CENTAURUS JOURNAL OF THE EUROPEAN SOCIETY FOR THE HISTORY OF SCIENCE

LUCA GUZZARDI

Multi-Messenger Astrophysics and the Epistemic Reasons for Cooperative Behavior

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

▼ **ABSTRACT** Cooperative phenomena in science are frequently viewed as the result of social forces and material conditions within a given social system of knowledge. In this context, scientific requirements often remain in the background, if not entirely overlooked, in discussions about what motivates cooperation. This paper challenges such interpretations using examples from the history of neutrino astronomy and recent multi-messenger discoveries. Revisiting the hierarchy of models proposed by Suppes (1962), it argues that the ethos of collaboration in multi-messenger astrophysics is primarily driven by epistemic constraints embedded within the models describing typical multi-messenger sources and processes. These constraints necessitate cooperation among multi-messenger astronomers, regardless of other motivations for their collaborative efforts and despite the complexities and challenges involved.

▼ **KEYWORDS** Multi-Messenger Astrophysics/Astronomy, SN 1987A, Neutrino Astronomy, Scientific Collaboration, Scientific Models, Data Models

▼ **ISSUE** Volume 67 (2025), issue 1

Luca Guzzardi 0000-0003-0622-4569/ • Università degli Studi di Milano, Italy, correspondence: Luca Guzzardi, Department of Philosophy, Università degli Studi di Milano, Via Festa del Perdono 7, 20122 Milano, Italy, luca.guzzardi@unimi.it

Cite this article: Luca Guzzardi, 'Multi-Messenger Astrophysics and the Epistemic Reasons for Cooperative Behavior', *Centaurus*, 67.1 (2025), 121–142
<https://dx.doi.org/10.1484/J.CNT.5.145169>

DOI: 10.1484/J.CNT.5.145169

BREPOLS

> The Emperor—so a parable runs—has sent a message to you, the humble subject, the insignificant shadow cowering in the remotest distance before the imperial sun .... The messenger immediately sets out on his journey; a powerful, an indefatigable man; now pushing with his right arm, now with his left, he cleaves a way for himself through the throng ...
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> *F. Kafka (1919),* An Imperial Message

1. Introduction

Some time ago I downloaded on my smartphone an application called OpenAMON, which is maintained and operated by the AMON-Astrophysical Multimessenger Observatory Network, a scientific program of many participant institutions, mostly observatories, that monitor the sky with the final aim to trace and study remote, rapidly fading cosmic sources and events—the so-called "transients."

The observing stations participating in AMON are sensitive to four types of signals: electromagnetic waves across the entire spectrum—from gamma rays to radio waves—gravitational waves, neutrinos, and cosmic rays. In order that a detection be claimed by a single observing station, the corresponding signal must be recorded above a certain confidence level. However, mostly due to the distance and short duration of the originating events, if individually considered some signals may be under that confidence level and appear as statistically indistinguishable from the background or any other kind of noise—in other words, they are "sub-threshold." AMON's strategy is that a combination of two or more sub-threshold signals may achieve the same level of confidence that allows a claim for a genuine detection.

From the OpenAMON app I periodically get this sort of message (received on March 16, 2022):

> Neutrino alert! An intriguing event has just been detected by the IceCube neutrino telescope! This event has a 36.5% chance to be a neutrino of astrophysical origin ... Is it the result of a blazar, a supernovae [sic] ...? This alert has been sent to astronomers around the world so they can point their telescopes toward the source of this event. Another signal from a different messenger could allow to identify the source and understand the mechanisms powering the emission.

Warning messages of this kind can be more or less properly understood depending on one's interest and level of education in astroparticle physics, an essentially novel field at the intersection of particle physics and astrophysics. However, even without profound notions in that realm, virtually any reader may recognize that: (1) the sender is interested in knowing about the source of an (elusive) particle detected by a certain experiment called IceCube—indeed, the question is whether this results from certain cosmic events like a blazar, a supernova, or something else; and (2) the sender needs cooperation from other scientists in order to gain that knowledge—

indeed, the alert is said to be shared with the astronomical community so that they can jointly detect signals from "messengers" of other species (that is, *not* neutrinos, whatever they might be) and clarify the nature of the source and the mechanisms behind the emission both of neutrinos and of those other messengers, in case they are detected. Moreover, the way the expectation about the potential of multiple joined observations is expressed seems to imply the sender believes that (2), the request to cooperate, is crucial, maybe vital, to gain (1), the knowledge about the source.

This paper aims to clarify the relation of component (2) to (1). Undoubtedly, these features are different by their very nature. Whereas (1) pertains to the epistemic structure of a certain group of phenomena, (2) suggests a certain social strategy, the adoption of which promises to solve the problem presented in (1). So, the question can be formulated in very general terms as follows: what kind of social framework can be designed to solve a certain epistemic assignment?

Framed in this manner, my subject here resembles social epistemology in its most classic sense—but with a peculiar nuance. The social epistemologist may wish to study whether and how variations in social frameworks lead to epistemic gains and losses. One of the earliest advocates of the field stated that its goal is to "identify the properties of epistemically well-designed social systems, that is, to specify the conditions under which a group of individuals … succeed, through their interactions, in generating a progressive sequence of consensus practices."[1] Of course, the epistemic structure sets up basic requirements, such as the research questions that should be answered in a certain investigation; but the social epistemologist is basically free to design a social system capable of maximizing the epistemic advantages and answering those questions.

