The Emergence of Multi-Messenger Astronomy, Part II: A Socio-Epistemic Network Analysis of Scientific Literature, 1997–2023

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▾ **ABSTRACT** After exploring the role of supernova research—understood as epistemic laboratories—in the later emergence of multi-messenger astronomy in the first part, this second article of our two-part study examines the rise and consolidation of the research field in the 21st century. Although often heralded as a novel and transformative approach, multi-messenger astronomy has roots in the convergence of earlier practices such as multi-wavelength astronomy, astroparticle physics, and gravitational-wave detection, each with their own distinct and evolving scientific subcultures. The study explores how these traditions coalesced, analyzing the processes that linked subcommunities and the roles of institutional frameworks, scientific collaboration, and thematic integration in shaping the field.

The paper combines quantitative analysis of scientific literature with the close reading of strategically selected scientific publications. Network science tools are employed in an exploratory fashion to trace patterns of collaboration and the

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evolution of research topics. We argue that the scientific literature explicitly framing itself as multi-messenger astronomy can be divided into three periods. The exploratory phase (1997–2008) saw very few papers using the term, largely within nascent programs in very-high-energy gamma-ray astronomy and astroparticle physics. During the emergence phase (2009–2015), researchers pursued the conceptual and operational integration of astroparticle physics in anticipation of the advent of gravitational-wave astronomy, with gamma-ray studies emerging as a central connecting research field in the network. Finally, the consolidation phase (2016–2023) was sparked by the first direct detection of gravitational waves and saw the realization of the multi-messenger observational programs previously envisioned. Our analysis reveals, first, that astroparticle physics served as the cradle of the multi-messenger approach—initially integrating high-energy neutrinos, cosmic rays, and gamma rays, and later incorporating gravitational waves both conceptually and, following their detection, empirically into a unified framework. Second, we show that forward-looking imaginaries—particularly the anticipation of gravitational-wave discoveries—profoundly shaped research practices and priorities.

▾ **KEYWORDS** History of Astrophysics; Multi-Messenger Astronomy; Socio-Epistemic Networks; Historical Network Research; Big Science; Co-citation Analysis
▾ **ISSUE** Volume 67 (2025), issue 1

Introduction

The emergence of new scientific fields and sub-disciplines has long been a central concern in the history and sociology of science, serving as a testing ground for diverse theoretical frameworks since Thomas Kuhn's seminal *The Structure of Scientific Revolutions*.[1] In the field of science and technology studies, research on this topic has employed a wide range of methodologies and theoretical perspectives, often rooted in social constructivist assumptions.[2] At the heart of these studies lies a critical question: how do epistemic transformations intersect with social dynamics in the establishment of new scientific fields?[3] In recent years, quantitative approaches have introduced novel empirical tools to explore these processes, offering fresh insights into the interplay between field formation and social change.[4] We contribute to this

1 Kuhn (1970).
2 The literature is enormous. See, for example, Mullins (1972); Bourdieu (1975); Lemaine, Macleod, Mulkay, & Weingart (2012); Fligstein & McAdam (2012).
3 See, for example, Hackett, Parker, Vermeulen, & Fenders (2017).
4 See, for example, Bettencourt, Kaiser, Kaur, Castillo-Chávez, & Wojick (2008); Herrera, Roberts, & Gulbahce (2010); Raimbault & Joly (2021).

ongoing debate by examining the emergence and consolidation of multi-messenger astronomy.[5]

As discussed in the introduction to this special issue, the field of multi-messenger astronomy is a recent and transformative development in astrophysical science. While its precise definition and scope are still evolving, multi-messenger astronomy is often described as a groundbreaking approach to understanding high-energy cosmic phenomena through the integration of diverse observational methods.[6] In the scientific literature, the novelty of multi-messenger astronomy is often emphasized, but limited efforts have been made to explore its historical roots or to investigate how this supposedly groundbreaking field emerged in relation to earlier or contemporary traditions such as multi-wavelength astronomy, gravitational-wave astronomy, and astroparticle physics. How did multi-messenger astronomy coalesce from these research traditions, and how were links between subcommunities established? What were the roles of institutional frameworks, scientific collaboration, and thematic integration in shaping the field?

The formation of multi-messenger astronomy can be seen as part of a broader trend toward interdisciplinary collaboration in high-energy astrophysics. However, it is not clear to what extent its development reflects a top-down process, driven by institutional efforts to foster cooperation, or a bottom-up phenomenon, rooted in grassroots scientific practices. The interplay between these dynamics remains to be investigated. Similarly, the conceptual and epistemic integration of diverse messengers—gravitational waves, neutrinos, cosmic rays, and electromagnetic signals across the entire spectrum—raises questions about the mechanisms by which distinct scientific subcommunities began to align their research agendas.

In the first contribution of our two-part study, we adopted a historico-epistemological perspective to examine how supernovae functioned as epistemic laboratories that fostered hybridization between disciplinary communities and gave rise to long-term trading zones, where shared research practices gradually matured up to the late 1980s.[7] In this second paper, we employ quantitative tools to chart collaboration patterns and topic evolution in the multi-messenger astronomy literature from the late 1990s to the present. Leveraging network science approaches, we examine how collaborative structures and research themes intertwined to reveal the integration of formerly separate fields. To interpret and contextualize the patterns uncovered by our network analysis, we conduct close readings of publications identified as central based on the quantitative results.

The paper is structured as follows. First, we introduce the conceptual and methodological framework underlying the quantitative analysis of the scientific literature. Next, we describe the corpus of the multi-messenger literature used in the analysis, proposing a periodization of its development. We then present the results of

5 The terms "multi-messenger astronomy" and "multi-messenger astrophysics" are often used interchangeably. This paper consistently adopts "multi-messenger astronomy."

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

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

co-authorship and institutional collaboration analyses, highlighting the structural transformations in scientific cooperation on multi-messenger astronomy over time. The subsequent section discusses the epistemic dimensions of multi-messenger astronomy through co-occurrence and co-citation network analyses, tracing the evolution of key research topics and intellectual bases. In the conclusion, we integrate findings from the socio-institutional network analysis with insights from the textual and co-citation analysis, arguing that they allow for a coherent three-phase periodization of the emergence of multi-messenger astronomy.

The Conceptual and Methodological Framework

Our quantitative analysis of the multi-messenger scientific literature combines two distinct methods within the socio-epistemic networks approach developed by Jürgen Renn's department at the Max Planck Institute for the History of Science during the 2010s. This approach posits that the creation of a new scientific field is inherently linked to social reconfigurations, which can be investigated by examining changes in the topologies of scientific collaboration networks over time. This framework employs concepts and tools from multi-layered network science to jointly analyze three different dimensions of the production of scientific knowledge: the social (encompassing networks of relationships among individuals and institutions), the material (such as papers, instruments, and artifacts), and the semantic (for example, research topics, terminologies, and conceptual frameworks).[8]

The socio-epistemic network approach is particularly well-suited for the study of multi-messenger astronomy, as the field's development has been characterized by extensive interdisciplinary collaboration and is described as epistemically novel. To uncover these dynamics, the analysis employs two complementary layers of network analysis. The social dimension of multi-messenger astronomy is explored by focusing on networks of collaboration at both the author and institutional levels. Co-authorship networks map out the collaborative relationships among scientists whose names appear together in the lists of authors of publications within a selected corpus. This network elucidates patterns of collaboration, identifying clusters of researchers working on common projects and key figures bridging disparate groups.[9] Similarly, the institutional collaboration network, derived from the affiliations of co-authors, highlights the degree of interconnection between different research institutions over time.

The material and semantic dimensions are explored jointly through three methods. The evolution over time of the conceptual vocabulary of multi-messenger scientific literature was investigated by combining term frequency analysis and keyword co-occurrence networks. The term frequency analysis provides a macroscopic view

8 Renn, Wintergrün, Lalli, Laubichler, & Valleriani (2016). Some applications of this method can be found in Lalli, Howey, & Wintergrün (2020) and Zamani et al. (2020).

9 Newman (2001).

of the thematic evolution of the field. By calculating the proportion of documents in which specific terms appear within each period, we identify the dominant research topics and trace their prominence over time. Although a straightforward method, this approach allows us to observe how the relative importance of different cosmic signals, and related scientific areas, has shifted over time. Keyword co-occurrence networks offer an additional layer of insight by mapping relationships between terms that co-occur in the author-assigned keywords of each publication within a selected corpus.[10] These networks reveal clusters of interconnected concepts that can be interpreted as thematic research areas within multi-messenger astronomy. By examining the topology of these networks—such as the density of connections and the centrality of specific terms—we can uncover conceptual links that have facilitated the merging of diverse research traditions into a cohesive framework. Finally, the intellectual lineage of multi-messenger astronomy is traced through co-citation analysis. Co-citation analysis examines how often two works are cited together, revealing the intellectual connections that underpin a scientific field. By clustering co-cited works, we identify the intellectual bases of the frontier lines of inquiry found in the citing papers. A set of papers published in specific years have their intellectual bases defined through citation patterns. This method of scientometric analysis is particularly suitable in providing a historic dimension to the development of a scientific field identified in a corpus of scientific publications.[11]

Whatever their nature—be it institutional collaboration, co-authorship, co-occurrence, or co-citation—networks and their evolution can be studied using tools from network science. These tools are designed to investigate both the overall structure and the roles of specific elements, analyzing how the entities that compose the network (known as *nodes* in network terminology) are connected to one another via *edges*. To assess the significance of these networks, we focus on specific features, such as the growth and composition of the *largest connected component*—the largest subset of nodes that are all interconnected, forming the most extensive set of nodes where any node can be reached from any other within that component—and the division of these largest components into different sub-groups. Key tools to uncover social sub-groups in networks are algorithms designed to define clusters of nodes whose relationship with each other is stronger than that with other nodes belonging to other clusters. Following established scientometric practice, we selected the Louvain algorithm from the available options due to its efficiency, scalability, and strong performance in detecting meaningful community structures in large networks.[12] To identify key connecting elements between different sub-groups, we employed a centrality measure called *betweenness centrality*, which is designed to measure the role of a

10 In bibliometrics, keyword co-occurrence is a standard method to map scientific fields and their evolution. For a few examples and discussions, see Donthu, Kumar, Mukherjee, Pandey, & Lim (2021); Emich, Kumar, Lu, Norder, & Pandey (2020); Gao et al. (2024); van Eck & Waltman (2010).

11 Boyack & Klavans (2010).

12 Blondel, Guillaume, Lambiotte, & Lefebvre (2008).

node in connecting different parts of a network.[13] By analyzing these networks across the different periods identified in the corpus of multi-messenger scientific literature —as defined in the next section—we trace the evolving integration of collaboration and discourse in multi-messenger science, from the term's first appearance in the literature to the recent past.

