Shaping a Multi-Messenger Universe: Historical and Epistemological Perspectives on the Changing Skyscape of astronomical Observation

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# Shaping a Multi-Messenger Universe

## *Historical and Epistemological Perspectives on the Changing Skyscape of Astronomical Observation*

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▼ **ABSTRACT** Multi-messenger astronomy has recently emerged and gained prominence in the scientific literature as a novel form of big science, characterized by organizational structures and epistemic practices that distinguish it from traditional large-scale endeavors. Despite scientists' recognition of the profound conceptual and social reconfiguration accompanying its rise, no in-depth historical analysis has yet been undertaken. The present special issue addresses this gap by offering the first historical exploration of the field's emergence. In the introduction, we examine the challenges of tracing the complex historical and conceptual relationships between multi-messenger astronomy and the diverse scientific domains now encompassed within it—especially astroparticle physics, multi-wavelength astronomy, gravitational-wave astronomy and neutrino astronomy—and of delimiting both the temporal span and the disciplinary contours of what should be included in its history. Underlying these efforts is the persistent ambiguity of the term "multi-messenger astronomy," which remains contested among practitioners. To navigate these complexities, we discuss how historical analyses lead to regarding

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multi-messenger astronomy not merely as a sum of disparate astrophysical methods but as a novel integrative paradigm with its own internal logic and collaborative practices. Our review of practitioner narratives further reveals at least three distinct perceptions of the epistemic cultures that shaped the field's rise: those who emphasize the role of real-time alert systems, those who stress the continuity of individual messenger disciplines, and those who highlight proto-multi-messenger episodes and near-misses. Finally, we introduce the contributions to this special issue, highlighting how these essays illuminate the interpretative and epistemological dimensions that compel us to revisit foundational debates about the field's defining characteristics and the interplay of diverse research traditions—inviting an interdisciplinary dialogue among historians, philosophers, and scientists on what truly constitutes multi-messenger science.

▾ **KEYWORDS** Multi-Messenger Astronomy, Astroparticle Physics, Multi-Wavelength Astronomy, Gravitational-Wave Astronomy, Neutrino Astronomy, History of Astrophysics

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## Introduction

Over the past two decades, a new branch of astronomy has increasingly come to be known as multi-messenger astronomy. Practitioners describe it as a research field that combines information carried by different types of so-called messengers, such as cosmic rays, neutrinos, and gravitational waves—all of which are generally associated with the most violent astrophysical phenomena—in addition to the main signals observed by traditional astronomy: photons in different parts of the electromagnetic spectrum, from radio waves to gamma rays.[1] One review even calls it a "new kind of big science" that is reshaping how astronomical observations are conducted. Compared to other kinds of big-science endeavors—such as large particle physics laboratories like CERN—the credited novelty of multi-messenger astronomy lies in features specific to astronomical research: while other big-science experiments are designed and planned with specific purposes to maximize information, the multi-instrument astronomical observation campaigns in multi-messenger astronomy are a fast-paced race to obtain the most out of the limited observation window. This involves using different types of independently operated instruments, located both in space and around the globe, that can perform complementary observations of transient events —phenomena characterized by extremely high energies, whose observable properties change on relatively short timescales, ranging from milliseconds up to months—within a very brief time after being alerted by an alert system. According to those

1 See, for example, Branchesi (2023).

stressing the novelty of the field, these features pose unique challenges in terms of global coordination.[2]

The emergence of what is considered a new "distinct discipline," providing insights from the complementary information of different cosmic signals, has sparked meta-scientific reflections and debates among physicists and astrophysicists.[3] These issues include: the reconfiguration of boundaries between different disciplines and the consequences that this has on their financial and political support; the need to define and redefine a shared language, mirroring the rapid evolution of research frontiers and their connected material cultures; and finally, the rapid geo-political reconfiguration of scientific collaborations, which also redefines local and global research policies and economies.[4]

As historians of science, we contend that these issues are best addressed by examining the broader historical processes that have shaped the field's emergence and evolution. Undoubtedly, this perspective must encompass the parallel rise and eventual fusion of several disciplines into today's multi-messenger astronomy. Multi-wavelength, neutrino astronomy, and gravitational-wave astronomy, alongside astroparticle physics, all emerged between the late 20th and early 21st centuries following different evolutionary processes. As these research areas were still consolidating, they were woven together into the larger multi-messenger enterprise.