To appreciate the problem, let us begin with a utilitarian perspective on cooperation in science. Drawing on Kitcher's *The Advancement of Science* (1995), we can view cooperative strategy as an optimal response to the problem of resource allocation. Researchers typically have a finite amount of resources—time, funding, skills, and so forth—to generate knowledge, each at some cost. According to Kitcher, collaborative research becomes advantageous when the resources required for individual researchers to achieve their goals independently exceed the resources needed to reach the same outcome collectively. The model can be refined further by distinguishing between "pure" agents, driven primarily by the pursuit of truth, and epistemically "sullied" agents, who may be motivated by personal interests such as priority, prestige, or career advancement. Even in these more complex cases, the collaborative approach is favorable when individual resource demands surpass the collective resources required to attain the same objectives. As research grows more specialized and complex, it becomes increasingly efficient for scientists to leverage each other's expertise, along with shared material and social resources, rather than working in isolation, in order to attain a certain epistemic goal.

Notably, Kitcher's economics-oriented approach treats knowledge in purely quantitative terms, framing cooperation as a social strategy to maximize a certain "quantity

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[1] Kitcher (1995, p. 303).

of knowledge" within finite resources. Yet, this knowledge quantity remains a "black box." While his analysis shows that scientific knowledge is affected by social constraints, it leaves open the question of how, if at all, epistemic constraints interact with these social dimensions.

In the present paper I argue that the "quality of knowledge" also matters *in designing the social organization of science*—that the epistemic structure of a problem can significantly shape the social framework in which the problem is developed and its solution is pursued. In particular, I claim that in cases such as that illustrated by my alert message, a peculiar, "cooperative" social structure is not only desirable in view of a social epistemological analysis but required by the epistemic constraints involved.

I want to stress that this claim should be taken literally: the epistemic dimension —the "quality of knowledge"—*also* matters. It matters *alongside* other factors that vary from case to case and, as such, cannot be anticipated in advance. Cooperation is a multifaceted phenomenon, encompassing numerous nuanced aspects, in which the epistemic constraints can play a more or less significant role, depending on the specific features of the historical cases considered. A full historical account of any specific case should distinguish the various constraints at play, show how they interact, and appreciate their relative weights. However, this full historical account is not—and cannot be—the aim of the present, very limited study. In the remainder of it, I content myself with providing evidence about the pivotal and relatively more important role played by the epistemic constraints in shaping the cooperative ethos of the researchers within the historical case under consideration: multi-messenger astrophysics.

2. SN 1987A and the Neutrino Signature of Supernova Explosions

The Astrophysical Multimessenger Observatory Network, together with its complementary counterpart, OpenAMON, belongs to a broad family of initiatives within the field of "multi-messenger astrophysics" or "multi-messenger astronomy."[2] Here, I intend to highlight that the establishment of similar networks, which share information and distribute alert messages about rapidly fading events (referred to as "transients"), is crucial for enabling the prompt identification of potential sources. Their strategy involves using the detection of specific signals to trigger observations of various types of messengers.[3]

The development of such networks has been driven by remarkable advances in detection and computing techniques over the past decades. These advances have been effectively utilized because emission models were developed, modified, and refined as data were collected. To realize why models played a so fundamental role, let

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[2] On multi-messenger astronomy and its origins see the Introduction of this Special Issue: Bonolis, Lalli, & La Rana (2025). On its scientific-technological features and challenges see Mészáros, Fox, Hanna, & Murase (2019). About the AMON endeavor, see Mostafá (2020).

[3] Other examples include the Gamma-ray Coordinates Network/Transient Astronomy Network (GCN/TAN), which evolved into the General Coordinates Network; and SNEWS, the Supernova Early Warning System.

us consider that virtually every cosmic source is a multi-messenger source, emitting diverse forms of radiation. However, different sources emit radiation differently, depending on the physical processes at play. These differences can include various features, such as the energies of the emitted particles, the duration of the emission, the timescales, and the sequence in which particles are emitted. To make sense of the plethora of received messengers and link specific emission patterns to potential sources, we rely on models—theoretical structures that help predict the types of particle fluxes a source might emit based on the physical processes involved. (I discuss more precisely the meaning and use of models in this context in Section 4.)

These theoretical structures have emerged from the development of particle physics during the 20th century and the rise of astroparticle physics, a historical process I will not detail here. Instead, I focus on how, at a certain point, an observed event suggested that since models of cosmic sources can predict emissions based on physical processes, the cycle could be reversed: we can infer the source starting from an observed particle flow.

On February 24, 1987, "W. Kunkel and B. Madore, Las Campanas Observatory [Chile], report[ed] the discovery by Ian Shelton, University of Toronto Las Campanas Station, of a mag 5 object, ostensibly a supernova, in the Large Magellanic Cloud."[4] On the same night, this bright object was also spotted by other astronomers at various stations located in the Southern hemisphere. The serendipitous sighting was in itself spectacular, since it was soon confirmed as the first supernova—then registered as SN 1987A—observed at naked eye since Kepler's (SN 1604).[5]

According to concepts developed since the 1960s, a significant release of energy in the form of neutrino emission would be integral to supernova explosions; however, the physical mechanism and the exact role of the emission remained unclear and alternative models were put forward.[6] Against this background, shortly after the optical sighting of SN 1987A, archival searches for neutrino detections at times compatible with the early phases of the supernova observations were made. These involved, in particular, the Kamiokande II detector, buried in the Kamioka mine, Japan; the IMB (Irvine-Michigan-Brookhaven) detector, located in the Morton-Thiokol salt mine (Ohio, US); the Liquid Scintillation Detector in the Mont Blanc Laborarory; and the Baksan Neutrino Observatory in the North Caucasus Mountains, in the Soviet Union.

In their paper resulting from the search, Hirata and coauthors reported that 12 neutrino events were detected by the Kamiokande sensors at approximately 7:35:35 Universal Time on February 23, 1987.[7] Other estimates suggest the detections were 11 or 16.[8] Around the same time, the IMB detector registered 8 events.[9] Other

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[4] Marsden (1987).

[5] For a more detailed history of SN 1987A observation and its influence on the development of multi-messenger astrophysics, see La Rana, Bonolis, & Lalli (2025).

