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Supernovae as Epistemic Laboratories

▼ **SPECIAL ISSUE ARTICLE** in *Shaping a Multi-Messenger Universe*, ed. by Luisa Bonolis, Roberto Lalli & Adele La Rana

▼ **ABSTRACT** The paper explores the historical development of supernova research in the 20th century and examines its role in the emergence of multi-messenger astronomy. Through an analysis of primary scientific literature and review sources, we show that theoretical and experimental investigations of supernovae, from the 1930s to the supernova 1987A and beyond, have fostered a crucial shift in astronomical research. Building on conceptual tools from history of science and social studies—such as Galison's "trading zones," Star and Griesemer's "boundary objects," and Renn's notions of "challenging objects" and "borderline problems"—this analysis shows how supernovae served as both enablers and drivers of productive confrontation and exchanges across disciplinary boundaries. Through key episodes we discuss how they bridged different research domains, shaping hybridized practices and expertise, in order to address complex questions that no single field could resolve.

Particular attention is given to the detection of SN1987A. Though not yet embedded in a mature multi-messenger framework, it revealed the latent infrastructure, interpretive gaps, and epistemic

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promise of a globally coordinated, real-time, multi-signal astronomy, anticipating more integrated approaches. Following this turning point, the article traces how collaborative practices gradually solidified into enduring forms of interdisciplinary work, laying the epistemic groundwork for multi-messenger science long before the term gained currency. We argue that supernova research functioned as a long-term trading zone, where experimental practices, theoretical models, and instrumentation co-evolved across disciplinary boundaries. By reconstructing this process, the paper contributes to a historical understanding of how new scientific fields emerge through the reconfiguration of existing ones.

This paper forms the first part of a twofold study on the emergence of multi-messenger astronomy as a new field of scientific inquiry. The companion study will integrate this contribution, by tracing the rise and consolidation of multi-messenger research networks through co-authorship and co-citation analysis in the 21st century.

▼ **KEYWORDS** Multi-Messenger Astronomy, History of Astrophysics, Supernova, Gamma-Ray Astronomy, High-Energy Astrophysics, Neutrino, Gravitational Waves

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> "SN is a heart of modern astrophysics"
>
> — *Berezinsky*[1]

Introduction

The recent emergence of multi-messenger astronomy has been described not only as a new field but as a transformative form of Big Science. Advocates of the field's novelty emphasize that it does not represent a conceptual revolution, but rather the adoption of innovative practices.[2] At its core is the convergence of various research traditions, each deeply rooted in distinct subcultures within astronomy.[3] [4]

The rise of multi-messenger astronomy presents significant challenges for historians, particularly in understanding the interplay between continuities and discontinu-

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[1] Berezinsky (1994, p. 484).

[2] "A New Kind of Big Science" (2020).

[3] For the definition of scientific subcultures, see Galison (1997).

[4] Bonolis & Leon (2022).

ities in scientific development.[5] Although its novelty is often emphasized in scientific literature, little effort has been made to examine its historical roots or to understand how it emerged from earlier or contemporary traditions, such as multi-wavelength astronomy, neutrino astronomy, and gravitational-wave research.

This paper is the first contribution of a two-part study investigating the emergence of multi-messenger astronomy as a new field of scientific inquiry.[6] The study as a whole adopts a dual methodology: while the companion paper uses network analysis to trace the gradual rise and structural consolidation of the field in the early 21st century, the present article offers a historical analysis of some relevant contextual factors that fostered the initial development of multi-messenger practices.

In this first contribution, we investigate the historical roots of multi-messenger culture by focusing on a particular class of astrophysical events: supernovae. Tracing developments from the 1930s to the present, the article shows how the study of supernovae catalyzed interactions among different scientific communities in the fields of astronomy and physics. In this context, the notion of *messengers* does not emerge as a technical given but as the historical outcome of shifting epistemic frames and institutional alignments. Through the emblematic case of supernova research, we aim at providing a historical lens to show why and how multi-messenger astronomy can be considered a genuinely novel form of inquiry—not simply the aggregation of distinct observational domains of astronomy.

Our study is grounded in the analysis of primary scientific literature and previous historiographical accounts, with the aim of weaving a new narrative thread through the history of supernova research. Rather than offering a comprehensive reconstruction, we revisit key developments with the intent of bringing into focus a dimension that has received little attention: the role of supernovae as *boundary objects*. Originally introduced by the sociologist Susan Leigh Star, the concept of boundary objects refers to entities that inhabit multiple disciplinary worlds simultaneously, serving as robust yet adaptable points of coordination.[7] These objects—whether physical artifacts, data sets, models, or concepts—are adaptable to local needs yet maintain a consistent identity across different communities. As Star and Giesemer point out, the objects of scientific inquiry normally inhabit multiple social worlds.[8] Boundary objects enable collaboration without requiring consensus, as they can be interpreted from different scientific angles by distinct communities while still facilitating joint work. While this concept has been successfully applied to historical studies in fields such as museum taxonomy, environmental science, and biomedicine, this article proposes to apply it to the domain of supernova research.[9]

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[5] The literature is enormous. For a classic analysis of this issue in the philosophical literature, see Agassi (1973).

[6] See the companion paper in this special issue: Lalli, Bonolis, & La Rana (2025).

[7] Star (1989).

[8] Star & Griesemer (1989).

[9] See, for example, Star & Griesemer (1989); Levesque, Gatti, & Bardati (2020); Reimers, Schellhammer, Borchers, Stowasser, & Linzbach (2025).

In doing so, we further draw on Peter Galison's notion of *trading zones* to illuminate how interdisciplinary coordination around supernovae was achieved.[10] First proposed to describe the localized sites of interaction between subcultures of physics —such as theorists, experimentalists, and instrument makers—trading zones refer to conceptual and material spaces in which actors with different epistemic commitments and languages develop shared procedures and hybrid practices, enabling collaboration without full theoretical unification.

The long historical arc of supernova studies—from early optical observations to the integration of neutrino and gravitational wave data—reveals how various theoretical and observational traditions gradually developed shared reference points around these phenomena. Supernovae thus serve as ideal sites to explore the formation of trading zones: conceptual and material spaces in which different research fields such as nuclear and particle physics; optical, radio, X-ray, and gamma astronomies; and relativistic astrophysics engage in local cooperation despite maintaining different epistemic commitments. These zones are not held together by unified theories, but by negotiated vocabularies, overlapping experimental aims, and evolving standards of data correlation. From this perspective, supernovae were not merely targets of observational effort, but active agents in the formation of a new interdisciplinary regime.

Recently, Sims has proposed a productive synthesis of the concepts of *boundary objects* and *trading zones*, arguing that both frameworks help to account for the social and cognitive mechanisms underpinning distributed scientific collaboration.[11] While boundary objects account for coordination across broader institutional domains, trading zones capture the material and discursive negotiations at specific sites of collaboration. Sims's focus lies primarily on the general dynamics of coordination in complex scientific environments. We extend this perspective to the specific case of supernova research. By doing so, we highlight how supernovae functioned as both boundary objects and focal points within emerging trading zones, thereby enabling the cross-disciplinary interactions that would ultimately lay the groundwork for multimessenger astronomy.