The debates surrounding multi-messenger astronomy—when considered in relation to the historical trajectories of the different research traditions now combined under its umbrella—raise a host of under-explored historical and epistemological questions. What precisely counts as *multi-messenger astronomy*, and what are the implications of calling diverse physical signals *messengers*? How does it connect, both historically and conceptually, to astroparticle physics, multi-wavelength astronomy, relativistic astrophysics, and observational cosmology, and what novel features set it apart from these traditions? Which communities—astrophysicists, gravitational-wave researchers, particle physicists, or astroparticle physicists—first adopted the term multi-messenger astronomy, and to what ends? Do these groups understand the term differently? Moreover, was the field's emergence driven primarily by new social configurations among previously distinct communities, or did it involve a deeper epistemic shift, as many practitioners claim? Finally, what has the rise of multi-messenger astronomy implied for how scientists define and delimit the various branches of astronomical inquiry?

While there is no ambition to provide definitive answers to all these questions, the articles in this special issue will address some of them to contextualize, within the evolving historical practices of astronomy throughout the 20th and the early 21st centuries, what practitioners have described as the disruptive emergence of a new field. More broadly, the special issue aims to foster discussion among science historians,

2 See, for example, "A New Kind of Big Science" (2020).
3 Mészáros, Fox, Hanna, & Murase (2019, p. 585).
4 See, for example, Addazi et al. (2022); Fryer (2024); Harwit (2021); *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* (2023).

philosophers, and active scientists, creating a venue for elucidating some historical and foundational bases of multi-messenger astronomy. This initiative follows some considerations for improving connections between historical and scientific research, as recently put forward by Kostas Gavroglu.[5] In this introduction, we provide some context for the articles in the special issue by discussing the main issues related to the definition of the field, its historical roots, and the historiographical debate. We conclude by situating the arguments of the articles within this broader context.

## The Emergence of a New Research Field? A Preliminary Look from Scientific Publications and Archival Documents

On February 11, 2016, the LIGO and Virgo Scientific collaborations publicly announced the first detection of gravitational waves, 100 years after Albert Einstein published his initial (erroneous) calculation of wake-like solutions for the field equations of general relativity.[6] The detected signal originated from the merger of two black holes—a highly catastrophic event that is believed to be observable only through the emission of gravitational radiation. The Nobel Prize-winning achievement marked the beginning of a new branch of observational astronomy, called gravitational-wave astronomy.[7]

Eighteen months later, an unprecedented global effort resulted in the first joint detection of gravitational and electromagnetic radiation from a single source. On August 17, 2017, a network of observatories—including three gravitational-wave detectors (LIGO Hanford, LIGO Livingston, and Virgo) and two gamma-ray satellites (Fermi GBM and INTEGRAL)—achieved a historic milestone: the first simultaneous detection of a binary neutron star merger, designated GW170817.[8] This violent event—now known as a kilonova—had long been theorized but never previously observed. Alongside gravitational waves, the merger generated both a short gamma-ray burst (GRB) and a bright electromagnetic afterglow. This event triggered an unprecedented multi-messenger follow-up campaign involving around 70 observatories worldwide, spanning the entire electromagnetic spectrum—from radio waves to gamma rays—and continuing from days to months after the initial detection. By combining gravitational-wave signals with data spanning the entire electromagnetic spectrum, researchers were able to confirm the nature of the event. Notably, the kilonova event of August 2017 was the first gravitational-wave detection to be corroborated independently by non-gravitational means. The multi-channel observation of GW170817 is widely regarded as the defining moment when multi-messenger astronomy evolved from a promising concept into an established, routine investigative practice.[9]

5 Gavroglu (2022).
6 For a long-term historical reconstruction, see Blum, Lalli, & Renn (2018) and references therein.
7 Bailes et al. (2021).
8 Abbott et al. (2017).
9 See, for example, Margutti & Chornock (2020).

In the years following these groundbreaking discoveries, multi-messenger astronomy has substantially grown within the scientific community and has become more coordinated on a global scale. This growth is exemplified by the establishment of a global network of real-time multi-messenger alerts by the late 2010s and of resources such as a Gravitational-Wave Candidate Event Database (GraceDB), the latter providing a location where information about candidate gravitational-wave events can be retrieved, and giving access to an open database that collects and makes available gravitational-wave data products.[10] These tools have complemented the unprecedented global network of heterogeneous instruments required to extract information from multi-messenger transient events.

Remarkably, the term multi-messenger began to surface in the astrophysical literature nearly 20 years before the first direct gravitational-wave detection in 2016. This early appearance suggests that some researchers were already anticipating a future in which technological advances would permit a coordinated, multi-signal view of transient phenomena.[11] Tracing the term's origins thus goes beyond mere semantics: it opens a window onto how new scientific fields take shape, how traditions of continuity and moments of rupture intertwine, and how institutional structures contribute to the construction of emerging disciplines.