[6] Zel'dovich & Guseinov (1965); Colgate & White (1966); Colgate (1968); Arnett (1968); Wilson (1971). For a review of extant models up to the SN 1987A observation, see Woosley & Weaver (1986).

[7] Hirata et al. (1987).

[8] José (2016, p. 297).

[9] Bionta et al. (1987).

potential detections, investigated in larger data samples, were excluded. The small number of registered particles was considered representative of the trillions of neutrinos that passed through the Earth around 7:35 UT on February 23, 1987, originating from the core collapse of a very massive star. Based on the observed position of SN 1987A, the progenitor was identified as Sanduleak −69 202, a blue supergiant in the Large Magellanic Cloud, belonging to a class of stars whose explosion had not been expected.[10]

The foundations of the descriptions of the core-collapse supernova mechanism, like that characterizing SN 1987A, have their origins in the 1930s, with Baade and Zwicky's celebrated paper on supernovae.[11] Many details remain elusive despite revisions, improvements, and considerable progress in computer simulations.[12] However, there is a wide consensus on the general outline of the final stages preceding the optical supernova burst. At the conclusion of their life cycle, stars more massive than 10 solar masses, like Sanduleak −69 202, the SN 1987A progenitor, evolve into a so-called onion-like configuration. They have a practically inert iron core surrounded by successive still-active, nuclear-burning layers of lighter elements: silicon, oxygen, carbon, helium, and hydrogen. Until this stage the star could counterbalance the gravitational inward pull with the energy released by fusing lighter elements into heavier ones. However, iron cannot fuse further without an energy supply, so the fusion in the core stops and the balance between the inner pressure of the core and the inward pull of gravity becomes unstable. Thus, with no energy to act efficiently against gravity, the collapse begins.

How exactly the implosion turns into an explosion is still matter of debate, but models essentially agree that, at a certain point, the pressure caused by collapse is so high that the inner core of the dying giant becomes incompressible and bounces off, releasing a shock wave that propagates through the material falling onto the core and finally reaches the outermost layers of the star. The different stages of this process are accompanied by phases of emission of highly energetic neutrinos, which aid in the propagation of the shock wave through the star and are finally dispersed into space as a shell whose radius grows at approximately the speed of light, leaving behind a highly compact object—a proto-neutron star that, according to specific conditions, degenerates into a black hole or (as in the case of Sanduleak −69 202) a neutron star. Meanwhile, whereas neutrinos are already on their way out of the exploding star, the electromagnetic fireworks commence in many if not all frequencies of light.

According to Arnett and coauthors, who provided the most extensive and detailed study of SN 1987A, the supernova both confirmed this general picture and provided new constraints to the models in use at that time.[13] With only poor or merely

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[10] Arnett, Bahcall, Kirshner, & Woosley (1989, p. 236). See Hillebrandt (1987) for the core collapse models at that time; Arnett et al. (1989, p. 632) for the progenitor identification with "Sanduleak −69 202" (that is, entry #202 with declination −69° in Nicholas Sanduleak's catalogue); Kleiser et al. (2011) and Handy, Plewa, & Odrzywołek (2014) for updated models taking into account the case of blue supergiant progenitors.

[11] Baade & Zwicky (1934).

[12] José (2016); Müller (2020).

[13] Arnett et al. (1989).

conjectural evidence available, core-collapse supernova mechanisms allowed for alternative descriptions. One possibility was the so-called "prompt hydrodynamical explosion," which predicted that the shock wave driving the explosion propagates unimpeded from the core to the outer space. As they explain:

> the difficulty, however, is that the expanding shock wave loses a great deal of energy as it beats its way upstream against the infalling outer core .... Larger iron cores ... are less likely to explode by this mechanism. It has proved difficult in practice to cause the explosion of iron cores larger than about 1.2 solar masses by the unaided prompt mechanism.

The competitor of the prompt hydrodynamical explosion model was the "delayed explosion mechanism," which was based on a model Stirling Colgate and Richard White advanced in 1966. This "draws upon the enormous energy released by the collapsing core during its first second. At least 99% of the binding energy of the neutron star that forms ... comes out in neutrinos." A final possibility, called "neutrino bombs," was considered by Bahcall and reported by Arnett and coauthors:

> most stellar collapses do not produce optically bright supernovae but instead emit essentially all of their energy as "neutrino bombs." This possibility implies a larger galactic stellar collapse rate than is inferred from optical surveys of supernovae, an implication that can be tested by monitoring with neutrino telescopes.[14]

Although the historical evidence is inconclusive, it seems natural to suspect that the neutrino searches conducted at the Kamiokande and IMB sites were initiated to test the general hypothesis that the majority of energy from core-collapse supernovae is released in the form of a neutrino flux. Specifically, this idea posits that "most of the binding energy released when a neutron star forms is ... emitted as neutrinos." Additionally, these efforts could potentially resolve the debate surrounding the dominant mechanism driving the explosion of stars like Sanduleak −69 202.[15] Unfortunately, in this latter—and arguably most significant—aspect, the evidence was not deemed entirely satisfactory. Nevertheless, the delayed-explosion mechanism emerged as a more promising explanation for several reasons, which are not central to the present discussion. Over time, increasingly complex models were proposed, incorporating a variety of physical processes involved in the core collapse of an exploding star.[16]

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[14] For the quotes, see Arnett et al. (1989, pp. 644–645). See also Colgate & White (1966); Bahcall (1989, esp. pp. 433–437).

[15] Arnett et al. (1989, p. 649). They also noted (p. 646) that "we ... know that the core collapsed to a neutron star because, for the first time, we saw the neutrino burst."

[16] Mezzacappa (2005).