To address the epistemic dynamism of supernova research, however, we introduce two additional concepts drawn from the history of science: *challenging objects* and *borderline problems*, as articulated by Jürgen Renn and collaborators. Challenging objects are phenomena, artifacts, or other parts of material culture that "do not lend themselves easily to treatment by the means available within existing frameworks of knowledge" and thus "offer the opportunity for conceptual transformations of those frameworks."[12] Examples of challenging objects considered by historians of science have been the projectile trajectory and the pendulum, which played a key role in Galileo's investigations about motion and in the rise of early modern science.[13] In

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[10] Galison (1999).

[11] Sims (2023).

[12] Renn (2008).

[13] Renn & Valleriani (2001); Büttner (2008).

addition, Renn argues that a special trigger of change in scientific knowledge is a borderline problem, a challenging object that sits at the intersection of distinct knowledge systems—such as thermodynamics and electrodynamics in the case of blackbody radiation—and compels their integration or restructuring. Borderline problems are particularly relevant "to understanding changes in highly developed, disciplinary science," as in these cases it is usual to encounter an object or problem that "falls under the domain of application of more than one system of knowledge."[14]

In the present contribution, the concepts of challenging object and borderline problem help us account not only for the cooperative hybridization around supernovae, but also for their deep epistemic productivity in destabilizing established frameworks and prompting new approaches. From this perspective, supernovae did not simply enable interdisciplinary collaboration; they actively challenged the theoretical resources of multiple disciplines simultaneously, such as nuclear physics, observational astronomy, general relativity, and particle physics.

By combining these conceptual tools—boundary object, trading zones, challenging object, and borderline problem—we examine how supernovae became not only coordination points across disciplinary boundaries, but also engines of transformation in the epistemic and institutional configuration of astrophysics.

A substantial body of authoritative literature exists on the history of 20th-century astronomy, as well as on the development of observations of various cosmic phenomena.[15] There are also important references regarding the evolution of supernova research.[16] Unlike existing accounts, however, this paper offers a novel historico-epistemological framework by applying the concepts described above to supernovae, interpreting them as epistemic laboratories that catalyzed interaction across disciplinary boundaries. In doing so, the paper highlights their emblematic role in the historical formation of multi-messenger thinking and in the epistemic consolidation of a new field of astrophysical inquiry.

The following sections adopt this conceptual framework to examine how cross-disciplinary collaborations around supernovae laid the epistemic and infrastructural foundations of what would later be formalized as multi-messenger astronomy. Rather than following a linear chronology, our aim is to offer a synthetic narrative that highlights the key turning points at which supernova studies became sites of interdisciplinary integration. The big-picture view of the historical trajectory of the supernova studies presented through the paper shows that the transformations were not merely technical or observational, but epistemic and institutional.[17]

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[14] Renn (2020).

[15] See, for example, Harwit (2021); Longair (2013).

[16] See, for example, Marschall (1994).

[17] For the importance of big-picture narratives, see Secord (1993).

The Relevance of Being Transient

To better frame our focus on the history of supernova research, it is important to consider a key distinction that practitioners make among astrophysical sources: the difference between continuous and transient emitters. Continuous sources, such as the Sun or orbiting binary star systems far from the coalescence phase, produce signals—electromagnetic, neutrino, or gravitational—that can be observed by integrating data over long timescales. In the case of the Sun, the sustained flux of photons and neutrinos has allowed researchers to probe the structure and dynamics of the solar interior. However, while solar studies involved more than one messenger, they emerged in the 1960s primarily within the framework of nuclear and particle physics, and with limited coordination across observational communities.[18] Thus, despite recent efforts to frame solar observations as precursors to multi-messenger astronomy, such a reading risks anachronistically projecting current conceptual frameworks onto a period in which neither the epistemic integration nor the collaborative infrastructure characteristic of multi-messenger science had yet emerged.[19]

Binary star systems, prior to their merger phase, also exemplify continuous sources. They were instrumental in shaping theoretical models of gravitational radiation in the 1980s and 1990s, which in turn played a central role in driving the shift from resonant bar detectors to large-scale interferometric observatories such as LIGO and Virgo.[20] In this context, binary systems functioned as boundary objects, sustaining collaboration among relativists, data analysts, and instrument scientists. But they also took on the role of challenging objects, as the effort to model and detect their gravitational emissions strained the limits of existing theoretical tools and experimental designs, prompting innovations in detecting technologies, waveform modeling, noise reduction, and data processing techniques. By the way, at the time of the writing of this paper, gravitational radiation from continuous sources remains undetected by the interferometric antennas available today.

Transient astrophysical events—such as core-collapse supernovae, gamma-ray bursts, and compact binary mergers—are short-lived, high-energy phenomena that unfold over timescales ranging from milliseconds to months. Their brevity, intensity, and multi-messenger emissions (photons, neutrinos, gravitational waves, cosmic rays) make them uniquely suited for coordinated, time-sensitive, cross-domain observation. In this paper, we argue that the emergence of multi-messenger thinking—and the development of the cultural, epistemic, and institutional forms that underpin it—has been shaped most profoundly by the study of such transients.

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[18] The Sun had already been studied across the entire electromagnetic spectrum—including radio and X-ray wavelengths starting from the postwar years. Neutrino observations began in the 1960s with the pioneering chlorine-based experiment by Ray Davis, but it was only later (in Europe, the Soviet Union, the United States, and Japan, in the 1980s–1990s) that the solar model was confirmed and the "solar neutrino problem" resolved. Neutrino detection enabled direct probing of the solar core, in contrast to electromagnetic radiation, which primarily reveals the outer layers and takes ~10^5 years to emerge from the interior.

[19] Hudson & Svalgaard (2019); Smith et al. (2025).

[20] La Rana (2022).

The distinctive features of transient astrophysical phenomena—such as the coalescence of neutron-star or black-hole binary systems, and core-collapse supernovae—position them as particularly fertile sites for drawing together communities with diverse epistemic commitments, including particle physicists, relativists, observational astronomers, instrument scientists, and so forth. Their sudden, fleeting nature demands rapid coordination and real-time data sharing, often pushing the limits of existing infrastructures and methodologies. As such, transient phenomena lend themselves to function as *trading zones*: localized arenas where distinct disciplinary cultures interact, developing shared tools, hybrid languages, and provisional standards of evidence. At the same time, their empirical richness and cross-domain relevance allow them to function as *boundary objects*, maintaining a recognizable identity (for example, "supernova") while accommodating multiple interpretations and investigative goals.

Yet transient events are more than sites of coordination—they also function as challenging objects, in that they often resist explanation within the bounds of existing theoretical frameworks. Supernovae, for instance, have long defied complete modeling due to the complex interplay of nuclear physics, fluid dynamics, neutrino transport, and relativistic effects. These limitations have driven significant epistemic innovation. Furthermore, transients can act as borderline problems—phenomena that sit at the intersection of mature but distinct knowledge systems, such as general relativity, particle physics, and astrophysics. Addressing them has required not only practical collaboration but conceptual realignment, as models and assumptions from one domain are forced into dialogue with those from another.