The earliest occurrence of the term multi-messenger in the physics literature dates to 1997, in a theoretical paper discussing gauge-mediated theories.[12] In this context, messenger multiplets were introduced in Grand Unification models. This early use of the term suggests a possible connection between the multi-messenger idea and reductionist research agendas aimed at providing a unified theoretical description of physical phenomena.[13]

While the potential connection between the multi-messenger concept and the reductionist epistemology of scientific unity is intriguing, the increasingly frequent use of the expression *multi-messenger astronomy* in the scientific literature seems more directly linked to the growing practice of astronomical correlation.[14] The term multi-wave has been used since 2000 for transient events such as gamma-ray bursts—the most powerful known explosions in nature—when counterparts to gamma radiation were discovered in X-ray and optical to radio wavelengths.[15] It is likely no coincidence that the term multi-messenger began to appear in astronomy around this same period. The next usage of the term in the scientific literature indicates that it emerged as a desirable perspective in papers discussing high-energy neutrino programs, such as the Baikal Deep Underwater Neutrino Telescope and the Antarctic Muon and

10 Dorner, Mostafá, & Satalecka (2021).
11 For an analysis of the scientific literature, see Lalli, Bonolis, & La Rana (2025) in this volume.
12 Dimopoulos & Giudice (1997).
13 The program for the search of unity in physics has been explored by the research group Historical Epistemology of the Final Theory Program at the Max Planck Institute for the History of Science. For a philosophical introduction, see Cat (2024).
14 As discussed by DeVorkin (2025), in this volume.
15 Klose (2000).

Neutrino Detector Array (AMANDA), which were entering into operation "with the expectation of ushering in an era of multi-messenger astronomy."[16]

Throughout the first decade of the 21st century—nearly 10 years before gravitational waves were directly detected—the term multi-messenger gained traction. It became routinely used in documents of scientific committees, and workshops were dedicated to it. For instance, the Third Workshop on the Nature of Unidentified High-Energy Sources, titled "The Multi-Messenger Approach to High-Energy Gamma-Ray Sources," was held in Barcelona in 2006.[17] This further indicates that the event usually credited as the beginning of the scientific field—the binary neutron-star merger discovery—occurred after the field had been already identified and even described by some scientific communities.

This view is confirmed by a cursory look at unpublished documents of international institutions. Archival materials reveal that, in the early 2000s, multi-messenger astronomy was beginning to take shape at the organizational level, as international bodies sought to coordinate disparate fields concerned with transient astrophysical phenomena. A key player in this process was the International Union of Pure and Applied Physics (IUPAP). Founded in 1922 to foster international cooperation in physics, IUPAP's role evolved after World War II through the creation of specialized commissions and working groups that reflected the increasingly complex disciplinary landscape of physics.[18] IUPAP thus provided an appropriate institutional setting for early conversations about the nascent field of multi-messenger astronomy.

In 1998, IUPAP established the Particle and Nuclear Astrophysics and Gravitation International Committee (PaNAGIC) to support coordination in the emerging domains of particle astrophysics and gravitational-wave research in relation to cosmology. PaNAGIC comprised two sub-panels: the Gravitational Waves International Committee (GWIC) and the High Energy Neutrino Astrophysics Panel (HENAP). These panels convened leading researchers engaged in various projects, including interferometric gravitational-wave detectors and high-energy neutrino observatories.

PaNAGIC's formation followed a dedicated 1997 workshop in Taormina, Italy, convened under the Mega Science Forum of the Organisation for Economic Cooperation and Development (OECD) and led by Italian particle physicist Alessandro Bettini. That workshop emphasized the need for a global framework to coordinate such projects, particularly in light of growing competition between nationally funded efforts.[19] The institutional proposal that emerged was to fully integrate the international culture of astroparticle physics, the new discipline then being established at the intersection of particle physics, astrophysics, astronomy, relativity, and cosmology.

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16 Barwick (2001).

17 Paredes, Reimer, & Torres (2007). Interestingly, it followed a previous meeting called "Multiwavelength Approach to Unidentified Gamma-Ray Sources," held 2 years previously; see Cheng & Romero (2005).

18 For a historical analysis of IUPAP and its changing roles throughout the 20th century, see Lalli & Navarro (2024), especially Lalli (2024).

19 "OECD Megascience Forum: Workshop on a Deep-Sea Neutrino Observatory" (1997). We are very grateful to Alessandro Bettini for having shared documents from PaNAGIC, as well as his own recollections in the unpublished manuscript Bettini (2023).