3. Neutrino Astronomy and the Prodromes of Extended Cooperative Efforts

Possible tests for hypotheses regarding supernova explosion physics and the role of neutrino transport were long pursued by the so far relatively small but steadily growing community of neutrino astronomers. Since the early 1980s, neutrino observatories had been constructed and operated with the aim of detecting stellar collapses.[17] While these efforts did not yield immediate success, they prepared researchers to promptly recognize the significance and potential of SN 1987A. Let us remember that in February–March 1987, the initial neutrino burst was identified in few neutrino observatory records after astronomers serendipitously spotted the supernova in the Southern Hemisphere sky. The neutrino astronomers were aware that the low number of detections would make impossible, in that case, any a priori association with an event in the Large Magellanic Cloud.[18] However, 5 years after SN 1987A they could see a bright future for their field because "an international network of massive underground neutrino detectors is being established whose collective sensitivity to supernova neutrinos will be unprecedented." The common effort was expected to enable identification of the sources, particularly in cases in which "one is interested in studying a galactic supernova's first hours or days or if the supernova is obscured in the optical by the dust of the galactic disk."[19]

To show this, they constructed a theoretical model of supernova neutrino bursts, emphasizing its flexibility: it "incorporates the various generic features in the neutrino signal during its many seconds of vigorous display, but is not tied to any one calculation" and "should be viewed as a synopsis of predictions for the next galactic neutrino burst."[20] Based on this, the response of known neutrino telescopes to a nearby neutrino burst was calculated and two possible methods for source identification were considered: one based on angular information from a small number of events and requiring single detectors, the other based on triangulation between at least three detectors. The single detector method probably had some disadvantages with the neutrino telescopes available to that point, but the angular resolution—a notion that is crucial for event localization and can informally be described as the degree to which the details of a detected object can be perceived as separated—would be too poor to provide reliable source information. Expected data, they emphasized, are not "terribly bad, but there are 10 stars visible to the naked eye in a 5° cone [like that calculated]. In that same cone, there are 10^8 galactic stars. Such imprecision is inherent in neu-

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[17] Descriptions and succint historical accounts are given in Alekseev, Alekseeva, Volchenko, & Krivosheina (1987) and Aglietta et al. (1989). For a history of neutrino astronomy in this context, see Suzuki & Koshiba (2009); Close (2012, Chs. 7–8).

[18] Burrows, Klein, Gandhi (1992, p. 3382).

[19] Burrows et al. (1992, p. 3361).

[20] Burrows et al. (1992, p. 3368).

trino astronomy." The triangulation method appeared more promising but required "the coordination of a network of detectors and accurate absolute event timing."[21]

Models like the one exemplified here served as motivations for broader goals, creating opportunities for action. Burrows and coauthors concluded with an appeal to future expectations concerning the

> exciting possibilities for supernova and particle physics that are emerging underground .... A permanent scientific presence underground has begun. If this generation of neutrino telescopes does not catch a galactic burst, succeeding ones certainly will. This paper is a set of general predictions concerning the character and scientific promise of what they might see.[22]

So far, these "general predictions" seem to be confined within the neutrino astronomer community. Burrows and coauthors were not straightforward about possible interactions with other fields—a prospect that is barely mentioned. They expected that source identification through neutrino-burst detection would have been useful in special cases where location through different means would be difficult or just impossible; however, in standard cases "this would be interesting, but unnecessary, since the defining optical emissions would be extravagantly obvious."[23]

In contrast, by the end of the 1990s, the reference to the larger astronomical community became explicit. While expressing confidence that a supernova could in principle be located by the neutrino signal, some neutrino astronomers were now ready to recognize that this "may offer an opportunity to give an early warning to the astronomical community, so that the supernova light curves can be observed from the earliest possible time."[24] The panelists of the "Particle, Nuclear, and Gravitational Wave Physics" group in the Decadal Survey of Astronomy and Astrophysics analogously noted that,

> since the neutrino signal from a supernova precedes the optical signal by hours, it could be useful to predict the onset of such a supernova to allow optical instruments to point and thereby see the early rise of the light curve.[25]

This concept was equally important for establishing a supernova watch program that finally developed into SNEWS, the Supernova Early Warning System, a network that distributes early warning messages to make possible direct observations of the early stages of supernova electromagnetic emissions. SNEWS exploits

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[21] Burrows et al. (1992, p. 3383). In particular, "given a base-line distance (d) between two detectors and a relative delay (Δt) in signal arrival, the angle (a) between the base line and the supernova is given by the simple relation $\cos a = c\Delta t/d$." Updated data and calculations were not consistent with this result and expected more precise results from single detectors: Beacom & Vogel (1999); Antonioli et al. (2004, p. 6).

[22] Burrows et al. (1992, p. 3383).

[23] Burrows et al. (1992, p. 3382).

[24] Beacom & Vogel (1999, p. 1).

[25] Astronomy and Astrophysics Survey Committee et al. (2001b, p. 135). The main goal of this Decadal Survey was "to carry out a broad scientific assessment of the field and to recommend new ground- and space-based programs for the decade 2000 to 2010." For a detail description, see Astronomy and Astrophysics Survey Committee et al. (2001a, pp. xv–xviii).