It is precisely this compound character—as boundary objects that foster the formation of trading zones, and as borderline problems that destabilize and reconfigure disciplinary boundaries—that renders transient phenomena historically central to the emergence of a multi-messenger research culture. Among these, supernovae stand out: the explosive deaths of stars, marked by abrupt increases in brightness, were among the earliest transient events observed in astronomy. Throughout much of the 20th century, they remained the only visible indicators of extreme astrophysical processes—a status that persisted until the discovery of quasars in 1963. Their long-standing empirical visibility, coupled with persistent theoretical challenges and cross-domain significance, makes them an ideal lens through which to reconstruct the historical roots of multi-messenger astronomy.

From Novae to Super-Novae: The Birth of a New Class of Astronomical Objects

The conceptual emergence of the supernova as an object of astrophysical inquiry cannot be reduced to observational discovery alone. Rather, it resulted from the convergence of distinct knowledge systems—astronomical observation, nuclear physics, and emerging models of compact stellar matter. This convergence took shape in the early 1930s through the collaboration between the astronomer Walter Baade and the physicist Fritz Zwicky, working between Mount Wilson Observatory and

Caltech. Their coining of the term *super-novae* marked more than a semantic shift: it signaled the articulation of a new epistemic object, one that challenged existing classificatory schemes in astronomy while also drawing on speculative ideas from theoretical physics.[21]

At this early stage, the supernova functioned as a challenging object in the strongest sense of the term: it defied integration into the available conceptual resources of both observational astronomy and stellar theory. Its empirical features—brightness, suddenness, rarity—stood in tension with established categories, while the proposed mechanisms behind it invoked still-hypothetical entities such as neutron stars and neutrinos, as well as the poorly understood phenomenon of cosmic rays. Supernovae thus catalyzed efforts to develop new theoretical frameworks, expanding the observational ambition of astrophysics. Supernovae were not only challenging objects, but borderline problems, in that their interpretation required interaction—and often confrontation—between two relatively mature and autonomous knowledge systems: observational astronomy, grounded in empirical classification and stellar evolution theory, and nuclear physics, increasingly concerned with the properties of dense matter and high-energy processes.

A paradigmatic example of contentious confrontation lies in Baade and Zwicky's visionary suggestion that the "super-nova process represents the transition from an ordinary star into a *neutron star*," which in its final stages consists of extremely closely packed neutrons.[22] This idea—derived from recent discoveries in nuclear physics (notably Chadwick's 1932 discovery of the neutron)—was met with deep skepticism by the astronomical community. Professional astronomers were very conservative, and very cautious, because their suggestion carried with it "grave implications regarding the ordinary views about the constitution of stars."[23]

Crucially, this moment also laid the groundwork for the formation of a trading zone between communities that, until then, had remained largely separate: astronomers focused on optical observations, physicists concerned with nuclear processes and elementary particles, and cosmologists grappling with the origins of cosmic expansion. Figures such as Zwicky, Baade, Millikan, Lemaître, and later Gamow and Schönberg participated in this zone, not by unifying their theories, but by creating shared problems, provisional languages, and hybrid practices that allowed their domains to interact. The suggestion that supernovae could generate cosmic rays, for instance, or mark the transition to a neutron star, opened a discursive space where speculative physics and observational astronomy could co-evolve, despite their differing standards of evidence and explanatory norms.[24]

Georges Lemaître, a pioneer of the expanding universe model, suggested that cosmic rays might be remnants of a highly radioactive process, in his model of the beginning of the cosmos as a giant explosion.[25] This idea may well have inspired Zwicky

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[21] Osterbrock (2001).

[22] Baade & Zwicky (1934c). Emphasis added.

[23] Baade & Zwicky (1934c). On the evolution of the concept of dense matter in stars, see Bonolis (2017).

[24] Baade & Zwicky (1933, p. 138); and Baade & Zwicky (1934a; 1934b; 1934c).

[25] Kragh (2012); Mitton (2020).

to propose supernova outbursts as a source of cosmic rays. Supernovae acted as boundary objects: flexible enough to be adapted by different research communities, yet stable enough to coordinate joint inquiry. For particle physicists, they became candidates for natural neutrino sources; for relativists, they pointed to extreme conditions of gravitational collapse; for astronomers, they were luminous transients to be catalogued and tracked. What allowed supernovae to operate as a common reference was not epistemic consensus, but the flexibility of the concept across domains, combined with its capacity to anchor collaboration. Over the following decade, this collaborative framework was deepened by observational efforts to identify supernova remnants (such as Baade's 1938 proposal that the Crab Nebula was the leftover of the 1054 event), and by theoretical developments linking neutrino emission to core collapse processes, as in the 1941 work of Gamow and Schönberg.[26] Although neutrinos had not yet been detected, their proposed role in stellar explosions offered a bridge between astrophysical phenomena and subatomic theory, further reinforcing the supernova's role as a multi-messenger object in formation.

In sum, Baade and Zwicky's early work on supernovae illustrates how a single object can operate at multiple conceptual levels: as a challenging object resisting easy explanation, as a boundary object anchoring interdisciplinary collaboration, and as a borderline problem forcing the interaction—and eventual restructuring—of distinct knowledge systems.

Nucleosynthesis and Radiation: Toward a Composite Model

By the early 1950s, supernovae had come to occupy a central position in the evolving intersection between nuclear physics and observational astrophysics. As cosmic ray studies revealed the presence of heavy nuclei mirroring stellar abundances, the question of the origin of the elements became an epistemic crossroads—one that required the integration of spectroscopic data, nuclear theory, and the emerging computational modeling of stellar processes.[27] This integration created both a theoretical demand and a collaborative opportunity: a prime example of a trading zone in which distinct disciplinary cultures—astronomy, nuclear physics, and later cosmology—engaged in shared practices while maintaining divergent commitments and tools.

At the center of this interaction was the supernova, now increasingly seen not just as an optical phenomenon, but as a boundary object linking observational signatures to theoretical models of nucleosynthesis. This object could be approached through spectral lines (as in Minkowski's classification work), through light curves (as developed by Baade), or through nuclear decay chains. Its flexibility allowed researchers from disparate domains to converge on a common object of inquiry without requiring theoretical unification. At the same time, its complex dynamics, particularly the formation and ejection of heavy elements, made it a challenging object—one that

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[26] Baade (1938); Gamow & Schönberg (1940; 1941).

[27] Freier et al. (1948); Haar (1950).

resisted straightforward explanation within any single disciplinary framework, and that pushed existing models of both stellar structure and nuclear interactions to their limits.