Influential figures such as Barry Barish, then principal investigator of LIGO and chair of IUPAP's particle physics commission, further advanced the initiative.

Although the term multi-messenger was not yet in common use, discussions within the PaNAGIC steering committee made clear that the envisioned coordination would eventually encompass neutrino, gravitational-wave, gamma-ray, and cosmic-ray observations. PaNAGIC's founding charter, approved in 1999, defined four scientific domains: non-accelerator studies of fundamental particles, astrophysical acceleration mechanisms, nuclear and particle processes in the universe, and gravitational-wave sources.[20] From its inception, the committee explicitly aimed to extend the logic of multi-wavelength astronomy into what would become multi-messenger astronomy. At its first meeting, French astrophysicist Isabelle Grenier explicitly stressed the need for a unified approach across messengers, while Barish framed GWIC's participation as a step toward full integration of gravitational-wave research into this broader observational regime.[21] PaNAGIC thus served as both a conceptual roadmap and an institutional vehicle for transforming scattered, domain-specific initiatives into a coordinated international field.

In the early 2000s, when scientific publications using the term multi-messenger were very rare, many of its earliest uses appeared in connection with PaNAGIC members and their projects. This suggests that multi-messenger astronomy's emergence as a field with a shared identity, long-term strategy, and institutional presence was initially sparked by such institutionalized international coordination. The 2011 reconstitution of PaNAGIC into the Astroparticle Physics International Committee (ApPIC), with multi-messenger astronomy at its core, affirms this trajectory.

To this point, we have presented a historical trajectory of multi-messenger astronomy describing the explicit use of the term to frame a set of practices. However, focusing on the term alone might set problematic limits on a historical research field as it may overlook similar practices that scientists had not (yet) identified under the same label. A compelling example is the detection of a handful of neutrinos emitted by Supernova 1987A (SN1987A), an extragalactic source in the Large Magellanic Cloud.[22] On February 23, 1987, three underground neutrino detectors—Kamiokande II in Japan, Irvine–Michigan–Brookhaven (IMB) in the United States, and Baksan in the Soviet Union—recorded a burst of neutrinos. Hours later, dozens of ground-based telescopes captured optical light curves, the International Ultraviolet Explorer (IUE) recorded ultraviolet spectra, Ginga logged X-rays, and the Australia Telescope Compact Array (ATCA) monitored evolving radio emission. Although not planned to work as a multi-detector network for supernova survey, the electromagnetic observatories and neutrino facilities were able to take advantage of their complementary observations ex post facto and to correlate data, providing unprecedented breakthroughs in supernova physics. Astrophysical signals were finally substantiating the computer simulations that had been developing since the second half of the

20 IUPAP (1998).
21 Minutes of the PaNAGIC 1st Meeting, Atlanta (1999, Mar. 27–28), PaNAGIC Collection.
22 Hirata et al. (1987).

1960s, modeling the core collapse of supernovae and highlighting the role played by neutrinos.[23] Even though the era's cryogenic bar antennas for gravitational-wave detection were not recording data during the supernova event, SN1987A represented the first extragalactic phenomenon observed by two different types of messengers—photons and neutrino particles. Therefore, it might be contended, as some do, that the SN1987A event was not only the start of neutrino astronomy but also the first multi-messenger observation, even though the term multi-messenger did not appear until many years later.[24] Historical analysis is necessary, however, to understand whether and how the practices of the current field named multi-messenger astronomy are related to this early attempt to combine observations of different kinds of signals, as we discuss in detail in one of our contributions to the special issue.[25]

This outline highlights the complexities involved in interpreting the historical roots of the field, challenging the conventional definition of multi-messenger astronomy in the scientific literature. By focusing on contexts and practices rather than scientific self-descriptions, we may uncover a completely different historical narrative of what constitutes multi-messenger astronomy. The issue is further complicated when considering the various ways scientists have attempted to define the field.