The Database of Publications in Multi-Messenger Astronomy and Its Periodization

To investigate the emergence of multi-messenger astronomy as a distinct research field using quantitative tools, we constructed a database—hereafter referred to as the MM corpus—comprising all publications indexed in Web of Science (WoS) up to 2023 that mention the term "multi-messenger" or "multimessenger" at least once in their titles, abstracts, or keywords.[14] We then manually verified that each occurrence of "multi-messenger" referred to the astronomical or astrophysical context, and excluded publications from unrelated disciplines.[15]

This selection criterion implies that our analysis is confined to the scientific literature authored by researchers who explicitly frame their work within the multi-messenger research field. It does not extend to scientific literature that could retrospectively be linked to practices now encompassed by this field but were not labelled as such at the time. At different points in time, any practitioner tends to define their field by selectively including or excluding of literature that can rationally reconstruct its history.[16] Our approach in this paper deliberately focuses on the discursive formation of the field, tracing how researchers themselves constructed and signaled a shared identity of multi-messenger science. The underlying assumption is that the explicit use of the term "multi-messenger" is not merely a matter of terminology but reflects the process by which scientists identified and intentionally established a research field and a corresponding community during its unfolding.[17] As such, this article complements our first paper in this special issue, which addresses the historical development of broader epistemic practices related to multi-messenger research

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13 Betweenness centrality measures how often a node lies on the shortest paths between other nodes in a network. A high betweenness score indicates that the node plays a crucial role in linking different parts of the network, acting as a bridge or broker between sub-groups. The betweenness centrality measure is introduced in Freeman (1977).

14 To ensure that our database was complete for its intended purpose, we also tested alternative expressions, such as "multiple messengers." This check confirmed the soundness of our approach: the broader phrase yielded no additional relevant astronomy literature and instead returned results outside our scope.

15 We excluded publications in neuroscience that referred to multi-messenger neurons.

16 For a recent discussion of such practitioner-led reconstructions of the past, see the *Isis* Focus section "Viewpoint: Science's Imagined Pasts" in Issue 108(4), especially Wilson (2017) and Blum (2017).

17 This assumption is grounded in numerous examples from the history and sociology of science, which argue that the development of new terminology is intrinsically linked to the formation of new research fields. See, for example, Kuhn (1970); Latour & Bastide (1986); Kline (2015).

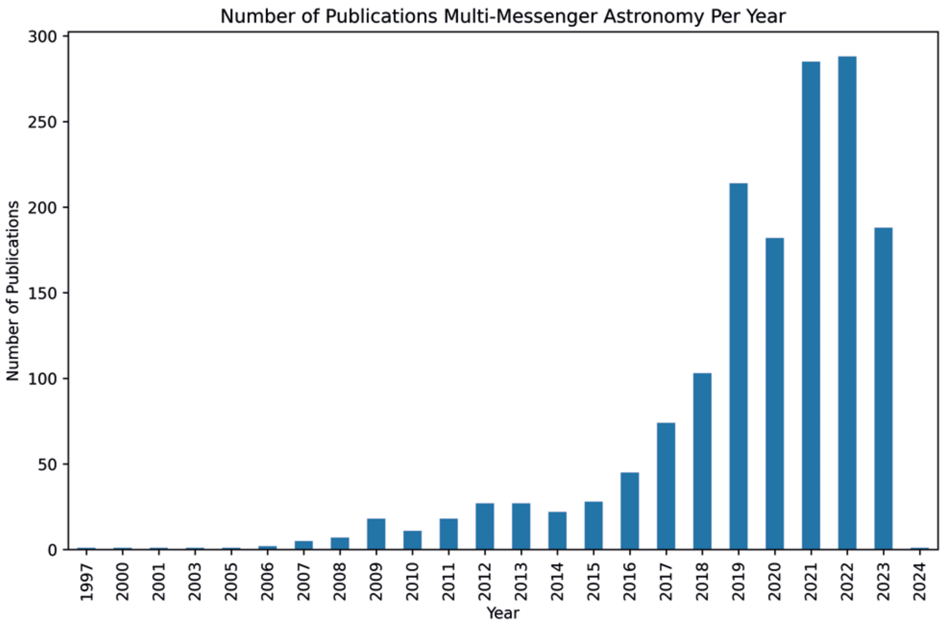

Figure 1. Yearly number of publications indexed in Web of Science that contain the term "multi-messenger" or "multimessenger" at least once in their titles, keywords, or abstracts, 1997–2023.

beyond explicit terminology, focusing on the long-term development of supernova research, especially on the role of Supernova 1987A.[18]

This approach yielded a dataset of 1,732 publications. According to the WoS classification scheme, which clusters publications into research areas based on citation relations, the large majority of these publications belong to the meso-topic category "Astrophysics & Astronomy," roughly one-quarter to "Particles & Fields," and just over 100 to "Nuclear Physics."[19] We then used Python scripts and regular expressions to transform the WoS-exported data and metadata into a spreadsheet containing, for each publication: year, authors, title, abstract, author-provided keywords, institutional affiliations, and the countries of those institutions. This spreadsheet served as the basis for both our socio-institutional network analysis and our term-frequency analysis.

The diagram in **Figure 1** illustrates the annual publication count of the MM corpus and suggests three successive phases in the explicit framing of multi-messenger astronomy. From 1997 to 2008 a small but steadily growing number of papers appeared. Between 2009 and 2015 the term "multi-messenger" was used continuously and with remarkable stability. Finally, from 2016 through 2023 the field experienced rapid expansion in output, a surge that coincided with the first announcement of

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

19 For the WoS classification scheme, see Waltman & van Eck (2012).

gravitational-wave detection in February 2016.[20] We propose to name these three stages the exploratory, emergence, and consolidation phases of multi-messenger astronomy literature, respectively.

In what follows, we apply network-science tools to explore both the socio-institutional makeup of the growing community of scholars explicitly engaged in multi-messenger studies and the epistemic dimension of their publications. We use our proposed periodization as a historical framework to identify and characterize with these tools the distinctive features of each phase.

The Socio-Institutional Networks of the Emergence of Multi-Messenger Astronomy

The Institutional Cooperation Network

To provide a general overview of institutional cooperation, we track, for each year from 1997 to 2023, both the total number of institutions represented in the MM corpus and the number of those institutions that belong to the largest connected component of the institutional cooperation network. This network is constructed annually by projecting co-authorship links onto the institutions of MM corpus authors. **Figure 2** highlights two key trends from 2007 onward: the rapid increase in institutions contributing to publications explicitly linked to multi-messenger astronomy (blue), and the growing connectivity among them over time, measured by the proportion of institutions within the largest connected component relative to the total number of institutions (green). Data before 2007 is less representative due to the limited number of publications in the MM corpus.

The three-phase periodization based on the annual publication counts is corroborated by the quantitative analysis of institutional participation. After 2015—coinciding with the first gravitational-wave detection in early 2016—the number of participating institutions surged. Crucially, this expansion took place within an already well-integrated network: by 2016, most institutions were already members of the largest connected component (green line in **Figure 2**). The consolidation phase is defined by the continued growth of this giant component, which absorbed nearly all new entrants from 2016 onward, as shown by the green line remaining around 95% throughout the period.

A detailed analysis of the institutional cooperation networks across the three phases reveals how such institutional collaborations in multi-messenger astronomy evolved over time. In the exploratory phase (1997–2008), the network was sparse, with most papers authored by single institutions and few instances of multi-institutional collaboration. A single, large connected component—comprising 14 different institutions—appeared only in 2008, and it originated not from a research

20 See also the introduction to this special issue, Bonolis, Lalli, & La Rana (2025). The discovery of gravitational waves was published in LIGO Scientific Collaboration & Virgo Collaboration (2016).

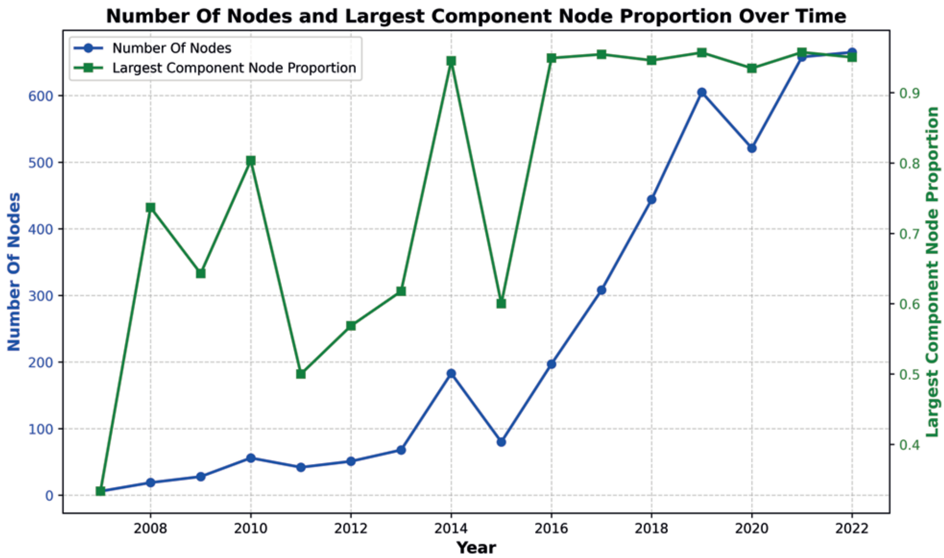

Figure 2. Number of nodes in the institutional collaboration network of multi-messenger astronomy, and proportion of nodes in the largest connected component over the total number of nodes per year, 2007–2023. The total number of nodes in the institutional collaboration network is shown in blue, while the proportion of nodes in the largest connected component is shown in green. Two distinct y-axes are used to represent these values.

paper but from a working-group report "on the status and future of very high energy (VHE) gamma-ray astronomy." Given this report's role in establishing the first multi-institutional cooperation in a publication explicitly invoking "multi-messenger," it warrants closer examination. The paper reported the discussion of the gamma-ray burst (GRB) working group, concentrating on future gamma-ray experiments to observe the highest energy emission ever recorded for such short-lived outbursts, the most powerful events observed up to now in the universe. This means that, during this exploratory phase, only one of the messengers (and indeed one related to very specific events) that formed part of the multi-messenger framework was being discussed in the multi-institutional report, which stressed the need for synergy among multiple, existing or upcoming, observatories as critical "for *both* the identification of [gamma ray bursts] and for multiwavelength/multimessenger studies."[21] Although the working group advocated for both national and international collaboration, all 14 participating institutions were US-based. Published on the eve of the emergence phase, this report suggests that coordinated institutional efforts—rooted in a specific national and domain-focused context—played a pivotal role in catalyzing the nascent multi-messenger research field.