The advent of digital computing further transformed this trading zone by providing the technological means to integrate and simulate these diverse knowledge systems. Computers enabled the development of advanced tools for astronomical data processing and theoretical modeling. In doing so, they not only expanded the epistemic reach of each discipline but also facilitated the emergence of a hybrid research culture, in which simulation, observation, and theory could be iteratively linked around a shared object.[28]

Among the key figures in this emerging epistemic space was Gamow, who played a pivotal role in linking cosmology, nuclear physics, and stellar evolution. Gamow and his coworkers attempted to explain the observed relative abundances of chemical elements by proposing that they are created in the primordial universe.[29] However, nuclear properties pointed to a different mechanism: that elements heavier than hydrogen and helium are actually produced through nucleosynthesis within the cores of massive stars.[30]

The unprecedented multicultural collaboration between astronomers and nuclear astrophysicists culminated in the so-called B^2FH paper (1957).[31] Authored by Geoffrey and Margaret Burbidge, William Fowler, and Fred Hoyle, the paper synthesized astronomical observations and nuclear theory into a unified account of element formation in stars and stellar explosions. It was the product of an extraordinary fusion of expertise—a collective output of the trading zone surrounding Caltech and the Mt. Wilson and Palomar Observatories. Though the paper formally addressed nucleosynthesis in general, it emphasized that the most efficient mechanism for dispersing heavy elements was the explosive ejection of matter during supernovae.

This marked a critical epistemic shift: supernovae were now conceived not only as transient light sources, but as cataclysmic events producing multiple signals: electromagnetic radiation, neutrinos, neutrons, and heavy nuclei. The interpretive framework required to make sense of this multi-output system could no longer be confined to a single disciplinary domain. Supernovae thus came to function not just as boundary objects but as challenging objects—empirical systems that exceeded the modeling capacity of existing frameworks and demanded their transformation.

Moreover, the supernova emerged as a virtual laboratory for testing hypotheses about nuclear structure and stellar evolution. Baade's light curves, which showed exponential energy decay, implied underlying radioactive processes and led to the first concrete linkage between supernova outbursts and the synthesis of heavy elements.[32] The explosion itself became the site where diverse emissions—photons, particles, and nuclei—were simultaneously generated and could, in principle, be correlated.

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[28] For a review outlining the general picture at the end of the 1950s, see Cameron (1959a).

[29] See also Alpher, Bethe, & Gamow (1948); Kragh (2005).

[30] A relevant example is Fred Hoyle's work between 1946 and 1954.

[31] E. M. Burbidge, Burbidge, Fowler, & Hoyle (1957).

[32] Baade, Burbidge, Burbidge, Christy, & Fowler (1956); Temesváry (1957).

In sum, the postwar nucleosynthesis debates and the emergence of the B^2FH framework consolidated the supernova as a multimodal epistemic object and as a potential emitter of very different kinds of signals.

Bridging Astrophysics and Particle Physics: Supernovae as Cosmic Accelerators

The reinterpretation of the Crab Nebula in the early 1950s marked a pivotal moment in the convergence of astrophysics and particle physics. Initially known as a bright optical remnant of a historical supernova, the Crab was redefined through the emerging lens of radio astronomy, which detected it as the first galactic radio source.[33] Its radio flux, a hundred times more powerful than the Sun's output across all wavelengths, exhibited properties inconsistent with thermal emission. As Greenstein and Minkowski concluded in 1953, "no model with purely thermal sources is adequate" for the radio emission from the Crab Nebula.[34] This anomaly rendered the Crab a challenging object, confronting astronomers with phenomena their models could not explain and inviting cross-disciplinary reinterpretation.

The turning point came with the application of synchrotron radiation theory, drawn from accelerator physics, to explain the Crab's emission.[35] When Baade confirmed high polarization in the Crab's optical light—as predicted by synchrotron models—the link between high-energy particle acceleration and astrophysical processes gained empirical credibility.[36] This redefinition transformed the Crab into a boundary object capable of sustaining collaboration between radio astronomers, optical observers, and particle physicists, each engaging with the object from distinct disciplinary vantage points.

These developments also activated a trading zone in which new interpretive languages emerged around the shared challenge of understanding cosmic acceleration mechanisms. Cosmic rays, long studied near Earth with little knowledge of their origin, could now be linked to violent astrophysical sources—particularly supernova remnants like the Crab. In 1956, Japanese physicist Satio Hayakawa proposed a model that framed supernovae as natural sites of particle acceleration, capable of producing both synchrotron radio emission and high-energy cosmic rays.[37] This marked a shift in cosmic ray studies from terrestrial phenomenology to extragalactic astrophysics, embedding them within the lifecycle of stars.

The Crab Nebula thus functioned not only as an observational bridge, but also as a borderline problem in Renn's sense: it occupied the conceptual fault-line between distinct knowledge systems—stellar evolution, radio astronomy, and high-energy particle physics—and compelled their reorganization. It facilitated the emergence

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[33] Bolton & Stanley (1949).

[34] Greenstein & Minkowski (1953, p. 12).

[35] Alfvén & Herlofson (1950); Shklovskij (1953); Ginzburg (1953; 1956), G. R. Burbidge (1956).

[36] Baade (1956a).

[37] Hayakawa (1956).

of shared concerns, hybrid tools, and eventually, the expansion of observational strategies into X-ray, gamma-ray and neutrino domains.

By the late 1950s, the advent of the space age enabled astronomers to extend observations into new spectral domains, including gamma-ray and X-ray astronomy, while early discussions of neutrino astronomy signaled a growing interest in detecting non-electromagnetic signals.[38] In parallel, efforts to observe ultra-high-energy cosmic rays using ground-based detector arrays and spaceborne instruments brought particle physicists into closer contact with the astronomical community. These developments positioned high-energy phenomena as a shared investigative frontier, where the methods, questions, and tools of astrophysics and particle physics began to interpenetrate, giving rise to a fertile trading zone.

In conclusion, the evolving understanding of supernovae—not merely as the luminous deaths of stars, but as powerful astrophysical engines capable of accelerating particles and producing non-thermal radiation—marked a pivotal shift in how these phenomena were conceptualized.[39] This transformation played a crucial role in bridging astrophysics and particle physics, establishing supernova and their remnants as key sites of interdisciplinary inquiry and setting the stage for the development of a multi-messenger approach to the cosmos.

The Violent Radio Universe and the Birth of Relativistic Astrophysics

As Geoffrey Burbidge noted in 1957, the Crab Nebula had become a "giant cosmical synchrotron," which revealed "how closely linked together are the observational astronomer on the one hand, and the nuclear and cosmic ray physicists on the other."[40] Supernova as a boundary object was connecting ever more disciplinary approaches.

This new integrative framework catalyzed the rise of relativistic astrophysics, a field rooted in the dynamics of compact objects, extreme energies, and the application of general relativity. Burbidge's energy estimates for the Crab and the jet from the galaxy Virgo A offered an early model of cross-domain synthesis, linking observations of jets and radiation with models of magnetic fields and particle populations.[41] These hybrid interpretations marked the formation of a trading zone, where shared tools and conceptual crossovers allowed the gradual fusion of observational astronomy with theoretical particle and field physics.

In the early 1960s, Fowler and Hoyle hypothesized that massive compact objects at galactic centers might collapse catastrophically—what they called "super-supernovae"—producing neutrinos and triggering nucleosynthesis.[42] Around the same time, the optical identification of 3C 273—a powerful radio source of unknown

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[38] On the transformation of postwar astronomy into a multi-wavelength discipline, see DeVorkin (1992).

[39] G. R. Burbidge (1959).

[40] Burbidge (1957, p. 264).