## What is Multi-Messenger Astronomy? A Problem of Definition

Even if one limits the analysis to the field actually defined by scientists as multi-messenger astronomy, the meaning and implications of this term remain unclear. Interestingly, the first paper and report mentioning *multi-messenger* in the current sense—thus referring to different signal carriers "so to take advantage of the complementary information they carry from astronomical sources"—do not introduce it as a new term, assuming it to be natural and self-explanatory.[26] In this emerging framework, the word *messenger* was first applied to the neutrino and subsequently extended to other kinds of carriers, by a compelling analogy, which is already a statement of intent: "Just as multi-wavelength studies have provided unparalleled insight on many astronomical sources, multimessenger studies by neutrino, gamma ray, and gravity wave detectors may be the Rosetta stone of cosmic accelerators."[27]

Those who explicitly defined the term at a later stage gave a spectrum of definitions that hardly convey a unique meaning. Some regard multi-messenger astronomy as the field that connects information related to all the fundamental forces of nature: the gravitational, electromagnetic, and weak and strong nuclear forces.[28] This definition aligns with the term's early use in relation to grand unification theories, identifying multi-messenger astronomy as a tool to explore the fundamental unity

23 A brief account of these early computational studies is given in Ruffini & Wheeler (1971).
24 Branchesi (2023); Li, Beacom, Roberts, & Capozzi (2024); G. P. Smith et al. (2025).
25 La Rana, Bonolis, & Lalli (2025).
26 Cerdonio (2000); *Astronomy and Astrophysics in the New Millennium: Panel Reports* (2001, p. 258).
27 Barwick (2001).
28 Bartos & Kowalski (2017).

of nature. Others, however, appear to focus more specifically on the objects of investigation, such as extreme, violent, dense, and energy-rich phenomena. These phenomena can only be properly understood by combining different sources of information, each produced by specific processes at their origin, pointing to the issues of limited information.[29] Therefore, multi-messenger astronomy might be interpreted as a succinct way of describing the field of astronomy that involves capturing all possible signals from the cosmos (different types of radiation and particles) and interpreting them to form a comprehensive, integrated understanding of the universe. Other descriptions of the field tend to emphasize the high level of coordination on a global scale required to pursue this kind of investigation, identifying multi-messenger astronomy with the real-time coincidence searches of transient events and the alert systems that affect astronomical practices.[30]

Given the various perspectives and nuances associated with the definition of multi-messenger astronomy in the scientific literature, it is detrimental to settle on a single definition for the context of this special issue. Instead, we aim to highlight the potential richness for historical research of preserving and exploring the multiple perspectives that have emerged in connection with multi-messenger astronomy.

The problem of definition relates to a deeper conceptual issue, which is the implications of the term for its connection with the individual messengers that compose the multi-messenger spectrum, both in terms of practices and concepts. In this sense, it is important to note that multi-messenger astronomy cannot be understood simply as the sum of single-messenger astronomies. In fact, it is scarcely possible to speak of single-messenger astronomy at all, even before the term multi-messenger was established and became common currency in the astronomical community. The electromagnetic spectrum alone requires various types of telescopes to observe different wavelengths, some of which can only be detected from outside the Earth's atmosphere (such as extreme ultraviolet, X-rays, and gamma rays). Additionally, effective neutrino astronomy would be impossible without detecting the electromagnetic counterparts necessary for correlation analysis, implying that neutrino astronomy belongs inherently to a multi-messenger perspective.

Multi-wavelength astronomy already offered the same big-picture potential. The unique characteristics of each energy band provide complementary information related to specific scientific and observational purposes. Comprehensive evaluation of the resulting data reveals a wealth of insights into the structure, nature, and history of the observed astrophysical system or object, and this in turn allow us to make further discoveries. Therefore, multi-wavelength astronomy involves a combined approach—one of the defining features of multi-messenger astronomy.

However, multi-messenger astronomy should not be understood merely as a straightforward extension of multi-wavelength astronomy, but rather as a qualitatively different approach that incorporates messengers beyond photons to investigate astrophysical phenomena. As we argue more extensively in one of our contributions to this

29 Branchesi (2023); Burns et al. (2020).
30 M. W. E. Smith et al. (2013); Mészáros et al. (2019).

special issue, the term multi-messenger—which emerged specifically in the context of transient events—goes conceptually beyond the multi-wavelength mapping of the sky across the entire spectrum.[31] Even if the expression multi-messenger astronomy is still looking for its own definition, articles in this special issue confirm that the term indeed represents a novel discipline that is more, both scientifically and semantically, than merely the sum of different astrophysical inquiry methods.

## The (Lack of) Historiography of Multi-Messenger Astronomy

Because multi-messenger astronomy—and the term itself—has only emerged in the past two decades, it is unsurprising that no historical studies have yet been undertaken, either by professional historians or by practitioners. What does exist appears in scientific publications, where authors underline the field's novelty and make some statements on its developmental trajectory. These brief practitioners' accounts offer only cursory remarks on how multi-messenger astronomy intersects with other evolving practices in astronomy and astrophysics. Although they avoid historical analysis, these accounts reveal how researchers themselves frame the field's emergence and negotiate the balance between continuity and discontinuity in astronomical and astrophysical practices.