21 Falcone et al. (2008, p. 611), emphasis ours.

In order to understand why this discussion emerged specifically in connection with GRBs, one should look at its recent developments. Extreme astrophysical events —such as cataclysmic explosions, relativistic outflows, high-energy pulsar environments, and black hole accretion—have expanded the frontiers of astrophysics beyond the capabilities of terrestrial laboratories. As the field evolved, astronomical sciences became increasingly differentiated by their technologies, objectives, and strategies. This shift, from broad sky mapping to question-driven approaches, was accompanied by a growing emphasis on complementarity, where concurrent measurements provided deeper insights into shared phenomena and the universe was increasingly perceived as an extremely high-energy laboratory.

GRBs were discovered in the late 1960s through a secret program monitoring nuclear test ban violations, although their existence was only announced in 1973 when such information was declassified.[22] They puzzled astronomers for decades, with progress only being made in 1997—crucially, the very year when "multi-messenger" started to appear in publications—when the BeppoSAX satellite detected an X-ray afterglow (GRB970228).[23] This breakthrough enabled multi-wavelength campaigns that linked GRBs to the optical transient associated with the X-ray afterglow and allowed the delayed observation of the optical and radio afterglow produced by the impact of the relativistic jet stream on the surrounding medium.[24] By the end of the 1990s, about a dozen GRBs had been studied, providing information on a number of parameters related to these extremely bright and powerful explosions. The results of these complementary observations "motivated observers to carry out long-term multi-wavelength studies of the afterglow."[25]

This was made possible by the launch of increasingly coordinated space-based observatories operated by multiple institutions. The launch of the Hubble Space Telescope in 1990—equipped for observations in the ultraviolet, visible, and near-infrared wavelengths—was soon followed by the Compton Gamma Ray Observatory in 1991, which extended observational capabilities to cover the electromagnetic spectrum from X-rays to gamma rays. The launch of the Chandra X-ray Observatory in 1999 fully ushered in the era of coordinated, multi-wavelength science campaigns from space.

The study of transient, high-energy phenomena gained momentum with BeppoSAX, which enabled real-time correlations between gamma rays emitted during such violent bursts and X-ray, radio, and optical observations of their long-lasting afterglows. These findings substantiated the suspicion that such extreme events are powered by processes such as the merger of binary neutron stars or black holes, both of which are predicted to produce gravitational waves. Gravitational waves were expected to arise from rapid nuclear collapse—a type of transient event considered detectable by interferometric observatories like LIGO and Virgo, which were under

22 Klebesadel, Strong, & Olson (1973).
23 Costa et al. (1997).
24 Frail, Kulkarni, Nicastro, Feroci, & Taylor (1997); Meegan (1998); Metzger et al. (1997); Paradijs et al. (1997).
25 Kulkarni et al. (1999, p. 389).

construction at the time.[26] This context fostered the exploration of coincident emissions, including electromagnetic radiation, gravitational waves, and neutrinos.

The emergence phase (2009–2015) witnessed a significant growth of the institutional cooperation network: its largest connected component grew to encompass over 250 institutions. In the scientific literature on emerging research fields, the formation of a giant component in the co-authorship network is viewed as evidence that a research field has been constituted.[27] By the same criterion, the rapid emergence of a densely connected giant component of institutions in publications explicitly referring to multi-messenger astronomy signals the rise of a novel research domain, at least at the institutional level. Notably, this emergence preceded the discovery of gravitational waves, which later broadened the spectrum of signals under investigation in high-energy astrophysics.

To characterize the emergence phase, **Figure 3** visualizes the giant component of the institutional cooperation network. This layout reveals a pronounced core-periphery structure: a densely connected central core of institutions is evident and confirmed by a core-periphery algorithm (**Figure 3a**).[28] Applying the community-detection algorithm introduced in the previous section further partitions the network into clusters of institutions (**Figure 3b**). Four major clusters emerge, with the blue cluster corresponding almost precisely with the central core in **Figure 3a**, and the other clusters mostly reflecting peripheral sub-groups. This pattern shows the consolidation of a tightly interconnected research core alongside distinct institutional sectors, linked by a handful of broker institutions that bridge the core and its periphery. As discussed above, betweenness centrality is a measure ideally suited to pinpoint these broker institutions.

The institutions that bridge the densely connected core and its peripheral clusters are international in scope, though still dominated by the United States.[29] The three most central institutions are all US-based: Penn State University, Caltech, and the University of Wisconsin. Penn State University's central role reflects its leadership in the Swift Observatory, a NASA satellite launched in 2004 to detect and locate gamma-ray bursts within the multiwavelength framework, and the Astrophysical Multimessenger Observatory Network (AMON), a global system established in 2013 to link observatories for the collaborative detection and analysis of cosmic events.[30] This underscores a key feature of the emergence phase: coordinated institutional efforts to build infrastructure for the rapid sharing of detection signals under an explicit multi-messenger paradigm. Caltech's centrality derives from its role in the LIGO Observatory, signaling the growing relevance of gravitational-wave detection in the

26 Abramovici et al. (1992); Caron et al. (1997).

27 Bettencourt et al. (2008).

28 The heuristic algorithm iteratively refines node scores to approximate core-periphery structures, drawing inspiration from Borgatti & Everett's (2000) approach—the standard scientometric method for identifying nodes that belong to the core rather than the periphery of a network.

29 INFN, the Italian National Institute for Nuclear Physics, is a decentralized organization comprising divisions and laboratories across Italy; it was therefore excluded from this discussion.

30 For Swift, see Gehrels et al. (2004); for AMON, see Smith et al. (2013).

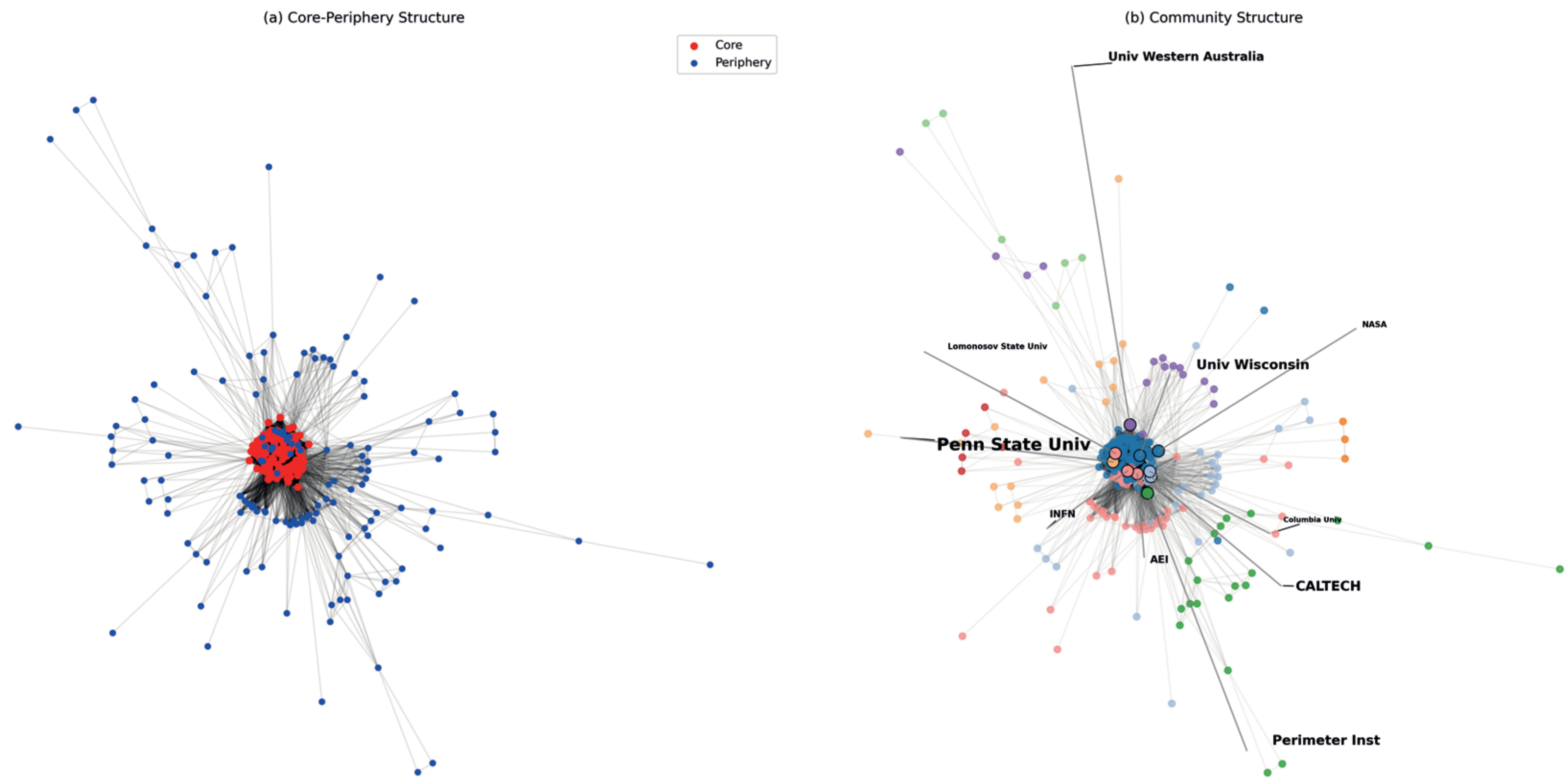

Figure 3. Largest connected component of the institutional collaboration network in multi-messenger astronomy, 2009–2015. In (a), nodes are colored red and blue to represent the core and periphery of the component, as determined using an algorithm derived from the Borgatti-Everett core-periphery algorithm. In (b), colors represent clusters identified through the Louvain community-detection algorithm. Label size is proportional to betweenness-centrality measures, with labels displayed for the 10 most central institutions.

emergence of multi-messenger astronomy, in view of the expected detection of gravitational waves.[31] The University of Wisconsin's centrality, on the other hand, is tied to its operational role in the IceCube Neutrino Observatory. Located deep within the Antarctic ice, IceCube is an enormous research facility designed to detect high-energy neutrinos from cosmic sources, which began operating in 2011. The continuity with the previous period is highlighted by the fact that, of the 14 institutions that were part of the largest connected component in 1997–2008, two were among the most central nodes in the 2009–2015 network, with Penn State University providing a clear link between the two periods.

In the consolidation phase (2016–2023), the institutional cooperation network expanded rapidly following the announcement of gravitational-wave detection in early 2016. It coalesced into a single, highly interconnected giant component of over 1,500 institutions, with no discernible core-periphery structure. Community-detection algorithms confirm that sub-communities are difficult to isolate, as institutional clusters are tightly interwoven. Centrality measures also show a shift in leading institutions compared to the prior period: various Chinese research organizations enter the network with high betweenness centrality, underscoring the field's growing internationalization.[32] Despite this growth and the emergence of new actors , institutional path dependency remains significant. Penn State University—central since the exploratory phase—continues to rank among the most central institutions in the 2016–2023 network, reflecting its foundational role in establishing the AMON institutional infrastructure for multi-messenger studies. Caltech is the only other institution to maintain a top-10 centrality ranking across both periods, consistent with LIGO's pivotal contribution to gravitational-wave astronomy and its influence on the consolidation of multi-messenger astronomy.