[41] G. R. Burbidge (1958a; 1958b). A radiation that Baade (1956b) had recently demonstrated to be strongly polarized.

[42] Hoyle & Fowler (1963).

nature, soon labeled *quasar*—confirmed the existence of these extremely energetic, distant sources. This object was as bright as an entire galaxy, and its incredibly high, unprecedented redshift placed it at cosmological distances, near the edge of the known universe.[43]

Quasars exceeded the descriptive power of any single discipline, forcing conceptual shifts in both physics and astronomy. They also provided an empirical basis for the reconfiguration of general relativity as a physical theory, after it had long existed primarily as a mathematical construct.[44]

Further observational breakthroughs soon followed. The discovery of pulsars in 1967—rotating neutron stars emitting periodic radio pulses—offered direct confirmation of supernova remnants as hosts of compact objects.[45] The Crab Nebula pulsar was recognized as such the following year.[46] This interpretation demanded tight collaboration between radio astronomers, nuclear theorists, and gravitational physicists. At the same time, computer simulations of core-collapse supernovae confirmed their role as sources of cosmic rays, neutrinos, and neutron stars, further reinforcing the supernova as a site of multi-emission significance.[47]

With the launch of X-ray satellites in the 1970s, a new observational domain opened. X-ray emissions from accreting matter near neutron stars and black holes revealed further layers of the violent high-energy universe.[48] These observations not only confirmed theoretical predictions but also demonstrated that such objects could serve as natural laboratories for exploring fundamental forces, from gravity to the strong and weak nuclear interactions.

By the early 1970s, supernovae, pulsars, quasars, and black holes were now seen as potential sources of a variety of signals—photons, cosmic rays, neutrinos—each governed by different physical processes and detectable by different techniques. These phenomena functioned as boundary and challenging objects, calling for cooperative approaches and driving epistemic and technological innovation.

Beyond the Electromagnetic Domains: Gravitational Waves

In 1966, John Wheeler offered a compelling metaphor for the epistemic landscape of supernova research.[49] At the time, it was still an open question whether the supernova event of July 1054 that gave birth to the Crab Nebula had left behind a neutron star, though the pulsar itself was only discovered in November 1968 at the Arecibo Radio Observatory. In this regard, he described the Crab Nebula as an object to

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[43] Hazard, Mackey & Shimmins (1963); Schmidt (1963).

[44] See Blum, Lalli, & Renn (2018); Eisenstaedt (1986).

[45] Hewish, Bell, Pilkington, Scott, & Collins (1968).

[46] Comella, Craft, Lovelace, Sutton, & Tyler (1969).

[47] Cameron (1959b); Colgate & Johnson (1960); Colgate, Grasberger, & White (1961); Colgate & White (1966).

[48] Bahcall, Rees, & Salpeter (1970). See also Ruffini & Wheeler (1971a; 1971b); Webster & Murdin (1972). In late 1960s, Donald Lynden Bell conjectured that the center of ordinary galaxies might host super-massive black holes: Lynden Bell (1969).

[49] Wheeler (1966).

be approached tentatively "from both sides," through astronomical observation and theoretical modeling of neutron stars. This dual approach captures the essence of what supernovae appeared to be: challenging objects that could not be fully understood nor satisfactorily observed within the confines of a single discipline. In order to detect the possible Crab Nebula neutron star, one should identify "what features of a superdense star may be observable."[50]

Among the possible observable features, Wheeler listed gravitational waves. Detecting gravitational radiation was another challenge to be attacked from multiple sides. It required a bold conceptual and technological leap, initiated in the late 1950s by Joseph Weber. Weber began designing resonant bar detectors to detect gravitational waves—even though, at the time, their very existence was still debated within the physics community.[51] Lacking precise models of astrophysical sources, Weber's experimental strategy was exploratory. His goal was to build increasingly sensitive devices and study their response to any gravitational signal strong enough to excite a response.

For potentially detectable signals to be produced, sufficiently cataclysmic non-spherical events had to come into play, with the deployment of very high masses and energies. Theoretically, a supernova event could meet these requirements. Since it involves highly nonlinear radiative processes, the formulation of a model of gravitational wave emission from a supernova required a computational approach. Between 1962 and 1966, the first papers presenting computer simulations of the collapse of a massive star appeared, under the simplifying assumption of spherical symmetry. This hypothesis excluded the emission of gravitational waves but facilitated the first numerical simulations of the processes underlying supernova explosions by Colgate, May, and White.[52]

At the same time, theoretical work on the supernova as a source of gravitational radiation began.[53] Investigations on gravitational-wave sources gained real momentum starting from Weber's 1969 claim of first detection and from his subsequent observations.[54] In the wake of the interest and hopes raised by Weber's alleged detections, the

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[50] Note that the first pulsar would be discovered only 1 year later, and that Richard V. E. Lovelace and collaborators would detect the pulsar of the Crab nebula in 1968, providing the first observational proof of the production of a neutron star as a remnant of supernova explosion.

[51] See Collins (2004); Kennefick (2007); Trimble (2017).

[52] A brief account of these early computational studies is given in Ruffini & Wheeler (1971b). The first numerical simulations of gravitational emission from supernova explosions date back to Adler & Zeks (1975), who considered a toy-model consisting of a point mass exploding into two equal point masses. More realistic simulations would arrive 10 years later with the calculations of Stark & Piran (1985).

[53] Wheeler (1966); Thorne (1969); Ruffini & Wheeler (1971b). The 1967 paper by A. Zee and J. A. Wheeler is mentioned in several other contributions as "to be published," but was apparently never released. Though unpublished, their work was nevertheless influential in fostering theoretical studies on gravitational wave emission from star collapse.

[54] Press & Thorne (1972); Trimble (2017). Weber (1969, p. 1320) explicitly mentioned supernovae as motivating his experimental setup: he justified the choice of the 1660-Hz resonance not only because dimensions of the bar "are convenient for a modest effort," but also because "this frequency is swept through during emission in a supernova collapse."

emergence of a brand-new observational field in astronomy was proposed with the title of "Gravitational-Wave Astronomy."[55]

A new trading zone took shape, where computer simulation, relativistic field theory, and astrophysical modeling interacted productively, despite significant epistemic and methodological gaps. The supernova, as a borderline problem, had expanded its boundaries to include general relativity and the emerging field of numerical relativity.

Weber's 1969 claim of gravitational-wave detection was met with excitement and skepticism. Although no electromagnetic counterpart was observed, computer simulations suggested that gravitational collapse could occur without optical display.[56] In the absence of electromagnetic confirmation, however, the frequent "bursts" reported by Weber raised more questions than answers—especially given that their number far exceeded expected galactic supernova rates.[57] This tension between theoretical expectations, crude simulations, and early experimental data exemplified not just the fragility of emerging trading zones, but the depth of the boundary problem posed by gravitational wave detection itself. With source models still under development, numerical simulations constrained by limited computational power, and detection technologies—ranging from cryogenic resonators to interferometric designs—still in flux, gravitational waves represented an exceptionally challenging object. They demanded coordination across multiple epistemic and technical frontiers at a time when none of them was fully mature.