> one unique feature of the neutrino signal … that it is *prompt*: neutrinos emerge on a timescale of tens of seconds, while the first electromagnetic signal may be hours or days after the stellar collapse. Therefore, neutrino observation can provide an *early alert* that could allow astronomers a chance to make unprecedented observations of the very early turn-on of the supernova light curve.[26]

Such a cooperative attitude among diverse fields and communities, that I will not follow further here, was prepared and ultimately relied on pre-existing projects, infrastructures, and agreements, which, in turn, powered "a new era of Big Science … fundamentally distributed and global in nature."[27] In the next two sections, I argue that the epistemic structure of the astronomical investigations here involved—basically meaning the way in which and the goals for which theories and experiments are constructed and research is pursued—played a pivotal role in feeding this cooperative culture, which is one fundamental piece of what we now call multi-messenger astrophysics or astronomy. So, without denying that social, economic, political, technological, and suchlike conditions all played a role in enabling the highly cooperative approach of multi-messenger astrophysics, here I am focusing on the epistemic component, which is probably the most underrated in the existing literature. To do this, I must first come back to the notion of model, which I have used rather informally so far but which has intensively been elaborated and debated in the last decades by many philosophers of science and in many and partly conflicting ways.[28]

4. Models and Their Guiding Virtue

As has often been observed, the use of theoretical structures generally referred to as "models" is ubiquitous in modern astronomy and astrophysics. When speaking of the modeling process, astronomers and astrophysicists may imply the use of numerical methods to infer, more or less inductively, an expected output from statistics about an input dataset.[29] The result of this process, usually based on ample collections of data, is sometimes called a "data model" or a "model of data," a notion that traces back to Suppes.[30] Starting from Tarski's logical concept of a model of a theory—

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[26] Antonioli et al. (2004, p. 3), italics in original. See also Habig & Scholberg (2020).

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

[28] An analytical review of the different positions in the field is given by Frigg & Hartmann (2020) in their entry "Models in Science" in the *Stanford Encyclopedia of Philosophy*. The context of the present article does not require taking sides in the ample dispute about what exactly a model is and how it relates to reality. However, to fix the ideas it is appropriate to consider two main conceptions. On one side, the advocates of the so-called "fiction view" argue that they basically are "fictions," thus employing fictional entities more or less like the characters of a novel: Frigg & Nguyen (2016; 2020); Godfrey-Smith (2009); Nguyen & Frigg (2022); Salis (2021). On the other side, the proponents of the "semantic approach" regard models as structures endowed with some kind of "morphism"—an isomorphism for some authors, a homomorphism for others—to a target phenomenon: for example, Suppes (1960); Van Fraassen (1980); Thompson (1983; 1986; 2007); Giere (1985); da Costa & French (2000). Ultimately, Van Fraassen (2008, pp. 309–311) has proposed that these two apparently different conceptions are indeed compatible.

[29] Hacking (1989); Bailer-Jones (2000); Sundberg (2010); Anderl (2016; 2019); Suárez (2013; 2023).

[30] Anderl (2016, pp. 666–668); Frigg (2022, pp. 97–103); Suppes (1962).

where, roughly speaking, a model is an interpretation of a theory in which all valid sentences are satisfied—Suppes argued that models in empirical sciences are concrete realizations of a theory's formal structure, in which all valid sentences of that theory are satisfied.[31] As such, they mediate the relationship between the theory and the target phenomena described. Suppes then proposed a hierarchy of models: just as (1) the *models of theory* are its possible, "valid" realizations; and (2) analogously, the *models of experiment* are its permissible realizations within a certain theoretical context; so (3) *models of data* are "possible realizations of the data" made to fit a prepared experimental environment (that is, a model of experiment). Models of data, Suppes concludes, are "designed to incorporate all the information about the experiment which can be used in statistical tests of the adequacy of the theory."[32]

Since data models are prepared to fit a model of experiment (for example, they are statistically analyzed to correct systematic and experimental errors and avoid random outliers), and, in turn, models of experiment are made to fit a model of a theory, the output data can be used to predict routinely expected results—"expected" given a certain model of a theory.[33] As I mentioned, Suppes considered this the highest level of his hierarchy of model concepts. This is not the appropriate place to assess the benefits and shortcomings of Suppes's view.[34] Here, I limit myself to pointing out that his insistence on the Tarskian, logical notion of a model led him to overlook an important aspect that has been explored in various ways since the end of the 19th century: theoretical models, aka models of a theory, often serve a representational role, developing a sort of narrative about the things modeled. They inform us about the features of a target phenomenon or system by utilizing tools from a different source domain. In other words, they describe the relationships between elements of the target system by drawing analogies to relationships within the source domain.

The target system can hardly be conceived as a static, non-temporal entity. Usually, a phenomenon flows from a certain state A to states B, C, D, and so forth. States B, C, D, and so forth are only partially known in advance, based on data and statistics of available data models. But the theoretical model could also predict other possible realizations that have not been observed so far. A theoretical model in

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[31] See, in particular, Suppes (1960).

[32] Suppes (1962, p. 258).

[33] A couple of examples provided by astrophysicist Jeremiah P. Ostriker (2000, pp. 2–3) in his Karl Schwarzschild lecture may epitomize Suppes's idea of models of data and their relation with the models of a theory: "Numerical studies serve the prosaic but extremely important role of allowing us to link observations through well-established theories, to factual information that we seek. Examples follow: 1) Our estimates for the relative abundances of the chemical elements in astronomical objects arise from modelling either stellar absorption spectra or emission spectra from gaseous nebulae. 2) We model stellar evolution, comparing with observations to obtain estimates of the mass, age and internal composition of the observed stars. This is the bread and butter of astronomy, without which observational results are useless. When the theories are old and very well established and the mathematical methods are well tested and customary, we even forget that we are performing an exercise of physical and mathematical modelling. We say that we 'observe' the temperature of a star or its mass when really we are doing no such thing: we are observing a spectral distribution or a light curve and inferring a temperature or a mass."

[34] For recent critical accounts, see, for example, Leonelli (2019); Bokulich & Parker (2021).

this sense typically uses the representational tools of the source domain to tell how, starting from a certain state, a number of admissible alternative states may follow, whereas other states are forbidden. Sets of possible outcomes are produced and can be tested recursively. Tests—whatever "test" could mean in the present context—eliminate some of them, leaving room for alternatives to be developed, improved, refined, and so forth.