The Co-Authorship Network

The co-authorship network offers a different, and more detailed, perspective on the evolving collaborative structure of multi-messenger astronomy. Examining the number of authors and the size of the largest connected component from 1997 to 2023 reveals two major peaks with almost all authors connected together in a giant component. This occurred in 2014 and 2017, corresponding to key collaborative publications (**Figure 4**). The first peak in 2014 is linked to a report on the preliminary, yet unsuccessful, search for coincident signals between high-energy neutrinos (IceCube) and gravitational waves (LIGO and Virgo).[33] The second, much larger peak in 2017 corresponds to the landmark discovery of a binary neutron star merger. This event brought together 3,614 authors across 50 major scientific collaborations,

31 Collins (2004).

32 These include large organizations comprising multiple sub-institutes like the Chinese Academy of Science—similar to the Italian INFN, which is the most central organization of the entire network—but also individual universities, such as Peking University.

33 IceCube Collaboration, LIGO Scientific Collaboration, & Virgo Collaboration (2014).

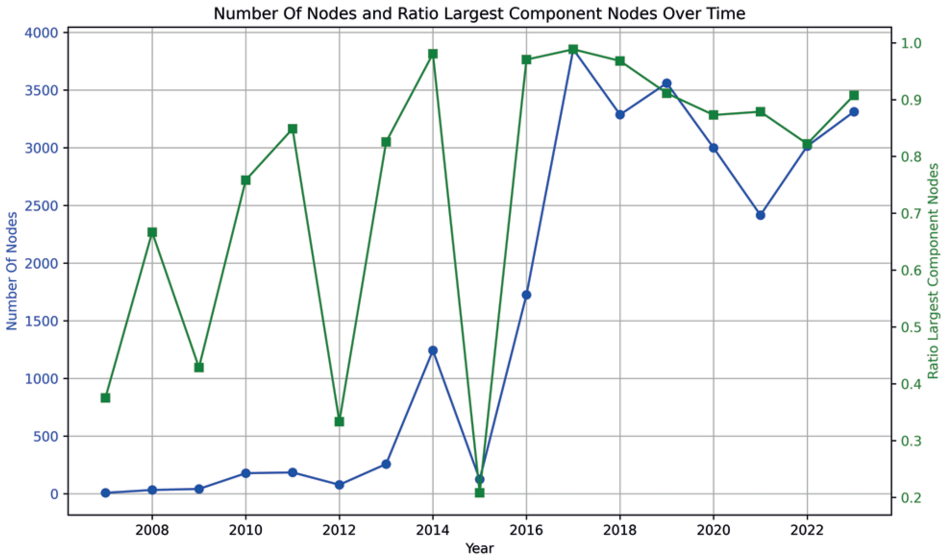

Figure 4. Number of nodes in the co-authorship network of multi-messenger astronomy, and proportion of nodes in the largest component over the total number of nodes per year, 2007–2023. The calculations are based on co-authorship networks constructed for each year. The total number of nodes in the entire co-authorship network is shown in blue, while the proportion of nodes in the largest connected component over the total number of nodes is in green. Two different scales are displayed on the y-axes.

resulting in over 6.5 million co-authorship edges. The study integrated gravitational-wave detections by LIGO and Virgo with observations of gamma-ray bursts by Fermi Gamma-Ray Burst Monitor and led to a massive electromagnetic follow-up campaign, encompassing signals across the spectrum.[34]

Exploring co-authorship networks across different periods is challenging due to the scale of big-team collaborations, involving thousands of authors and millions of co-authorship links. Publications of extensive cooperation in specific years significantly influence network topology, often connecting the majority of authors through large multi-collaboration projects. This dense connectivity can obscure more discrete scientific subcommunities.

To mitigate this distortion, we excluded the years 2014 and 2017, which saw the publication of two such large-team papers. For the emergence phase, we instead examined the network from 2009 to 2013; for the consolidation phase, we focused on the years immediately before and after 2017 (that is, 2016 and 2018). In each window, we applied the community-detection algorithm described above to identify subcommunities, interpreted these clusters through close readings of the publications

34 Abbott et al. (2017).

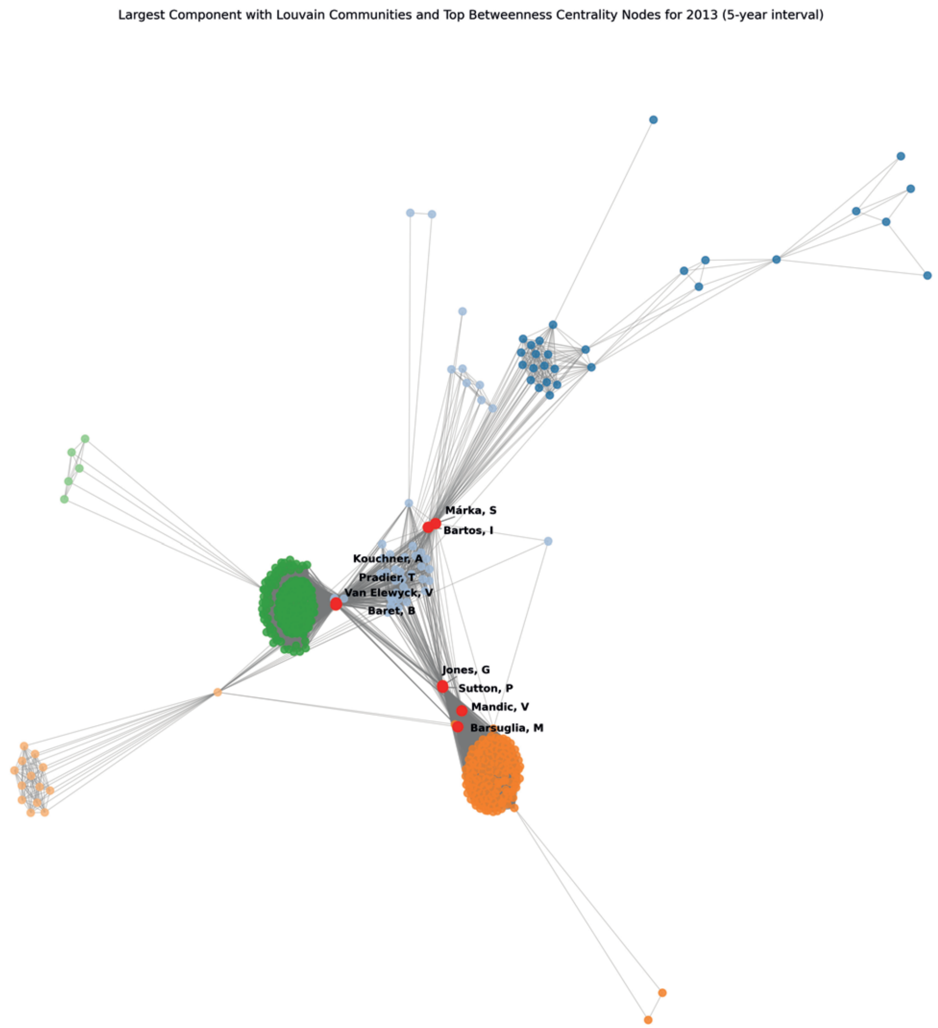

Figure 5. Giant component of the co-authorship network in multi-messenger astronomy, 2009–2013. Different colors represent clusters of authors retrieved with the Louvain algorithm. Labels indicate the 10 authors with the highest betweenness-centrality measures, highlighting those who served as key connectors between the various communities of co-authors in the network.

that forged their links, and assessed individual authors' roles in bridging between sub-communities.

Between 2009 and 2013, the co-authorship network (**Figure 5**) reveals the preparatory groundwork for multi-messenger astronomy. Four main clusters emerged. The largest cluster (orange) was associated with the prospect of future gravitational-wave detection, particularly in relation to the Einstein Telescope project.[35] The green cluster centered on correlations between ultra-high-energy cosmic rays and high-energy neutrinos, combining data from the ANTARES neutrino telescope and the world's largest cosmic-ray detector, the Pierre Auger Observatory.[36] A smaller cluster (blue) was instead related to the presentation of the AMON observatory network as a strategy to support the multi-messenger observation of transient phenomena from multiple observatories. The light-blue cluster is essential in connecting all three different subgroups. Notably, this cluster does not represent direct research collaboration. Instead, it reflects scientific discussions on the potential to usher in an era of multi-messenger astronomy. These discussions primarily focused on integrating gravitational-wave detection—anticipated to occur once the Advanced LIGO and Virgo detectors were ready—and high-energy neutrino detection using advanced observatories such as ANTARES and IceCube.[37] Betweenness-centrality analysis shows that nearly all authors linking the orange, green, and blue clusters do so exclusively via this light-blue group—demonstrating that without these conceptual dialogues, the network would have remained fragmented into isolated collaboration teams.

The co-authorship network analysis of the emergence phase of our periodization thus reveals largely independent groups laying the groundwork for multi-messenger astronomy as an observational field. Only in 2014 did the first large-scale multi-messenger analysis appear, emerging from a collaborative effort to search for coincident high-energy neutrino and gravitational-wave signals. As noted above, this initial attempt was unsuccessful—no significant coincident events were observed—but it nonetheless established upper limits on joint-source rates across a range of emission models and refined methods for integrating neutrino and gravitational-wave data in anticipation of next-generation gravitational-wave detectors, which were being upgraded at the time.[38] The social network analysis shows that throughout the emergence phase, "multi-messenger" was chiefly invoked in specific sub-projects, all tied together by discussions of its future promise—particularly the expectation that Advanced LIGO and Virgo would soon detect gravitational waves and formally include them among the signals encompassed by the multi-messenger framework.

This happened in February 2016 with the first detection of gravitational waves. That year witnessed a dramatic transformation in the co-authorship network of the MM corpus, providing further evidence of the onset of what we termed the consolidation phase. A giant component emerged, connecting thousands of researchers across multiple research teams. The 2016 network visualization shows four main subcommunities, distinguished by their focus on specific research areas (**Figure 6**). The largest sub-community (orange) represents the LIGO-Virgo collaboration. Another was centered on IceCube in cooperation with gamma-ray observatories like MAGIC (Major Atmospheric Gamma Imaging Cherenkov Telescopes) and

35 See especially Punturo et al. (2010).

36 Adrián-Martínez, Al Samarai, et al. (2013). For the role of correlation as the traditional astronomical practice feeding into the multi-messenger framework, see DeVorkin (2025).