Practitioners often point to the global, real-time alert infrastructure as a defining innovation of multi-messenger astronomy. This system grew out of traditions of rapid information sharing for high-energy transient events and is essential for triggering follow-up observations of other messengers once a first signal appears. According to some reconstructions, it evolved from protocols developed in the early 1990s when very-high-energy gamma-ray burst observatories—designed to be lightweight so they could slew rapidly—relied on precise sky coordinates to capture fleeting bursts. The first alert system to be created in the multi-wavelength astronomy framework was the Gamma-Ray Coordinates Network (GCN), a NASA-led service that from 1992 broadcast gamma-ray burst positions to observatories worldwide within seconds, enabling optical, X-ray, and radio telescopes to target the exact location almost immediately. The extension of this practice to other kinds of signals, in a more proper multi-messenger perspective, occurred in 2013 in relation to neutrino observations with the establishment of the Astrophysical Multimessenger Observatory Network (AMON), which aggregates subthreshold triggers from instruments such as AMANDA (the early under-ice neutrino telescope operational from 1997 to 2009) and its successor IceCube (the cubic-kilometer neutrino array at the South Pole).[32] From this perspective, many researchers view multi-messenger astronomy not as an abrupt revolution but as the natural—and long-anticipated—culmination of iterative technical advances, with rapid GRB follow-up campaigns laying the groundwork for a unified, responsive observatory network.

31 La Rana, Bonolis, & Lalli (2025).
32 M. W. E. Smith et al. (2013); Mészáros et al. (2019).

Other narratives see instead the roots of multi-messenger astronomy in the progressive understanding of the variety of signals coming from space. They often begin with two 1960s breakthroughs: the Vela satellites' serendipitous discovery of extraterrestrial gamma rays—originally intended to monitor Soviet nuclear tests—and Raymond Davis's detection of solar neutrinos in the Homestake mine, which revealed particles so weakly interacting that they demanded novel detection strategies.[33] In these accounts, two themes stand out. First, each new messenger delivers "valuable, but epistemically limited" information about its source, underscoring the incompleteness of single-signal observations.[34] Second, the landmark 2016 detection of gravitational waves served as a catalyst: it instantly prompted practitioners to overlay electromagnetic follow-ups, thereby inaugurating a fully integrated multi-messenger approach, which was epitomized by the combined study of neutron-star mergers in 2017.

Another strand of practitioner lore emphasizes proto-multi-messenger episodes and near-misses. Commenting on the "remarkable success" of the 2017 discovery, solar astrophysicists emphasized that, amid the excitement, it had been overlooked that the Sun is a source of various messengers, as had been understood since the 18th century. Furthermore, they stressed that the link between ultraviolet radiation and the arrival of cosmic rays, as identified by Scott Forbush in the 1940s, is a prime example of "multi-messenger information," a concept that has long been standard in solar and heliospheric physics.[35] However, the most celebrated example remains Supernova 1987A discussed above, which is sometimes described as heralding "the first multi-messenger observations."[36]

Astronomer Martin Harwit highlights a different dimension of innovation in multi-messenger science—one rooted not in epistemology but in the economics of knowledge production. He points out that, traditionally, each research domain concentrating on a single messenger has built its own specialized toolkit to sample the three fundamental "phase-space" dimensions—spatial, spectral, and temporal—across both low and high resolutions. By contrast, a multi-messenger strategy can economize on resources by assigning each messenger the role at which it excels: for instance, using radio and optical telescopes to observe specific spatial details, X-rays to study high-energy phenomena and environments, neutrinos to probe dense astrophysical matter, and gravitational waves to investigate the dynamics of extremely massive objects. However, Harwit also cautions that this efficiency may come at an epistemic cost: overly compartmentalizing each messenger risks obscuring unexpected correlations and serendipitous discoveries that emerge when signals are explored more holistically.[37]

These varied practitioner narratives—whether focused on alert systems, successive discovery-driven expansions, or proto-multi-messenger experiments—still leave

33 Klebesadel, Strong, & Olson (1973); Bahcall & Davis (2000).
34 Abelson (2022).
35 Hudson & Svalgaard (2019, p. 10).
36 Branchesi (2023); Li et al. (2024); G. P. Smith et al. (2025).
37 Harwit (2021, pp. 240–241).

many of our historical questions unresolved. They also raise other methodological challenges. Chief among these is how exactly to define and delimit the history of multi-messenger astronomy when its roots clearly extend to practices that long predate the term itself. Moreover, although most accounts portray the 2017 multi-messenger discovery of a neutron-star merger as the culmination of a well-prepared field, few interrogate the foundations of that anticipation—particularly how much it rested on confidence that Advanced LIGO and Advanced Virgo, after their 2010s upgrades, would finally detect gravitational waves. As a result, the precise relationship between hopes for a multi-messenger era and expectations for direct wave detection remains poorly understood.