Despite its limitations due to the emphasis on the logical-semantic view, Suppes's conception provides a clear perspective on models in which mathematics plays a significant role, moving away from the notion that scientific constructions are grounded in raw, unmediated data. In essence, it posits that the data are meaningful only within specific experimental or observational contexts, which themselves are defined by broader theoretical frameworks. When we adopt a representational view of models, it follows that once data models are constructed, they may serve as representations of the phenomena under investigation.

Finally, Suppes's hierarchy should not be understood in a temporal or developmental sense, as if theory precedes experiment, which in turn precedes data. Rather, it has a logical order. A theoretical model can emerge in diverse ways—a matter of historical contingency—but once established, it constrains possible experiments, which then delimit the data to be gathered. Although some data may refine the theoretical model, the data, once standardized and modeled, can be seen as representations of a phenomenon anticipated or described by the theory. A key challenge here is that data models can, and often do, align with multiple experimental and theoretical models. This challenge is typically resolved by cross-checking various interpretations until the scientific community reaches a consensus and "experiments end."

5. Cooperation as an Epistemically Constrained Social Practice

The dynamics of models sketched above should be further refined to achieve generalization but can shed significant light on some interesting features of the SN 1987A case study. In the above-quoted extended study, Arnett and coauthors included, mentioned, and described theoretical models for several objects: for SN 1987A in particular, for the evolution of massive stars and Type II supernovae explosions, for blue supernova progenitors like Sanduleak −69 202 and red supergiants, for presupernova phases, for physico-chemical processes involved in the different stages of the explosion (nucleosynthesis, neutrino emission, and emission spectra), and so forth. These theoretical models are linked to standardized observations: "models of experiments" in Suppes's sense, which generate data that fit in, and are used to improve, corresponding "models of data." Here we find, for example, the aforementioned neutrino archival search at Kamiokande and IMB facilities, from which a data model of the measured properties of the registered neutrino events has been extrapolated.[35] These datasets satisfied *some* theoretical models but were in contradiction

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[35] Arnett et al. (1989, p. 655, Table 3).

with others, and provided insufficient evidence in yet other cases. As we have seen, the registered neutrino burst was a crucial factor in eliminating the prompt hydrodynamical explosion mechanism for stellar masses comparable with Sanduleak –69 202. Moreover, the neutrino signal in the range of energies observed for SN 1987A could only be explained by the gravitational collapse of the stellar core to either a neutron star or a black hole, and the data were more consistent with a neutron-star outcome rather than a black hole.[36]

Of course, other features that, for many reasons, were not and could not be covered by models remained and still remain elusive. But the theoretical models revealed a lot about the fates of the entities and the processes involved, suggesting which processes astronomers should expect and—approximately—in which order they would appear. In this sense, they not only crucially helped design the observational environment to test hypotheses, like in Suppes's conception, but, as representations, they developed possible narratives that enabled researchers "to make *relevant and appropriate inferences* over time."[37] Moreover, being linked to "models of experiments," they provided what can be termed a practical guidance, since predictions about the emitted particles—their types as well as the order in which they might come—indirectly suggest who (that is, what kind of experimental setup, observational facility, and so forth) could perform the observations.

Furthermore, my revisited version of Suppes's concept of models captures other important features of the historical cases presented in Sections 2 and 3. Let us remember that the recorded neutrino emissions from SN 1987A confirmed and partially enhanced existing models of supernova core-collapse explosions. Although many details about the flux features remained unclear due to the limited number of detections, the sequence and approximate timescales of the prompt neutrino burst, along with its correlation with subsequent emissions of other particles in stars with masses similar to Sanduleak –69 202, aligned with expectations.

Following this discovery, the theoretical possibility of prompt neutrino detection for source identification began to be taken more seriously and appeared feasible. Neutrino astronomers recognized that neutrino data from SN 1987A alone were insufficient to identify a supernova candidate. However, they anticipated that, in principle and in the future, they could reverse the approach—starting with early neutrino flux detection and correlating it with a class of associated phenomena. Consequently, they constructed more refined theoretical models and proposed feasible experiments to satisfy these models, while, at the same time, developing new generation detectors with enhanced capabilities. In the end, astronomers designed a scenario in which they could start from data about a detected neutrino burst, compare them with their data models, and identify a supernova. As we have seen, some models of source localization via neutrino burst detection included, as a potential "model

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[36] Arnett et al. (1989, p. 691).

[37] I borrow the phrase within the quotation marks from Massimi (2022, p. 145, italics in original) and her idea that (perspectival) models act as "inferential blueprints" insofar as they open up "windows on reality"—on how reality will appear once a particular "vantage point" is adopted.

of experiment," triangulation among different stations: a form of cooperation-based experimental setup that satisfied the corresponding theoretical models. In sum, cooperation appeared to be a feasible approach.

In the realm of multi-messenger astrophysics, the situation is structurally similar but with a remarkable twist, which is peculiar to it. A general characteristic of objects relevant to this field is that emissions of different particles are nearly coincident. Again, this concept is instantiated with SN 1987A, which not only demonstrated that a neutrino burst was the initial signal of a core-collapse supernova but also illustrated the rapid succession of other signals in the earliest phases.[38] The same applies to other transient phenomena as well, such as neutron-star binary mergers to binary black-hole mergers, flaring blazars, and tidal disruption events. Models for these processes, sources, and associated emissions have been refined through novel observational data obtained from increasingly sophisticated detectors. These models predict the order, energies, and approximate timescales of the emissions; detectable signals like gravitational waves, gamma-ray bursts, high- and low-energy neutrino fluxes, and so forth, come out to be very fast processes that often indicate the beginning of a violent but rapidly fading event with nearly coincident signals.[39] All this requires that, especially in the initial phases, observations must be made at nearly coincident times by distant, coordinated stations, which must communicate with each other to exploit the information about the expected messengers.