37 Ando et al. (2013).

38 IceCube Collaboration, LIGO Scientific Collaboration, & Virgo Collaboration (2014).

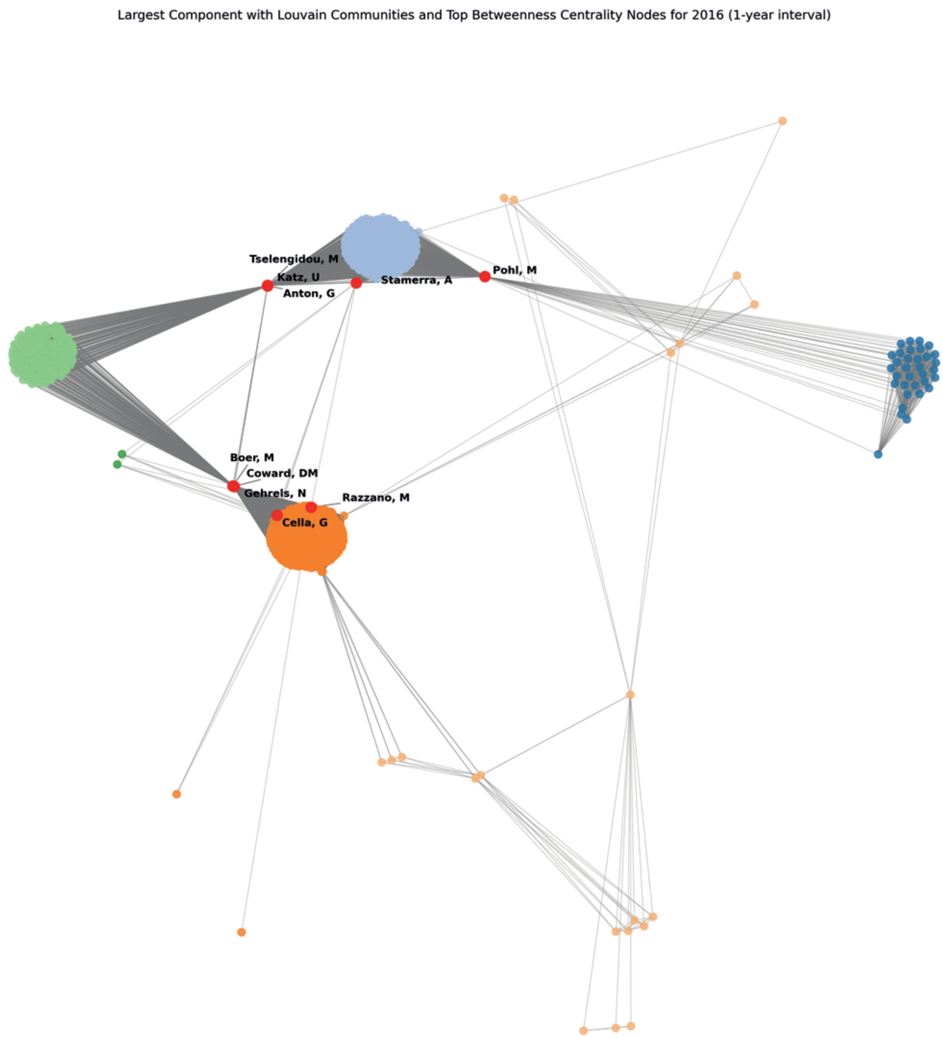

Figure 6. Giant component of the 2016 co-authorship network in multi-messenger astronomy. Different colors represent clusters of authors. Labels indicate the 10 authors with the highest betweenness-centrality measures, highlighting those who served as key connectors between the various communities within this network.

VERITAS (Very Energetic Radiation Imaging Telescope Array System) to explore neutrino-triggered observations of very high energy gamma-rays (light blue).[39]

39 IceCube Collaboration, MAGIC Collaboration, & VERITAS Collaboration (2016). MAGIC is characterized by a very lightweight system of telescopes that can reorient and target a location within approximately 25 seconds after receiving alerts from satellites or other Cherenkov detectors.

A third sub-community (green) focused on the ANTARES observatory, working with optical and X-ray observatories to investigate electromagnetic counterparts to neutrino events.[40] The final sub-community was oriented toward future X-ray observations, notably the LOFT-P mission.[41]

These subcommunities were densely connected internally but sparsely linked to one another, with a handful of individuals—identified by high betweenness centrality—serving as crucial bridges. We examined the roles and specializations of these key scientists in the 2016 MM corpus network. The ANTARES cluster (green) is connected both to IceCube and to the LIGO-Virgo collaboration. Its ties to IceCube were established by Uli Katz, Gisela Anton, and Maria Tselengidou, all of whom co-authored papers in both collaborations in 2016.[42] This was related to the development of an efficient neutrino reconstruction technique at the Erlangen Centre for Astroparticle Physics (ECAP) at Friedrich-Alexander-Universität Erlangen-Nürnberg. In contrast, the ANTARES–gravitational-wave connection was driven by a specific research field, namely GRB research, the main area of research of the scientists creating the connection. David M. Coward focused on GRB afterglows and gravitational-wave detection; Neil Gehrels specialized in GRBs and gamma-ray astronomy, serving as principal investigator of the Swift gamma-ray satellite; and Michel Boer specialized in observing GRBs across X-ray and other wavelengths.[43] Thus, also in the case of the analysis of the co-authorship network, GRB studies emerged as pivotal, providing the primary inter-cluster conduit in this nascent giant component during the emergence phase. The 2016 network captures collaborations in the period immediately following the first gravitational-wave detection and just before the landmark multi-messenger observations. Although a giant component had formed, the network shows that its inter-cluster links remained relatively weak and were chiefly anchored in GRB research.

The year 2017 saw a dramatic shift, as the discovery of the binary neutron star merger catalyzed the integration of these subcommunities into a highly connected network, which can be observed by exploring the co-authorship network in the year after the 2017 discovery. By 2018, the co-authorship network had stabilized, with a giant component of nearly 3,200 authors. While the network was slightly less connected than in 2017, it was much more cohesive than the 2016 one (**Figure 7**). Distinguishable clusters included IceCube and related gamma-ray teams, gravitational-wave collaborations like LIGO-Virgo and the Japanese Kamioka Gravitational Wave Detector (KAGRA), and optical astronomy teams such as the Dark Energy Survey Collaboration. However, the high level of interconnectedness meant that many smaller collaborations could no longer be easily delineated as distinct

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40 Adrián-Martínez, Ageron, et al. (2016).

41 Wilson-Hodge et al. (2016).

42 IceCube Collaboration, MAGIC Collaboration, & VERITAS Collaboration (2016); Adrián-Martínez, Ageron, et al. (2016).

43 The very weak link between the IceCube and gravitational-wave clusters seems less relevant for the interpretation, as it appears to be based on national collaborations; see Patricelli et al. (2016).

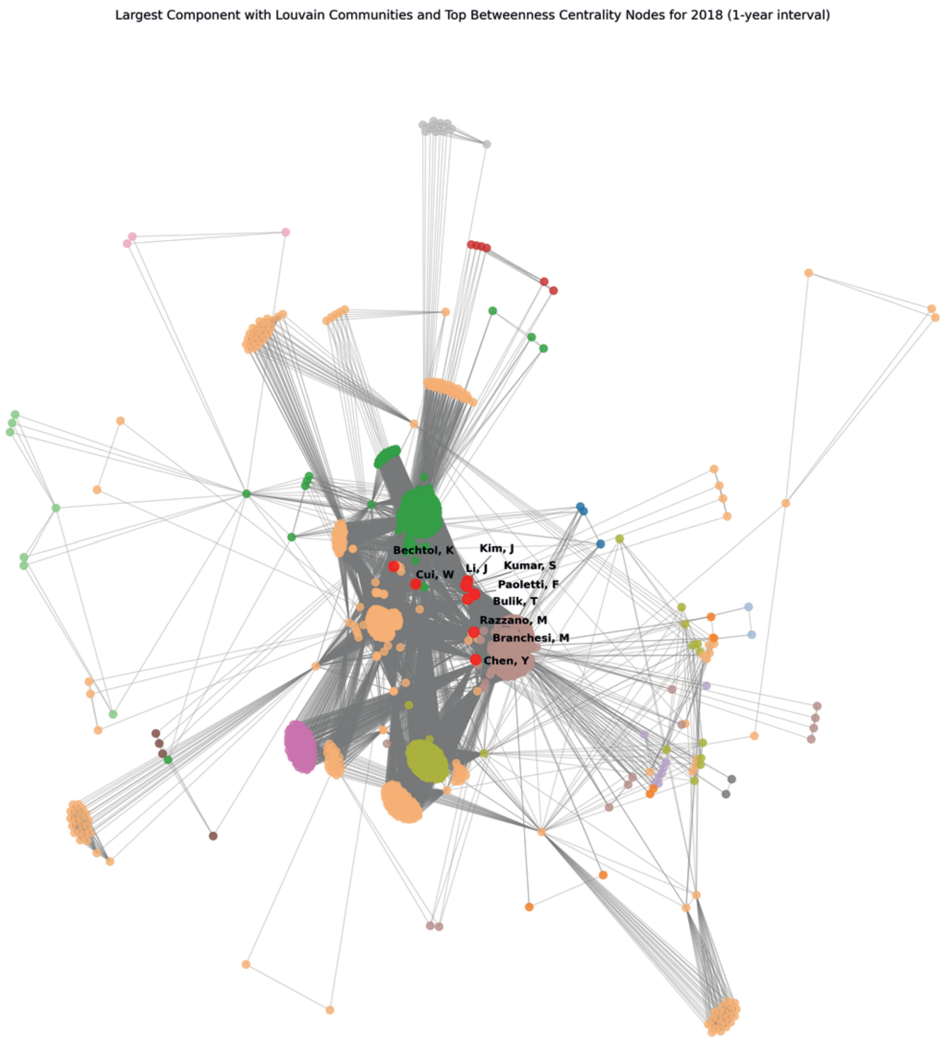

Figure 7. Giant component of the 2018 co-authorship network in multi-messenger astronomy. Different colors represent clusters of authors. Labels indicate the 10 authors with the highest betweenness-centrality measures, highlighting those who served as key connectors between large subcommunities within the network.

groups (see the many groups of authors identified as a unique cluster in peach orange).