Despite the eventual failure to reproduce Weber's results, his experiments helped institutionalize the notion that gravitational waves could become a new observational channel, one that would require tight coordination across instruments and signals. In the early 1970s, coordinated campaigns involving radio, X-ray, and infrared telescopes —alongside neutrino detectors—were launched in response to Weber's signals.[58] Although no correlated events were found, these parallel efforts marked an early attempt to connect disparate observational strategies. While lacking the structured coordination characteristic of later multi-messenger astronomy, they reflected a growing awareness of the need to correlate signals across different detection channels.

Beyond the Electromagnetic Domains: Neutrinos

Although still considered highly hypothetical throughout the 1940s, the neutrino gradually emerged as a central protagonist in the evolving picture of stellar collapse and supernova explosions, eventually becoming one of the defining signatures of extreme astrophysical events. As mentioned above, this shift was triggered by a conceptual breakthrough: the 1940 paper by George Gamow and Mario Schönberg, which linked late-stage stellar evolution to catastrophic gravitational collapse via the

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[55] Press & Thorne (1972).

[56] Arnett (1969); Wilson (1971).

[57] See Press & Thorne (1972).

[58] See the review paper, Partridge (1975).

emission of an enormous flux of neutrinos.[59] Their insight extended the epistemic shift first set in motion by Baade and Zwicky in the 1930s, when they defined supernovae as sites of extreme physical processes, linking optical transients to compact stellar remnants and cosmic ray production. In the same spirit, Gamow and Schönberg reframed the supernova as a deeply energetic nuclear process governed by weak interactions, neutrino dynamics, and relativistic collapse. This redefinition consolidated the supernova's role as a borderline problem, not only reinforcing the supernova's status as a conceptual hinge between once-separate domains of knowledge, but also possibly expanding its observational windows to include neutrinos.

By the early 1950s, the neutrino had become a test case for speculative physics as well as a symbol of the expanding reach of observational ambition. Against the backdrop of early detection attempts using the Hanford nuclear reactor, and even before the particle's official first detection in 1956, Philip Morrison explicitly framed the idea of "neutrino astronomy," envisioning neutrinos as future carriers of astrophysical information beyond the electromagnetic spectrum.[60] Immediately after its detection, the neutrino began to be concretely considered as a potential cosmic signal alongside electromagnetic radiation.

Because of their weak interaction with matter, neutrinos travel vast cosmic distances virtually unimpeded, making them ideal messengers for probing the core dynamics of supernovae—otherwise inaccessible to optical or radio telescopes. Their observational potential catalyzed a new class of speculative models and detection efforts, inaugurating a trading zone where particle physicists, nuclear theorists, and astrophysicists negotiated shared questions and experimental strategies. Importantly, these discussions began to shift the focus of astrophysical research away from purely electromagnetic observations, setting the stage for multi-messenger epistemologies.

Meanwhile, parallel developments in radio and gamma-ray astronomy, often linked to the interpretation of cosmic ray phenomena, gave rise to new observational strategies aimed at tracing high-energy, non-thermal processes.[61] These spectral domains became increasingly understood not simply as regions of the electromagnetic continuum, but as functionally distinct channels—distinct kinds of messengers—each probing different physical regimes and interactions, and capable of revealing complementary aspects of violent astrophysical events. As the post-Sputnik era enabled access to gamma-ray, ultraviolet, and X-ray observations from space, a growing awareness emerged that every band opened a unique observational window, grounded in its own detection technologies, specialized data analysis techniques, and theoretical models. This diversification of techniques and epistemic cultures effectively transformed the electromagnetic spectrum into a multi-signal platform, well before the formal emergence of multi-messenger astronomy.

This vision was captured in 1960 by Kenneth Greisen, who emphasized the distinct diagnostic potential of each radiation type "for telling the story of special

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[59] Gamow & Schönberg (1940; 1941).

[60] Cowan, Reines, Harrison, Kruse, & McGuire (1956); Morrison (1956, p. 66).

[61] Shapiro (1996, p. 897).

processes occurring in different parts of the universe, and about the conditions of matter and fields that make these processes possible."[62] While estimating neutrino event rates from the Crab Nebula, Greisen expressed hope that neutrino detection would soon become a standard investigative tool in both physics and astronomy—a hope that illustrates how the conceptual integration of neutrinos as astrophysical messengers was beginning to take hold.

A significant milestone in the practical pursuit of neutrino astronomy came with the solar neutrino problem. The Sun was the first astrophysical object studied through multiple messengers: photons and neutrinos. In the early 1960s, Ray Davis launched a pioneering neutrino detection experiment, using a massive underground detector to shield from cosmic ray background. The first successful detection of solar neutrinos was reported in 1968, inaugurating solar neutrino astronomy and confirming key predictions of the standard solar model.[63] Davis's project, though primarily embedded in the logic of particle physics, illustrated the growing technical and conceptual interest in non-electromagnetic signals. These efforts were soon joined by additional underground detectors built to study atmospheric neutrinos, which in turn stimulated speculative estimates of neutrino fluxes from distant astrophysical sources, including supernovae.[64]

Crucially, it was in the study of core-collapse supernovae that these developments found their most compelling synthesis. As theoretical models and relativistic astrophysics advanced in parallel, supernovae increasingly appeared as sites of convergence —where photon emission, neutrino outbursts, cosmic ray production, and (eventually) gravitational waves could all be traced to a single catastrophic event. The pulsar, as a compact remnant of such explosions, began to concentrate diverse observational expectations: high-energy X-ray and gamma emission, relativistic magnetic fields, neutrino bursts, and gravitational wave signals. In this sense, the supernova—and specifically the Crab Nebula—emerged not only as a boundary object, facilitating collaboration across multiple observational traditions, but also as a borderline problem, requiring cross-field conceptual adjustments to accommodate its complexity.

By the late 1960s, the supernova had become a paradigmatic challenging object: epistemically unruly, observationally rich, and methodologically generative. It increasingly demanded collaboration across a growing number of domains—stellar evolution theory, nuclear and particle physics, observational astronomy, relativistic astrophysics, numerical relativity, and so forth—while exposing the limitations of each discipline when treated in isolation.

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[62] Greisen (1960, p. 63).

[63] Davis, Harmer, & Hoffman (1968); Bahcall, Bahcall, & Shaviv (1968).

[64] See, for example, Zeldovich & Smorodinskii (1962); Pontecorvo (1963, Section 13); Chiu (1964, 1966). For an overview of neutrino astronomy, see Bahcall (1989); and for high energy neutrino astronomy, see Markov & Zheleznykh (1961); Zheleznykh (2006).

SN1987A as a Turning Point

On the night between February 23 and 24, 1987, a supernova explosion became visible from the southern hemisphere, within the Large Magellanic Cloud. Indicated as SN1987A, it was the brightest supernova since Kepler's nova and the first to be studied with the full range of modern instrumentation. In addition to electromagnetic signals, it emitted a large amount of neutrinos into space, allowing the first detection of extragalactic neutrinos.[65] It was the first time an astrophysical phenomenon was observed through two distinct types of signals—later termed "messengers." This event marked the advent of neutrino astronomy.