More general histories of 20th-century astrophysics seldom mention multi-messenger astronomy, yet several of the different research dominions now merged within this framework—multi-wavelength astronomy, astroparticle physics, and gravitational-wave astronomy—have attracted some historical attention. Multi-wavelength astronomy involves coordinating observations across the entire electromagnetic spectrum, from radio and infrared through ultraviolet, X-rays, and gamma rays. While it is sometime represented as an extension of traditional optical techniques, historical accounts have shown that this expansion was driven not merely by new telescopes, but by the integration of advances in modern physics—detector technology, imaging methods, and theoretical models—that fundamentally reshaped observational practice and the interpretation of stellar and extragalactic phenomena.[38]

Rare historical accounts of astroparticle physics appear chiefly in practitioners' reviews, which themselves emphasize the absence of a single textbook definition. In its broadest sense, astroparticle physics emerged from early cosmic-ray research and gradually incorporated additional signals—gamma rays, neutrinos, and even gravitational waves—alongside a variety of objects of study, experimental techniques, and theoretical frameworks. Although its roots extend back to century-old cosmic-ray investigations, the term *astroparticle physics* only coalesced in the late 1980s. According to historical narratives, this shift reflected growing intersections between cosmology and particle physics and was spurred in part by social and economic pressures—most notably the scaling back of major accelerator projects in the United States.[39] More recent historical analyses underscore that the harbingers of such developments can be traced back to the 1950s and the 1960s. During this period, astronomy expanded to encompass the entire electromagnetic spectrum, and non-photonic messengers were included among the range of potential cosmic signals for studying the universe. This favored cross-fertilization between different disciplinary cultures and communities.[40]

Gravitational-wave astronomy presents a historiographical paradox: it attracted detailed historical interest even before its formal launch with Advanced LIGO's first direct detection in September 2015 (jointly announced by the LIGO and

38 Longair (2006, p. xi).

39 Cirkel-Bartelt (2008); on the demise of the particle accelerator Superconducting Super Collider in the United States, see Riordan, Hoddeson, & Kolb (2018).

40 Bonolis & Furlan (2025); Furlan & Bonolis (2025).

Virgo Scientific Collaborations in February 2016). Its deep prehistory begins with Einstein's 1916 prediction of gravitational waves in the wake of general relativity, continues through decades of theoretical debate over their physical reality, and includes the controversies sparked by Joseph Weber's contentious 1969 claim of detection with resonant bar antennas, the results of which subsequent experiments failed to reproduce. These layered controversies—both conceptual and about experimentation—have prompted historians and sociologists to explore both the epistemic foundations and the social dynamics of gravitational-wave research over the 20th century.[41] Yet, despite this rich body of work and the pivotal role of gravitational-wave observations in sparking multi-messenger campaigns, no study explicitly examines how gravitational-wave astronomy was integrated into—or reshaped—the multi-messenger framework.

## Toward a History of Multi-Messenger Astronomy: The Articles in the Special Issue

Having outlined the key historiographical challenges, we now turn to the articles in this special issue and their contribution to addressing some of the questions mentioned in this introduction. To probe continuity versus discontinuity—and to question claims of novelty—David DeVorkin adopts a longue durée perspective. He shows that the core practice of correlating disparate signals dates back to the birth of astrophysics in the late 19th century, when the advent of spectroscopy inaugurated what he dubs the "great correlation era." From the outset, astronomers linked stellar spectra to other measurements—positions, motions, and brightness variations—to extract physical meaning. Over subsequent decades, each instrumental advance, from new detectors to innovative telescopes, expanded the perceptual frontier, but always through the same fundamental activity of correlation. DeVorkin traces how this practice was slowly standardized, culminating in the discovery in the 1930s of the velocity–distance relation for galaxies—a breakthrough that itself required extended negotiation among observers, theorists, and instrument builders. By foregrounding this deep history of correlation, he argues, we can see multi-messenger astronomy not as a rupture but as the latest chapter in a stable, evolving epistemic tradition.[42]

We squarely address the historical process related to the emergence of multi-messenger astronomy in a two-part study that employs a double methodology. In our first contribution, we focus on the long-term development of supernovae study, understood as epistemic laboratories that were instrumental in the later rise of multi-messenger practices. By applying a variety of epistemological approaches, we show that supernovae—the catastrophic and extraordinarily luminous explosions marking the death of massive stars—acted as boundary objects and trading zones for the merging of different research traditions in physics and astronomy, as well as challenging