The co-authorship network analysis described above illustrates how separate subcommunities—each focused on a specific messenger and associated cooperation team—gradually began to interact and merge. Individuals with high betweenness centrality reveal the expertise, techniques, or research areas that bridged these subgroups. To identify these key connectors, we tracked which authors ranked among the most central across multiple annual networks (**Figure 8**). Imre Bartos, Kohta Murase, and,

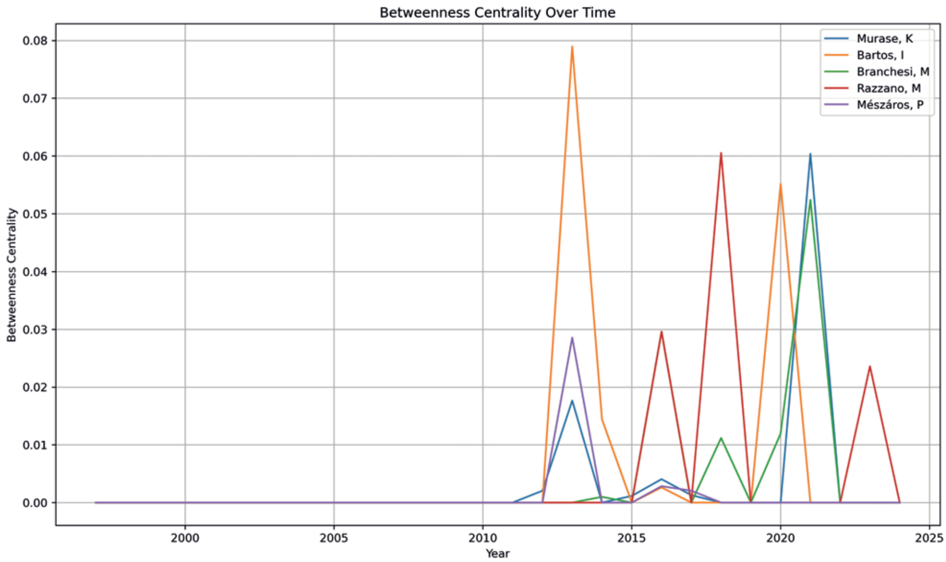

Figure 8. Betweenness centrality over time for the five authors most frequently ranked among the 20 most central nodes in the yearly co-authorship networks of multi-messenger astronomy, 1997–2023.

to a lesser degree, Marica Branchesi emerge as central connecting nodes in both the emergence and consolidation phases, while Massimiliano Razzano emerges as a connecting node only from 2016 onward, during the consolidation phase. The centrality of Bartos and Murase highlights the relevance of neutrino research during the emergence phase and continuing through the consolidation phase, connecting this research to a theoretical and infrastructural framework for multi-messenger astronomy in relation to ultra-high energy cosmic rays and gamma-ray research. Razzano and Branchesi were, instead, relevant to connecting gravitational-wave research to neutrino and gamma-ray research, and to electromagnetic counterparts, respectively, highlighting the rising prominence of gravitational-wave detection during the consolidation phase.

The combined institutional-collaboration and co-authorship analyses trace a clear socio-institutional transformation from the late 1990s through the late 2010s. In the exploratory phase, "multi-messenger" appeared only sporadically, and cooperation efforts were isolated within a few specialized domains—most notably gamma-ray burst research. During the emergence phase, institutional links proliferated: distinct research areas remained largely siloed, but discussions and frameworks—such as AMON—coalesced, especially around the anticipated discovery of gravitational waves, laying the groundwork for a unified field. Operational collaborations then took shape among neutrino observatories, ultra-high-energy cosmic-ray detectors, and gamma-ray telescopes, with gravitational-wave detection rising in prominence and social visibility just before Advanced LIGO's first observation. Finally, in the consolidation phase, the network became so dense—both institutionally and in terms of co-authorship—that its original subgroups dissolved into a single, highly integrated multi-messenger astronomy community.

The Textual and Co-citation Analysis of Multi-Messenger Astronomy over Time

Mapping the Emergence and Transformation of a Scientific Field Through Textual Analysis

Having charted the socio-institutional networks that underpin the explicit formation of a large, international research community, we now turn to how authors have framed the field's topics over time. A preliminary overview of the main research topics characterizing the three identified periods can be obtained through a quantitative textual analysis of the abstracts in the MM corpus. Trends in the abstracts' most frequently used words serve as proxies for the research topics in the MM corpus during each period. Key terms were identified by calculating the ratio between the documents in which a given term appeared and the total number of documents published within the respective period. Although straightforward, this approach effectively captures the relative prominence of words closely associated with the distinct signal types encompassed by the multi-messenger framework.[44] The most frequent terms in each period align directly with the astrophysical signals that define multi-messenger astronomy: “neutrino,” “cosmic,” “gamma-ray,” “gravitational,” and “electromagnetic.” By examining the context and co-occurring words in the abstracts, we could confirm that “cosmic” refers to cosmic rays, “gravitational” to gravitational waves, and “electromagnetic” to electromagnetic counterparts.[45]

Examining the proportion of abstracts that include each of these words across our three phases provides a preliminary gauge of the shifting prominence of different messengers in literature explicitly framed as multi-messenger astronomy (**Figure 9**). In the exploratory phase (1997–2008), the term “multi-messenger” was primarily associated with neutrino astronomy, cosmic-ray physics, and, to a lesser extent, gamma-ray astronomy and gamma-ray burst research. During the emergence phase (2009–2015), these areas converge in terms of relevance within the MM corpus, reflecting a growing uniformity. This trend is characterized by an increase in the frequency of the abstracts including the terms “gravitational” and “electromagnetic,” alongside a relative decline of the term “cosmic,” while “neutrino” remains the most frequently used term in connection with multi-messenger research. In the consolidation phase (2016–2023), following the first detection of gravitational waves and their

44 Sparck Jones (1972). This approach has been chosen after having evaluated multiple alternatives, including the more common Term Frequency–Inverse Document Frequency (TF-IDF) method.

45 The term “cosmic rays” is used in the established scientific sense of high-energy particles and nuclei originating from astrophysical sources whose flux drops rapidly with increasing energy.

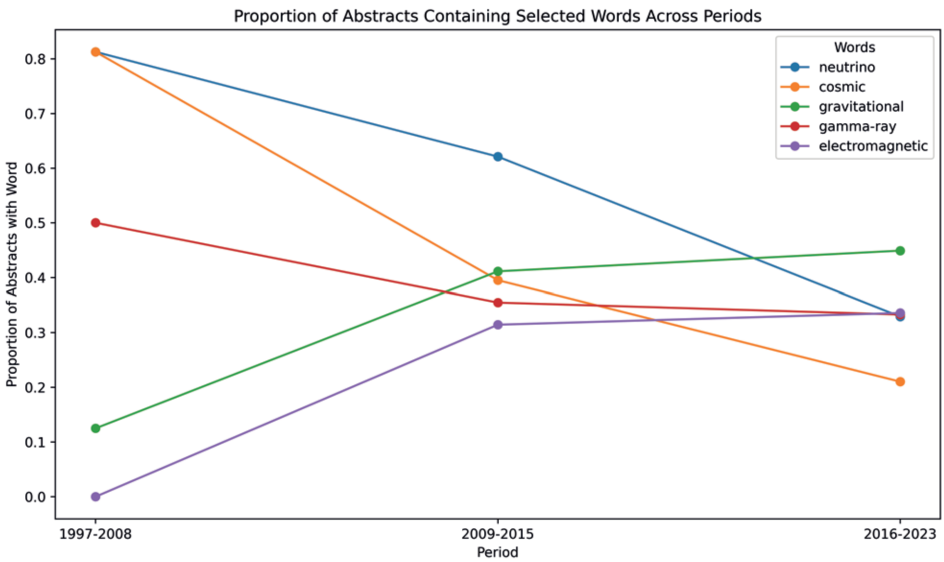

Figure 9. Normalized document frequency proportions across three periods (1997–2008, 2009–2015, and 2016–2023) for the terms "neutrino," "cosmic," "gravitational," "gamma-ray," and "electromagnetic." The document frequency proportion reflects the ratio of abstracts containing each term to the total number of abstracts in each period.

incorporation into the multi-messenger framework through actual observations, this uniformity becomes even more pronounced. Strikingly, the frequencies of "gamma-ray," "electromagnetic," and "neutrino" are nearly identical, with "gravitational" emerging as the most frequent keyword, while "cosmic" declines in prominence compared to earlier periods.

This frequency analysis suggests that the research agendas explicitly aimed at developing a multi-messenger framework initially stemmed from neutrino astronomy, cosmic-ray physics, and gamma-ray astronomy. Gravitational-wave astronomy and electromagnetic counterparts entered the discourse later, yet notably before the first gravitational-wave detection. This progression corroborates our socio-institutional network findings from the previous section: during the exploratory phase, an institutional cluster coalesced around a gamma-ray burst working group within astroparticle physics, and subsequent links between different messengers were driven primarily by discussions of future multi-messenger opportunities pending gravitational-wave discovery.

This interpretation is further confirmed and elaborated through an analysis of the connections between the keywords selected by the authors of the publications

46 For *VoSviewer*, see van Eck & Waltman (2010); for *Gephi*, see Bastian, Heymann, & Jacomy (2009).

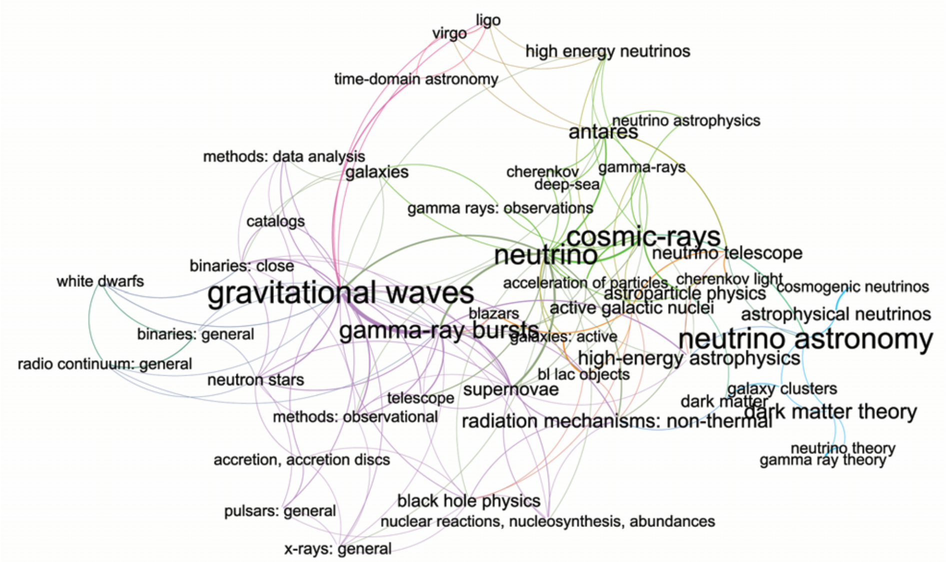

Figure 10. Co-occurrence network of keywords in the MM corpus, 2009–2015. The nodes represent the 48 keywords used by authors that appear at least twice during the period under consideration, with similar keywords grouped as the same term and general or obvious terms (for example, "multi-messenger") excluded. Label size is proportional to betweenness centrality, and colors indicate six clusters identified using the Louvain clustering algorithm. Visualization and analysis were conducted using *VoSviewer* and *Gephi*.[46]

in the MM corpus. The network analysis of keyword co-occurrence, clustered into subsets, allows us to identify the subfields that scientists explicitly associated with the emerging multi-messenger framework. In the exploratory phase, the number of papers is too small to make a detailed quantitative analysis particularly useful. Nevertheless, our analysis confirms that the main areas of focus during this time were neutrino astrophysics and cosmic-ray research.