The 1987 supernova was first spotted through its spectacular flare of optical light, but it was only a posteriori that scientists recognized the earliest recorded signals as neutrinos detected by Kamiokande, Irvine-Michigan-Brookhaven (IMB), Baksan, and the Liquid Scintillation Detector (LSD) in the Mont Blanc underground laboratories.[66] The temporal gap between the neutrino burst and the optical light curve—neutrinos escaping the collapsing core, photons delayed by the dense stellar envelope—offered direct evidence for long-hypothesized models of core collapse.[67] SN1987A was the kind of event astrophysicists had been waiting for since the pioneering papers by Baade and Zwicky in the 1930s. Marking the birth of extrasolar neutrino astronomy, it provided confirmation of the basic principles of the stellar collapse, unprecedented insights into the dynamic processes of supernovae, and information about the nature of neutrinos themselves.

The nearly simultaneous neutrino detections by Kamiokande-II and IMB, recording 11 and 8 events respectively, were quickly accepted and cited as foundational observations. Baksan's five events—consistent in timing—received less attention due to Cold War-era barriers and uncertainties. More controversial was the earlier burst recorded by LSD in Mont Blanc, some 4.5 hours before the others. Unconfirmed gravitational wave signals, reported by resonant bar detectors in Rome and Maryland, coincided roughly with LSD's signal.[68] Unfortunately, none of the cryogenic resonant antennas especially designed to detect gravitational waves from supernovae (at Baton Rouge, CERN, and Stanford) was operational at the time. The early neutrino burst detected by LSD was met with skepticism, and has remained a subject of debate, lacking independent confirmation except for the still more controversial alleged detection of gravitational radiation. This has prompted speculative interpretations ranging from a two-stage collapse scenario to special microlensing configurations.[69] This interpretive complexity—multiple detectors with differing results, unconfirmed

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65 See the following review papers: Trimble (1988); Dar (1997); Fransson et al. (2007); Vissani, Costantini, Fulgione, Ianni, & Pagliaroli (2011).

66 Hirata et al. (1987; 1988); Bionta et al. (1987) and Bratton et al. (1988); Alekseev, Alexeyeva, Krivosheina, & Volchenko (1987; 1988); Aglietta et al. (1987).

67 Neutrinos, originating from the core, escape the progenitor star directly, whereas optical photons must diffuse through the expanding supernova envelope.

68 Aglietta et al. (1989). Recent analysis of the correlations between Rome, Maryland, and Mont Blanc, also useful as reviews, are here: Alexeyev (2010); Galeotti & Pizzella (2018).

69 De Rujula (1987); Hillebrandt et al. (1987); Preparata (1990); Imshennik & Ryazhskaya (2004); Schatz (2015).

signals, unclear cross-messenger correspondence—exemplifies SN1987A's status, and supernovae's in general, as a challenging object. It exposed limitations in the existing epistemic infrastructures and forced scientific communities to confront unresolved questions in modeling, signal interpretation, and inter-laboratory communication. It also opened a fragile trading zone, where shared interpretive strategies began to emerge between astrophysicists, neutrino physicists, and gravitational wave researchers, even in the absence of full coordination.

A comparison of the detectors involved in the neutrino detections reinforces this point. LSD and Baksan Scintillation Telescope had been specifically designed for low-energy supernova neutrinos. Kamiokande-II and IMB, by contrast, were large-scale proton decay experiments—driven by Grand Unified Theory predictions—yet their sheer size and technical robustness made them the main sources of credible data. This mismatch between experimental intent and scientific outcome underscores the fragmented epistemic landscape of the time: a moment when supernovae could bring fields together, but not yet under a common conceptual banner.

The serendipity of this outcome testifies how, in 1987, the conceptual framework of multi-messenger astrophysics was still inchoate and largely implicit; the material and immaterial culture that would later define it had not yet taken shape. The terms "messengers" and "multi-messenger" to denote the different carriers of information that originate from astrophysical sources would come to the fore only at the very end of the 1990s.[70] Nevertheless, the SN1987A proved to be a "main rehearsal" of real-time supernova observation, as Bruno Pontecorvo pointed out, and acted as a catalyst for what would later become the multi-messenger approach.[71]

The very way the news of the appearance of SN1987A spread in the diverse scientific communities exemplifies a meaningful difference between the coordinated effort characterizing multi-messenger astronomy and the uncoordinated search of the late 1980s. While the optical appearance of SN1987A was rapidly communicated through IAU Circular No. 4316, triggering a swift and organized response across the astronomical community, the neutrino and gravitational wave communities were informed via informal channels.[72]

In his Nobel lecture, Masatoshi Koshiba recalled that they had informally "heard that there was a supernova explosion in the southern sky." Indeed, the news arrived at Kamiokande on February 25, two days after the first sighting, via a handwritten fax from a Penn. State University physicist to a US colleague at the University of Tokyo

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[70] See introduction and companion paper in this special issue: Bonolis, Lalli, & La Rana (2025); Lalli, Bonolis, & La Rana (2025).

[71] See Berezinsky (1994, p. 484).

[72] Telescopes across the southern hemisphere were swiftly redirected to observe the brightening supernova. This rapid mobilization highlights the longstanding culture of collaboration/correlation and real-time information exchange that has characterized the astronomical community since well before the digital era. See, in this special issue, DeVorkin (2025).

who was part of the Kamiokande II team.[73] Similarly, in Rome, the gravitational wave group learned the news via a phone call from the Mont Blanc.[74]

This asymmetry in communication practices reflected the deeper structural division between disciplines. Astronomy had long cultivated a culture of real-time coordination and collaborative observation. Neutrino physics and gravitational wave detection, by contrast, lacked both the protocols and the institutional linkages to act swiftly in concert. In this sense, SN1987A made visible the need for more robust cross-field infrastructures—a recognition that would later give rise to systems like the Supernova Early Warning System (SNEWS), operating since 2005.

Following DeVorkin's reasoning in this special issue, the SN1987A event exemplifies the continuation of a longstanding epistemic strategy in astronomy: the correlation of diverse observational modalities to understand cosmic phenomena.[75] Yet as discussed by Guzzardi, SN1987A also exposed the limits of uncoordinated observation.[76] In this regard, SN1987A was not merely a technical milestone, but a powerful historical episode that exposed the limits of fragmented observation and catalyzed the shift toward an integrated, multi-platform approach.

Supernova 1987A and the 2017 Kilonova: Highlighting the Turn to Multi-Messenger Astronomy

The observation of SN1987A has sometimes been retrospectively interpreted as the first effective multi-messenger event.[77] For our historical perspective, it is worthwhile to point out a distinction between an astrophysical event that *produces* a coincidence of two or more kinds of signals and one that *marks* the institutional and conceptual birth of multi-messenger astronomy as a field. As highlighted by some, SN1987A was the first astronomical event to generate a photon–neutrino coincidence, thereby hinting at the physical feasibility of a multi-signal approach.[78] However, this did not yet entail a coordinated multi-messenger framework or the formation of an integrated scientific culture, as we have argued in this paper. While it is straightforward to interpret the observations of SN1987A as anticipations of multi-messenger practices, it is worthwhile to note that the term “multi-messenger” did not appear until more than 10 years later, as the result of a process that we have discussed in this contribution by analyzing the special case of supernova research. While recent literature does apply the label “multi-messenger” to SN1987A and refers to it as a major milestone in this sense, such retrospective designations reflect the consolidation of a paradigm that gradually took shape in the subsequent years.[79] By contrast, the detection of the

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[73] Beier (2006).