Not only do the complexity of both the astrophysical events and the sources emitting the signals, as well as the specialty of these signals, require data to be gathered independently from stations capable of detecting the peculiar features of a distinct messenger, based on different methodologies, assumptions, technologies, and with diverse scientific cultures in the background. But also, the requirement for nearly simultaneous observations depends on epistemic, not practical, constraints. Because signals are expected to be both nearly coincident and of different types, dedicated stations using distinct observational methods are necessary. No single observer or instrument could feasibly capture all required data alone; even a hypothetical machine with vast computational power would still need a network of specialized, coordinated stations—thus requiring some basic form of cooperation. This basic form of cooperation encompasses any approach that aims to achieve a result through operations performed by a group of individual contributors, whether human or otherwise, working in reciprocal coordination. It stems directly from epistemic requirements inherent to the relevant models: the theoretical model of a transient event dictates that coordinated observations from independently operated instruments are essential for identifying the source and studying its features accurately; cooperation, then, is not merely a practical choice but a necessary strategy for achieving specific epistemic goals. To paraphrase an academic adage: "cooperate or perish."

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[38] To have an idea of the emission timescales in the earliest phases and their development in time, see the light curve diagram in European Southern Observatory (2007).

[39] A detailed account would need a separate study for each case but the pattern briefly sketched here appears consistent with the historical background given in recent multi-messenger literature; see, for example, Abbott et al. (2017); The IceCube Collaboration et al. (2018); Holoien et al. (2019).

Of course, as already noted, the cooperative attitude also relies on pre-existing projects, infrastructures, and agreements. However, it is the epistemic constraints at play that provide these pre-existing projects, infrastructures, and agreements with a common context and significance. It is because our models of highly energetic cosmic processes are constructed as they are and make the predictions they make, that we can exploit pre-existing cooperation infrastructures, use agreements in force and sign new ones, put forward financial plans, formulate projects, take advantage of available technologies and develop new ones, fine-tune strategies to gain international support, and improve collaborative schemes.

6. Concluding Remarks: The Ethos of Collaboration and Multi-Messenger Astrophysics

What I am arguing can be summed up in few words. Many experiments and researches appear necessarily cooperative for many different reasons: practical, technological, economic, and so forth. However, a distinctive feature of multi-messenger astrophysics in this regard is that it is a highly cooperative enterprise mainly because of one epistemic characteristic: the expectation, based on the theories (models) by which we understand our physical world, that we would not be able to gain a certain knowledge unless we join and integrate our individual efforts. This does not only suggest that a cooperative, or a collaborative, attitude should be adopted but renders it, *ceteris paribus*, inevitable. Multi-messenger astrophysics is irreducibly cooperative *for epistemic reasons*.[40]

Although it is important to distinguish between different levels and types of collaboration, this has not been my aim. I am referring to a cultural element or an ethos rather than any specific form of cooperation involved in the examples I explored or mentioned throughout this paper. By “cooperative attitude,” I mean a disposition to behave in a certain way or an inclination towards an idealized conduct, rather than an actual behavior. Thus, when I argue that a cooperative attitude is inevitable in multi-messenger astrophysics, I mean that the ethos of collaboration is integral to the emergent multi-messenger scientific culture and cannot be separated without causing this entire scientific culture to break down.

However, that a cooperative attitude is inevitable does not entail that cooperation is or will necessarily be realized *in general*. To be sure, it does not imply that an

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[40] Between “collaboration” and “cooperation” there can be differences or not, depending on their respective definitions, which it is not my aim to analyze here. In the hard sciences the term “collaboration” often has a formal usage, describing a research project put forth by cooperating institutions or scientists, a consortium, and so forth. To avoid confusion, and somewhat arbitrarily, in this paper I have mostly used “collaboration” when referring to some formal contexts, whereas “cooperation” is intended to mean a social behavior, a certain working mode that involves joint and symmetrical action by any number of individuals (or individual teams). I think that the requirement of symmetry—“in order that you cooperate with me, I must cooperate with you”—must be emphasized. It means that cooperation is more than, and should be distinguished from, collective or multi-actor knowledge. In this sense, science and many other social activities are examples of *collective* knowledge but not necessarily *cooperative*. See Guzzardi (2024) for this notion of symmetry.

actual cooperation is inevitable as soon as epistemic constraints are in place. Other circumstances may hinder or promote the cooperative efforts, and a recognition of the relevant epistemic constraints can help identify those hindrances and competitive attitudes threatening possible achievements (if they can be removed is, of course, quite a different issue).

Let us take an example of a failed collaboration from another highly cooperative field, namely gravitational-wave astronomy. Nowadays, with the growing number of detected events, models have been refined and one instrument alone can potentially reveal a merger of binary black holes empowering a gravitational wave, whereas three detectors are still necessary to locate the source. However, for the first detection of gravitational waves from a binary black-hole merger on September 14, 2015, at least two co-working interferometers were needed. In this regard, there was a striking asymmetry between the U.S. and the European communities. The USA could act autonomously, due to their LIGO antennas in Hanford and Livingston. Hence, although the European Virgo antenna in Italy was undergoing an upgrade and was thus off-line in September 2015, the detection succeeded anyway. In an idealized reverse situation (with Hanford-Livingston off-line and Virgo operating), the gravitational wave pulse would have not been detected.

The epistemic reasons for building at least two detectors in Europe were known long since and led to the so-called EUROGRAV report in 1988, "highlighting the relevant scientific case of having at least three interferometric detectors in Europe and … presenting the EUROGRAV collaboration as the coordinating body capable of developing the network."[41] The epistemic constraints were distinctly recognized —unfortunately, this did not suffice to overcome the intrinsic difficulties of the at-that-time small and divided European gravitational-wave community, which lacked coordination and common vision. This does not mean that the decision not to build two interferometers for gravitational waves in Europe was due to a willful violation of the epistemic constraints at play—it mostly depended on a lack of funding. However, this story may teach us two things: (1) if epistemic constraints are in place, cooperation—though essential for appropriately pursuing the desired epistemic goals —may still be hindered by other factors; and (2) if epistemic constraints are violated, the consequences can potentially be disastrous and jeopardize the attainment of the desired scientific goals.