The landscape becomes more nuanced in the period 2009–2015 (**Figure 10**). During the emergence phase, the network analysis identifies five central keywords: "gravitational waves," "neutrino," "neutrino astronomy," "cosmic-rays," and, to a lesser extent, "gamma-ray bursts," again identifying the main signals included in the multi-messenger framework. While the Louvain clustering algorithm reveals six distinct clusters, the network visualization, in **Figure 10**, shows that two major clusters dominate the co-occurrence network of keywords. The first cluster is centered on the keyword "neutrino" in strong connection with the keyword "cosmic-rays." The second cluster is organized around the keyword "gravitational waves," which is in turn closely linked to "gamma-ray bursts."

These two major clusters reflect distinct areas of focus. The first, clearly associated with astroparticle physics (encompassing also the green and blue clusters, along with portions of the orange cluster), connects research on topics like dark matter.

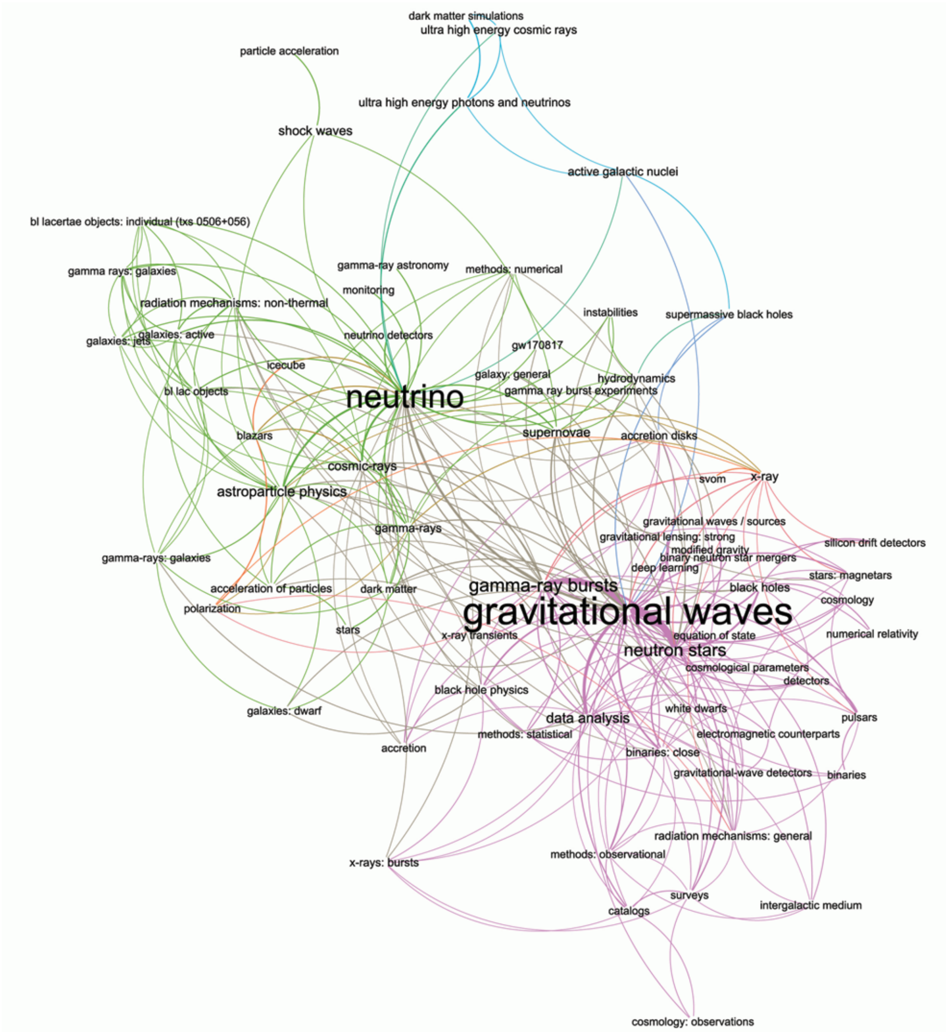

Figure 11. Co-occurrence network of keywords in the MM corpus, 2016–2023. The nodes represent the 72 keywords used by authors that appear at least twice during the period under consideration, with similar keywords grouped as the same term and general or obvious terms (for example, multi-messenger) excluded. Label size is proportional to betweenness centrality, and colors indicate six clusters identified using the Louvain clustering algorithm. Visualization and analysis were conducted using *VoSviewer* and *Gephi*.

The second cluster relates more directly to gravitational-wave astronomy, which incorporates studies of gamma-ray bursts and multi-wavelength astronomy (though the latter does not explicitly appear as a keyword in the dataset). This second cluster is oriented toward investigations of compact stellar objects and binaries, or black holes, all potential sources of gravitational waves or GRBs.

Figure 10 suggests that during the emergence phase, the dominance of astroparticle physics observed in the exploratory phase began to merge with gravitational-wave astronomy in order to study phenomena that could not adequately be addressed through astroparticle physics or multi-wavelength astronomy alone. This merging is further underscored by the strong connections between the keyword “gravitational waves” and other central keywords in the network, while the keyword “gamma-ray bursts” exhibits its strongest connection with “gravitational waves” rather than with the other most central keywords in the network.

As expected, the consolidation phase (2016–2023) is marked by a significant increase in the number of keywords (**Figure 11**). This growth reflects both the surge in publication outputs and the transformation of the field with the operational deployment of gravitational-wave detectors within multi-messenger research. Despite this expansion, the network's structure remains largely consistent with the previous period, featuring two primary keyword clusters: one centered around “gravitational waves” (purple cluster) and the other around “neutrino” (green cluster).

In this period, “gravitational waves” emerges as the most central keyword in the network and is strongly connected to newly prominent terms such as “neutron stars.” While “cosmic-rays” and “gamma-ray bursts” maintain their structural connections within the network, their centrality diminishes compared to the earlier period. Additionally, the keyword “electromagnetic counterpart” now appears within the network. However, its role remains relatively marginal, as it is primarily connected to terms within the purple cluster centered on “gravitational waves.”

Mapping the Evolving Research Agendas in Multi-Messenger Astronomy with Co-citation Analysis

This sub-section presents the co-citation network of the MM corpus, created using *CiteSpace*, a tool designed to visualize the temporal evolution of the intellectual bases of scientific research fronts through clusters of co-cited papers (**Figure 12**).[47] Cluster labels were generated by the Latent Semantic Indexing algorithm, which identifies the most relevant words from the titles of citing papers to suggest thematic content, a method chosen for its ability to capture underlying semantic patterns and reduce noise in textual data.[48] While these labels provide initial insights, they require interpretative validation through close reading of most cited papers in each cluster. Our analysis shows that, while reductive, the labels effectively indicate the progression of the scientific foundations underlying citing papers that explicitly position their research within the framework of multi-messenger astronomy from the early 2000s to 2023.

The earliest cluster, labeled “black holes” (mean publication year: 2006), includes papers focusing on ultra-high-energy cosmic rays and high-energy gamma astronomy. A later cluster, labeled “ANTARES neutrino telescope” (mean year: 2011),

47 Chen (2006; 2013).

48 For the Latent Semantic Indexing, see Deerwester, Dumais, Furnas, Landauer, & Harshman (1990).

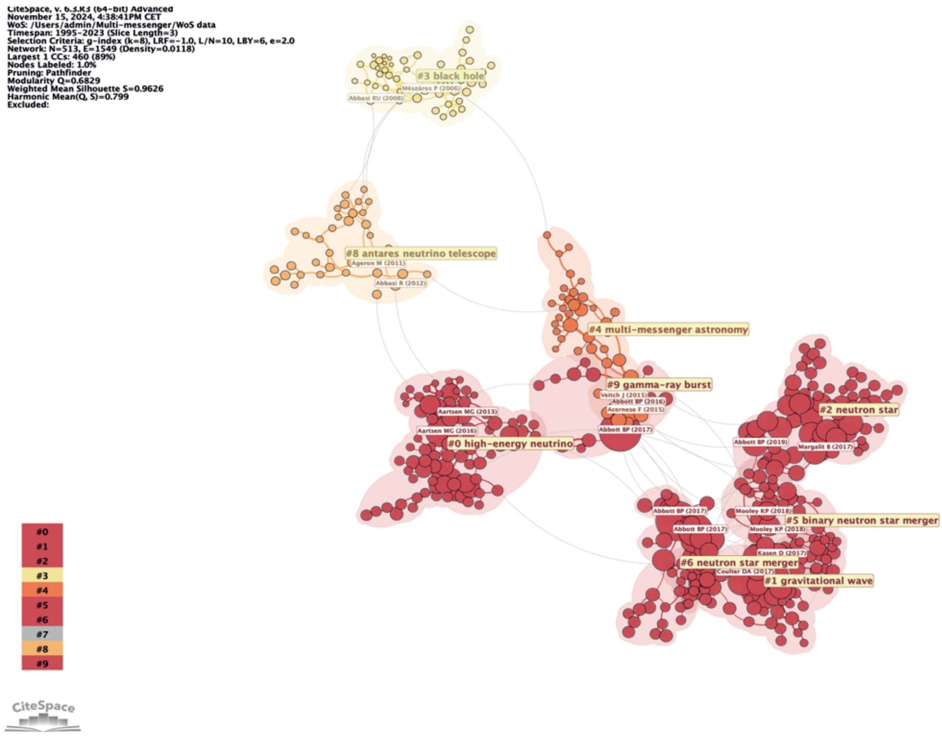

Figure 12. Co-citation network of the MM corpus, constructed using the most cited publications for 3-year timespans from 1997 to 2023. The co-cited papers are grouped into nine clusters, identified using the community-detection algorithm embedded in the software *CiteSpace*. The figure includes only clusters containing more than nine papers and connected to the largest connected component. Colors represent the temporal development of the network, ranging from the lightest (Cluster 3: "black hole") to the darkest (Cluster 2: "neutron star"). The cluster numbers correspond to their size, with Cluster 0 being the largest and Cluster 9 the smallest.

focuses on high-energy cosmic neutrino searches. A transitional cluster, labeled "multi-messenger astronomy" (mean year: 2012), bridges these earlier themes with more recent developments, highlighting discussions on advanced gravitational-wave detectors (Advanced LIGO and Virgo) and the potential for observing electromagnetic counterparts of binary mergers.