[74] Giganti (2019).

[75] DeVorkin (2025).

[76] See, in this special issue, Guzzardi (2025).

[77] See, for example, Branchesi (2023); Li, Beacom, Roberts, & Capozzi (2024); Smith et al. (2025).

[78] Salesa Greus & Sánchez Losa (2021).

[79] Branchesi (2023); Li et al. (2024); Smith et al. (2025).

neutron star merger GW170817 in 2017—widely regarded as the inaugural event of multi-messenger astronomy—represented not only a multi-messenger signal but also the operational realization of the field, characterized by global coordination across gravitational wave observatories, gamma-ray detectors, and electromagnetic telescopes.[80]

First detected by the LIGO and Virgo gravitational wave interferometers as a binary neutron star merger, the event was followed—within seconds—by a short gamma-ray burst observed by the Fermi and INTEGRAL satellites. Crucially, this triggered a global mobilization of over 70 ground- and space-based observatories across the electromagnetic spectrum, which identified and monitored the optical, ultraviolet, X-ray, and radio afterglows of the merger.[81]While no associated neutrino signal was recorded, the overall event exemplified a fully coordinated, multi-platform investigation built on pre-established protocols, real-time alert systems, and shared data frameworks.

Unlike the fragmented response to SN1987A, the 2017 event was characterized by real-time, globally coordinated action. This unprecedented integration relied on a robust computational infrastructure capable of rapidly processing gravitational wave data, cross-matching candidate signals, disseminating alerts, and coordinating observations in near real time. The maturation of a technological ecosystem supporting multi-messenger work was crucial: powerful distributed computing resources, interoperable data formats, fast alert systems, and digital archives for open data access. Global observatories could now act not just in parallel but as parts of a dynamically networked research infrastructure.

In stark contrast to SN1987A, GW170817 was not only a physical convergence of multiple messengers, but the culmination of an institutional infrastructure specifically designed to capture such coincidences. What had been a fragile and improvised trading zone in 1987 had become, by 2017, a robust transdisciplinary ecosystem—anchored by systems such as the Astrophysical Multimessenger Observatory Network (AMON)—with clearly articulated scientific goals, reciprocal epistemic dependencies, and a shared conceptual language.[82] In this sense, GW170817 did not merely confirm the feasibility of multi-messenger observations—it inaugurated a new epistemic regime in which the convergence of fields such as astroparticle physics; optical, ultraviolet, X-ray, radio, and gravitational wave astronomy; and computational science became institutionalized.

If SN1987A represented a pivotal boundary object that revealed the promise and limits of early cross-disciplinary engagement, GW170817 can be seen as the operational manifestation of multi-messenger astronomy as a mature, coordinated scientific enterprise.

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[80] Abbott et al. (2017). See, for example, Abelson (2022); Mészáros, Fox, Hanna, & Murase (2019).

[81] Paradijs et al. (1997); Frail, Kulkarni, Nicastro, Feroci, & Taylor (1997); Metzger et al. (1997).

[82] Other examples are the Gravitational-wave Optical Transient Observer (GOTO), the Global Relay of Observatories Watching Transients Happen (GROWTH), and the Gamma-ray Coordinates Network (GCN).

Conclusions

This paper has argued that supernovae played a catalytic role in bringing together disparate scientific traditions and experimental strategies, acting not merely as early observational targets but as epistemic and infrastructural pivot points. In this respect, supernovae—and particularly SN1987A—can be regarded as epistemic laboratories that fostered and contributed to shape the emerging field of multi-messenger astronomy. To understand the complex and uneven process that led to the emergence of multi-messenger thinking, this paper has drawn on a set of conceptual tools: boundary objects, challenging objects, borderline problems, and trading zones. Each offers a distinct analytical perspective: the notion of boundary object captures how supernovae served as shared empirical anchors for different communities; the category of challenging object emphasizes their capacity to expose gaps in existing models and provoke new lines of inquiry; the idea of borderline problem foregrounds the deep theoretical tensions they triggered across epistemic boundaries; and the concept of trading zone highlights the emergence of new languages, tools, and collaborative strategies in the absence of full disciplinary integration. Taken together, these categories allow us to reconstruct how supernova research became a key driver in the construction of a multi-messenger epistemology. At the same time, they support a broader argument advanced by this paper: that multi-messenger astronomy is not simply the additive result of multiple "single-messenger" astronomies, but rather the historical and epistemic emergence of something conceptually new.

As argued by Galison, the coalescence of new fields often begins in trading zones, where different communities collaborate around shared problems using locally negotiated languages and protocols. Supernovae functioned as such zones throughout the 20th century, allowing scientists from disparate backgrounds to coordinate practices, build instruments, and develop compatible models. What began as loosely coupled collaborations in shared theoretical or experimental spaces ultimately gave rise to a more cohesive epistemic culture, one that would evolve into the structured, institutionalized field of multi-messenger astronomy.

Supernovae created the conditions for a profound transformation in scientific practices and frameworks. The interactions they demanded—across domains as varied as nuclear physics, particle theory, relativistic astrophysics, neutrino detection, and radio astronomy—did not merely accumulate observations across different messengers. Instead, they gave rise to trading zones where conceptual translation, infrastructural innovation, and institutional alignment became necessary to engage with phenomena that resisted disciplinary reduction. Multi-messenger astronomy emerged from these zones as a distinct epistemic project, one in which new questions, hybrid tools, and integrative strategies were constructed around the irreducible complexity of astrophysical events like supernovae. In this sense, it remains a field in search of its own definition—not merely a methodological expansion, but a novel way of probing the universe.

Over time, the trading zones born around supernova multiplied and expanded to encompass additional domains. As the supernova evolved into a mature boundary object, it accumulated an array of borderline problems, each arising at the intersection of distinct research domains: nuclear physics, observational astronomy, relativistic astrophysics, computational science, and so on. In many respects, the supernova stands as a paradigmatic challenging object, confronting researchers with a constellation of open questions, none of which could be resolved within the confines of a single discipline. Supernovae thus offer a privileged window onto the epistemic roots of multi-messenger astronomy, revealing the layered and asynchronous processes that unfolded along the many boundaries these objects inhabit. For each theoretical, experimental, and technological research field involved, supernovae pushed against established limits, both expanding disciplinary frontiers and fostering the development of trading zones where hybrid competences could emerge. Like an intricate skein of threads, the supernova resists localized unraveling: tugging on any one strand sets the others in motion, such that the resolution of one problem necessarily reverberates across other domains. In this way, supernovae exemplify how multi-messenger astronomy has emerged—not as a mere aggregation of single-messenger approaches, but as the epistemic transformation of astronomical practice into something fundamentally more interconnected, dynamic, and conceptually novel.

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