41 Blum, Lalli, & Renn (2018); Kennefick (2007); Collins (2004; 2010; 2017); La Rana (2022).
42 DeVorkin (2025).

objects and borderline problems that required an interdisciplinary approach.[43] By employing this historico-epistemological approach we address the issue raised at the beginning of this introduction, namely whether and to what extent multi-messenger astronomy constitutes a novel form of scientific inquiry. Furthermore, while we acknowledge that in recent narratives Supernova 1987A is retrospectively interpreted as the first multi-messenger observation, we argue that such a designation overlooks key features that characterize contemporary multi-messenger research.[44]

The second contribution of our two-part study employs, instead, quantitative tools to trace the social and thematic evolution of literature explicitly framed as multi-messenger astronomy in the 21st century. We generate and interpret charts based on co-authorship, co-citation, and word co-occurrence networks, supplemented by close readings of publications selected for their centrality. Our findings reinforce the idea that multi-messenger astronomy was long anticipated: although the term multi-messenger surged in use after the first gravitational-wave detection in 2016, it appeared and was routinely employed well before this event. We propose a three-phase periodization of this self-identified literature: an exploratory phase from the first use in 1997 to the first multi-institutional cooperation in 2008; an emergence phase from 2009 to 2015, during which the term was steadily employed in prospective discussions, especially in anticipation of gravitational waves from the newly upgraded Advanced LIGO and Virgo; and the consolidation phase sparked by the first direct detection of gravitational waves in 2016, which formally incorporated gravitational waves alongside photons (from radio to gamma rays), cosmic rays, and neutrinos into the multi-messenger framework. Our analysis highlights both the pivotal role of very-high-energy gamma-ray astronomy and astroparticle physics in the first two phases and the epistemic significance of trust in forthcoming gravitational-wave detections for building the infrastructure and conceptual foundations of the emergent field.[45]

Multi-messenger astronomy also foregrounds questions of cooperation and organizational form. As both DeVorkin's study and our articles show, integrating diverse practices and subcultures—developed over decades—became imperative in the early 21st century under the multi-messenger umbrella. Given its big-science character, this integration operates at the level of teams rather than individuals. In this special issue, Guzzardi adopts a social-epistemological approach to examine how such complex cooperation emerged historically. He argues that the field's cooperative ethos is driven chiefly by epistemic constraints—those constraints and opportunities intrinsic to combining different messengers—rather than by external social or material factors alone. To support this claim, Guzzardi delves into modelling processes in neutrino astronomy and its extension to other signals, focusing especially on the coordinated follow-up of Supernova 1987A, which some practitioners regard as a proto-example of the multi-messenger approach.[46]

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43 For the combination of concepts of trading zones and boundary objects, see Galison (1999); Sims (2023). For the concepts of challenging objects and borderline problems, see Renn (2008).

44 La Rana, Bonolis, & Lalli (2025).

45 Lalli, Bonolis, & La Rana (2025).

46 Guzzardi (2025).

Our scientometric analysis, confirming some of the practitioners' perspective, identifies the first direct gravitational-wave detection as a watershed that transformed multi-messenger astronomy from anticipation to realization. Yet this milestone also unsettles what counts as *direct observation* within astronomical practice, particularly in multi-messenger contexts. Skulberg and Elder, drawing on both the history and philosophy of physics, probe this question through a case study of supermassive-black-hole imaging campaigns. They demonstrate that members of the collaboration teams themselves held divergent notions of directness, with some emphasizing raw signal acquisition and minimal post-processing, and others pointing to the instrumental synthesis and algorithmic reconstruction required to produce an image. By comparing these competing interpretations to the concept of directness in LIGO's gravitational-wave detections, Skulberg and Elder show that the epistemic weight of *direct* hinges on the specific measurement techniques and the disciplinary norms of each observing community. This analysis underscores a central challenge in multi-messenger astronomy: the integration of different cultures that bring distinct—and sometimes conflicting—conceptions of what it means to observe directly.[47]

Together, these contributions provide the first historical reconstruction of multi-messenger astronomy's emergence and illuminate interpretative and epistemological dimensions that prompt us to revisit foundational debates about its constituent research domains and defining characteristics—thereby inviting a broad, interdisciplinary dialogue among historians, philosophers, and scientists on what truly constitutes multi-messenger science.

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47 Skulberg & Elder (2025).

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