The other clusters correspond to the third phase of our periodization, which sees the expansion of the field following the inclusion of gravitational-wave detection. The "gamma-ray burst" cluster (mean year: 2017) occupies a central structural position in the network, linking the multi-messenger cluster to all others. Influential papers within this cluster include those reporting the discovery of gravitational waves, as well as the detection of the binary neutron star merger GW170817, the first multi-messenger observation that combined gravitational-wave signals with other kinds of signals, such as gamma-ray burst GRB170817A, and the subsequent electromagnetic observation campaign.[49] The relevance of this event lies in its role in confirming the validity of the multi-messenger framework and marking its consolidation as a large-scale, active research field.

In relation to this cluster, two distinct sets of clusters define the field's expansion. The largest, labeled "high-energy neutrino" (mean year: 2016), focuses on high-energy cosmic neutrino research, particularly related to the IceCube Neutrino Observatory. This cluster is topologically more isolated compared to the other clusters related to the gravitational-wave-driven expansion of multi-messenger astronomy, which are centered around the discovery of the binary neutron star merger. The latter set includes four clusters: "binary neutron star merger," which encompasses theoretical predictions and analyses of this physical process enabling signal detection; "neutron star merger," which focuses on papers related to GW170817; "gravitational wave," which addresses electromagnetic counterparts of gravitational-wave events involving the neutron star merger; and the most recent cluster "neutron star" (mean year: 2018), which explores neutron star properties revealed through such multi-messenger observations.

The combination of textual and co-citation analyses provides a coherent picture of the field's epistemic evolution, as defined by papers explicitly situating themselves within the multi-messenger research area. During the first period, multi-messenger discussions were dominated by astroparticle physics, including research on high-energy cosmic rays, gamma-ray astronomy, and high-energy neutrino studies (notably linked to the ANTARES observatory, operational since 2006). In the second period, explicit mentions of "multi-messenger" reflect efforts to conceptually connect astroparticle physics with gravitational-wave astronomy, even before gravitational waves were observed. This highlights the community's effort to conceptualize a unified framework, which is particularly evident in the "multi-messenger astronomy" cluster in **Figure 12**, where citing papers explicitly proposed multi-messenger astronomy as a new field encompassing gravitational waves. However, this connection remained prospective, as gravitational waves had not yet been detected.

The third period, post-2016, shows the consolidation of multi-messenger astronomy as an established framework, driven by actual observations explicitly labelled as such. The keyword "gravitational waves" becomes the most central, while terms like "neutron stars" gain prominence following the GW170817 observation. However, the co-citation network reveals a separation between two major intellectual bases: first, research on high-energy neutrinos, especially related to IceCube; and second, gravitational-wave-centered research on binary neutron star mergers and their electromagnetic counterparts. This division mirrors the co-occurrence network's structure, where "neutrino" and "gravitational waves" dominate as central keywords of two identifiable sets of keywords in **Figure 11**. This identification of two major research areas suggests that, while multi-messenger astronomy has solidified as a unifying

49 LIGO Scientific Collaboration & Virgo Collaboration (2016); Abbott et al. (2017).

framework—especially following the realization of gravitational-wave observations—neutrino-based research remained somewhat distinct, largely because neutrinos did not play a significant role in the 2017 discovery.

Conclusion

The integration of socio-institutional network analysis with document-frequency metrics, keyword co-occurrence and co-citation network studies, and close readings of strategically identified publications yields a coherent account of multi-messenger astronomy's emergence in the early 21st century. This account rests on a tripartite periodization—the exploratory (1997–2008), emergence (2009–2015), and consolidation (2016–2023) phases—which is consistently validated and characterized by each analytical approach. The term "multi-messenger" emerged at the turn of the millennium, reflecting a growing consensus that the universe's most violent, transient events could only be fully understood by integrating neutrino detections, electromagnetic observations across the spectrum, cosmic-ray measurements, and yet-to-be-observed gravitational-wave signals. Our quantitative analysis shows that this integrative vision first took shape within three astroparticle-physics domains: neutrino astronomy, cosmic-ray research, and very-high-energy gamma-ray burst studies. Since its own emergence in the late 1980s, astroparticle physics marked the convergence of astrophysics, particle physics, and cosmology into a unified field, providing a fertile ground for integrating diverse research paths such as cosmic ray, neutrino, and gamma-ray studies.

The MM corpus during the exploratory phase underscores the prominence of the "cosmic triad" (cosmic rays, neutrinos, and gamma rays) as the foundation of an approach that was explicitly framed as multi-messenger.[50] These efforts extended beyond traditional electromagnetic observations to include new types of telescopes capable of detecting non-electromagnetic signals and expanding the observed energy window. Discussions on the complementary roles of neutrinos and gamma rays in probing dense astrophysical environments also fostered early multi-messenger practices within astroparticle physics.

During this phase, gamma-ray bursts provided a crucial model for extending correlation practices to other messengers. Practices from multi-wavelength astronomy in observing gamma-ray burst afterglows demonstrated how correlating data across multiple channels could yield insights that surpassed separate analyses. This transition from multi-wavelength to multi-messenger astronomy was facilitated by successful observations in the late 1990s and the anticipated capabilities of upcoming observatories, such as cosmic neutrino observatories and, prospectively, gravitational-wave advanced detectors. Yet the socio-institutional network of authors explicitly using the term "multi-messenger" in their scientific output clearly shows that such a view was a prospective one: the socio-institutional network remained non-existant except

50 Ahlers (2013).

for a US-based working group explicitly discussing the future of very-high-energy gamma-ray astronomy.

The period from 2009 to 2015 marked the clear emergence of a small multi-messenger sub-field. Operational observatories like IceCube and ANTARES, alongside space-based gamma-ray instruments such as Fermi-LAT, propelled this emergence. IceCube's detection of high-energy astrophysical neutrinos in 2013 was a turning point, validating neutrinos as essential cosmic messengers and catalyzing discussions on coordinated multi-messenger efforts. Simultaneously, the capabilities of gravitational-wave detectors such as Advanced LIGO and Virgo, still under construction, inspired theoretical discussions about coincident observations across different signals, further shaping the conceptual landscape. Although gravitational waves had not yet been directly detected, collaborations among gravitational-wave, neutrino, and gamma-ray teams began to form, recognizing the promise of coincident observations. These efforts gave rise to novel socio-institutional structures—most notably real-time alert systems, such as AMON—reflecting a field rooted in existing capabilities yet crucially driven by the promise of an imminent gravitational-wave detection.

The consolidation phase, beginning in 2016 with the first direct detection of gravitational waves, heralded the actualization of multi-messenger astronomy as a cohesive and recognized field. The successful observation of binary neutron-star merger GW170817 showcased the effectiveness of synergistic observing strategies conceived in the previous phase. To practitioners it became clear that coordinated, multi-channel measurements offered insights into astrophysical processes that no single messenger could provide, thereby validating the multi-messenger paradigm. This breakthrough catalyzed a rapid expansion of the field, fostering new observatories, technologies, and collaborations aimed at exploring the universe's most extreme phenomena. Starting from 2017, the co-authorship network had evolved from the loosely connected subcommunities of 2016 into a highly integrated institutional and social structure, reflecting the field's newfound cohesion.

Our integrated approach—combining scientometric analysis of the MM corpus with close readings of strategically selected publications—indicates that the early, explicit use of the term "multi-messenger" in scientific literature reflects a deliberate effort by scientists to establish a unified research field. This field linked advances in neutrino, cosmic-ray, gamma-ray, and other observational research domains under a common umbrella with the goal of enhancing their distinctive significance within the proposed broader multi-messenger framework. This effort extended beyond terminology, for it was rooted in institutional and conceptual developments aimed at uniting diverse subcultures within a shared scientific framework. The specific practice of correlating data from different signals, observed using distinct techniques to study transient phenomena across observatories worldwide, required an unprecedented level of coordination.

Although gamma-ray-burst experts were instrumental in extending multi-wavelength methods toward a multi-messenger paradigm up to 2016, it was developments in gravitational-wave astronomy that provided the compelling vision of a fully integrated field. Crucially, this vision was not solely conceptual; it also demanded a socio-institutional reconfiguration of the research community's practices—including data-sharing, alert systems, and the broader coordination of big-science infrastructures. This transformation was made necessary not only by geographical dispersion of the observatories, but more importantly by their fundamentally different scientific natures. What began as tentative, astroparticle-physics-driven collaborations eventually solidified into a big-science enterprise with the landmark 2017 observations, in which gravitational-wave detection was pivotal. Our findings highlight how future-oriented imaginaries—particularly the anticipation of gravitational-wave discoveries and the parallel investment in advanced observatories—played a central role in shaping scientific practices, community-building, and research agendas during the emergence of multi-messenger astronomy.[51]

This paper complements the historical perspective developed in the first contribution of our two-part study. The first article examined the epistemic and institutional genealogy of the field through the lens of supernova studies, arguing that supernovae —particularly SN1987A—functioned as epistemic laboratories. By employing concepts such as trading zones, boundary objects, challenging objects, and borderline problems, we showed how supernova studies posed challenges that could not be solved within a single field of inquiry, thereby bringing disparate observational and theoretical traditions into confrontation and ultimately fostering interdisciplinary collaboration, before a unified multi-messenger framework was articulated. We also argued that, while this work was instrumental in creating the pre-conditions for the inception of multi-messenger astronomy, the emergence of this research domain in the 21st century has some distinctive features that make it a novel form of collective inquiry. The analysis in this paper confirms and extends these findings by showing how, from the 1990s onward, such collaborations were gradually stabilized, institutionalized, and reframed under the label of multi-messenger astronomy.

Notably, our network study reveals that the conceptual and institutional consolidation of the field seems to predate the growth of the use of the term "multi-messenger" in scientific publications. This aligns with the suggestions in the introduction to this special issue that international committees—such as the IUPAP's Particle and Nuclear Astrophysics and Gravitation International Committee (PaNAGIC)—played a foundational role in articulating a shared identity across research areas like gravitational-wave detection, neutrino astronomy, and high-energy gamma-ray research. This observation points to a crucial area for further historical investigation: archival research into the early activities of PaNAGIC and related working groups would allow for a more comprehensive understanding of how top-down coordination efforts interacted with bottom-up scientific practices to shape the field. Combining historical reconstruction with network analysis, our investigation contributes to shedding light on the interplay of epistemic, institutional, and collaborative dynamics in the formation of a a scientific field perceived as novel by practitioners, in spite of the

51 In a sense this socio-technical vision elaborated before the detection of gravitational waves has some similarities with the concept of socio-technical imaginaries as formulated by Jasanoff & Kim (2009).

difficulty of clearly defining it. Multi-messenger astronomy did not simply emerge from conceptual synthesis, but from the co-evolution of practices, infrastructures, and anticipatory imaginaries. By integrating complementary methods and perspectives, our two-part study gives a contribution to a richer understanding of how scientific innovation is not only epistemically driven, but socially and institutionally enacted.

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