches became evident early on in the wake of a supernova explosion near the Milky Way. In 1987, 12 neutrinos were reported from Supernova 1987A, which occurred in the Large Magellanic Cloud, 150 000 light years away from Earth. This was the closest such event since the construction of the first neutrino detectors. These neutrinos taught us a lot about the inner workings of these violent explosions. They also led to the assembly of the SuperNova Early Warning System (SNEWS). SNEWS quickly and automatically sends alerts to partner observatories in the event of neutrino detections by participating neutrino observatories, to warn them that a nearby supernova has occurred and give them time to prepare to observe it from early on, when emission is still stronger. Neutrinos leave the collapsing star hours before the explosion reaches the star's surface and become visible, making early warning particularly helpful.

On the high-energy front, in 2016 IceCube began to send public alerts for every registered high-energy neutrino that has a high chance (50%) of being of cosmic origin. The typical angular error associated with these events is one degree, which makes the search for electromagnetic counterparts feasible. The network of follow-up telescopes includes x-ray-observing satellites as well as ground-based telescopes. Furthermore, follow-up searches are triggered for neutrino multiplets (two or more neutrinos clustered in time and direction). If the sources of high energy emission are transient or variable, i.e. supernovae or variably-emitting galactic centres (active galactic nuclei or AGN), these methods provide a direct route to their identification.

### *3.3.3 More than two messengers*

The concept of early warning can be further expanded to include interesting events other than supernovae, and to include all cosmic messengers. Additionally, one does need to to be certain that something interesting happened. Hints of an event may be enough to initiate a search over multiple messengers, and the results of these searches could, together, be enough to unquestionably establish the occurrence of a cosmic event. The idea of multimessenger searches for so-called *sub-threshold events*—below the detection threshold when considering only an individual messenger—led to the inauguration of the Astrophysical Multimessenger Observatory Network (AMON). AMON aims to facilitate the sharing of information collected through all cosmic messengers, making it possible to dig deeper into the noise and carve out faint events that would otherwise go undetected. The network will also be useful for alerting telescopes around the world if an interesting multimessenger signal is found, so that additional observations can be made in time.

A particularly interesting possibility would be for a combination of gravitational waves and high-energy neutrinos to trigger electromagnetic follow-up observations. Both detector types are sensitive over the whole sky, alleviating the burden of pointing them in the direction of a potential event. Since everything that is observed is recorded, one can also 'go back' in time, and, say, check to see if there was an interesting, but faint, gravitational wave signal before an observed neutrino. Furthermore, if both neutrinos and gravitational waves are observed in coincidence, the joint signal will have the pointing precision of neutrinos, which is potentially hundreds of times more accurate than it is for gravitational waves. Hence, neutrinos can be a useful gateway for locating the electromagnetic counterparts of gravitational-wave signals.

## 4 Outlook

Identifying multimessenger sources is a substantial challenge. Poor source localization by gravitational-wave detectors and the often short available time window for follow-up observations requires a new level of cooperation between new and old forms of astronomy. The past few years have seen a transformation the speed and breadth of the data sharing that underpins efficient multimessenger strategies, with remarkable success. Cooperative ventures such as LIGO–Virgo's and IceCube's electromagnetic follow-up program, gamma-ray burst circulars, the Supernova Early Warning System and the Astrophysical Multimessenger Observatory Network have created an integrated network of observatories that can react rapidly to discoveries, or even hints, of exciting cosmic events.

The next decade will see the proliferation of multimessenger observations, as well as the construction and upgrade of large-scale instruments that will broaden the means and targets of follow-up observations. LIGO, Virgo and other gravitational-wave detectors will increase their sensitivity by enhancing the current instruments and possibly by developing and integrating new technology. The construction of new generation of Earth-based gravitational wave instruments (LIGO Cosmic Explorer and the Einstein Telescope), or the first space-based gravitational-wave observatory (eLISA) may begin. The IceCube neutrino detector is planning a major upgrade that will increase its instrumented volume, and sensitivity, ten-fold. A large-scale neutrino observatory, called KM3NeT, is currently being built in the Mediterranean sea, complementing IceCube's sensitivity in the other hemisphere. Optical astronomy will be boosted in the early 2020s by the Large Synoptic Survey Telescope and other wide-field as well as extremely large instruments that will provide regular updates on the state of the Universe, and on extreme events, at unprecedented depths. Radio observation capabilities will be magnified fifty-fold by the Square Kilometer Array, which is currently under construction in Australia and South Africa. We will also expand the observable horizon for the highest-energy photons with the Cherenkov Telescope Array.

The unprecedented expansion of observational capacity and enhanced cooperation between collaborations and instruments will surely bring about exciting discoveries. We can expect an early proliferation of the number and type of observable events, while at later stages the available large number of discoveries will enable deeper, detailed explorations of these phenomena.

## 5 Conclusion

Multimessenger observations are an emerging branch of astronomy, poised to disrupt our understanding of the most energetic cosmic events, the evolution of the Universe and possibly some of the fundamental laws of physics.

Two new cosmic messengers—gravitational waves and neutrinos—have recently come within observational reach, opening new avenues for studying the depths of distant events. Our detectors' sensitivity to these new messengers, as well as to electromagnetic emission, is expected to expand rapidly in the next decade.

Observational efforts will be coordinated between a large number of telescopes to enable effective and timely observations. Beyond rapid information exchange, this will require extensive theoretical understanding and prioritization to focus scarce resources in the right direction.

Multimessenger astronomy is a pioneering field in which even some basic questions have not yet been answered. This is mostly uncharted territory, with ample opportunities for newcomers and students.

## Suggested literature

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