Concluding, and coming back to multi-messenger astrophysics, I am not suggesting that people collaborate solely based on strict epistemic reasons, nor am I claiming that epistemic reasons are the only motivations for establishing large-scale cooperative efforts in multi-messenger astrophysics. Rather, I contend that in multi-messenger astrophysics, the relationship between epistemic constraints and cooperative behavior is of a particular kind. Multi-messenger astronomers cannot but cooperate *due to stringent epistemic requirements*, regardless of additional motivations or the complexity of the collaborative process. Their scientific goals cannot be reached

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[41] La Rana (2022, p. 22). I am indebted to Adele La Rana for highlighting the significance of this episode also in personal discussions.

unless they cooperate, whether other reasons for cooperation are present or not, and notwithstanding the costs of collaborating.

However, this form of cooperation, which may be termed epistemically constrained collaboration, is not unique to multi-messenger astrophysics. Similar dynamics may characterize other scientific fields, as epistemically constrained collaboration can take diverse forms depending on the specific requirements of the field involved.[42] What renders the case of multi-messenger astrophysics special is the unique epistemic constraint shaping its collaborative ethos: the study of transient phenomena. As discussed in previous sections, this focus—realized through a layered structure of models—necessitates nearly simultaneous observational campaigns, with a key issue being "the timely notification of newly discovered events … requiring a reliable system of alerts and fast communication."[43] More generally, it demands a high degree of coordination across a dispersed network of relatively independent instruments, making cooperation indispensable.

Acknowledgements

An earlier version of this paper was presented at the 43rd National Congress of the Italian Society for the History of Physics and Astronomy (Padua, September 5–8, 2023). I am very grateful to the participants for their comments. My warmest thanks to the editors of this Special Issue for their useful comments and for their proposal of sharing and harmonizing our contributions, as well as to two anonymous reviewers for their valuable suggestions and criticisms. Many colleagues and friends have read and commented on previous versions of this paper. I am particularly grateful to Luisa Bonolis, Stefano Furlan, Marco Giammarchi, Francesco Guala, Niccolò Guicciardini, Adele La Rana, Chiara Lisciandra, Eugenio Petrovich, Mauricio Suàrez, and Emilie Skulberg.

Funding Statement

This research has been funded by the Department of Philosophy "Piero Martinetti" of the University of Milan, under the Project "Departments of Excellence 2023–2027" awarded by the Ministry of University and Research (MUR).

References

Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., … Woudt, P. A. (2017). Multi-messenger observations of a binary neutron star merger. *The Astrophysical Journal, 848*(2), L12. https://doi.org/10.3847/2041-8213/aa91c9

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[42] For other possible examples and a more general analysis of this phenomenon, see Guzzardi (2024).

[43] "A New Kind of Big Science" (2020). See also Cenko et al. (2020, p. 4); as well as the Introduction of this Special Issue: Bonolis, Lalli, & La Rana (2025).

Aglietta, M., Badino, G., Bologna, G., Castagnoli, C., Castellina, A., Dadykin, V. L., … Yakushev, V. F. (1989). Search for neutrinos from collapsing stars at Mont Blanc. In F. Giovanelli & G. Mannocchi (Eds.), *Frontier objects in astrophysics and particle physics* (pp. 103–120). Bologna, Italy : Italian Physical Society. Retrieved from https://ui.adsabs.harvard.edu/abs/1989foap.conf..103A

Alekseev, E. N., Alekseeva, L. N., Volchenko, V. I., & Krivosheina, I. V. (1987). Possible detection of a neutrino signal on February 23, 1987 with the Baksan underground scintillation telescope of the Nuclear Research Institute of the Soviet Academy of Sciences. *Pisma v Zhurnal Eksperimentalnoi i Teoreticheskoi Fiziki, 45,* 461–464.

Anderl, S. (2016). Astronomy and astrophysics. In P. Humphreys (Ed.), *The Oxford handbook of philosophy of science* (Vol. 1, pp. 652–670). Oxford, UK: Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199368815.013.45

Anderl, S. (2019). Implicit changes of model uses in astrophysics, illustrated on the Paris-Durham shock model. *NTM Zeitschrift Für Geschichte Der Wissenschaften, Technik Und Medizin, 27*(4), 515–546. https://doi.org/10.1007/s00048-019-00225-8

A new kind of big science. (2020). *Nature Review Physics, 2*(9), 445. https://doi.org/10.1038/s42254-020-0231-3

Antonioli, P., Fienberg, R. T., Fleurot, F., Fukuda, Y., Fulgione, W., Habig, A., … Zichichi, A. (2004). SNEWS: The SuperNova Early Warning System. *New Journal of Physics, 6,* 114. https://doi.org/10.1088/1367-2630/6/1/114

Arnett, W. D. (1968). On supernova hydrodynamics. *The Astrophysical Journal, 153,* 341. https://doi.org/10.1086/149669

Arnett, W. D., Bahcall, J. N., Kirshner, R. P., & Woosley, S. E. (1989). Supernova 1987A. *Annual Review of Astronomy and Astrophysics, 27,* 629–700. https://doi.org/10.1146/annurev.aa.27.090189.003213

Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, & National Research Council. (2001a). *Astronomy and astrophysics in the new millennium.* Washington, DC: National Academies Press. https://doi.org/10.17226/9839

Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, & National Research Council. (2001b). *Astronomy and astrophysics in the new millennium: Panel reports.* Washington, DC: National Academies Press. https://doi.org/10.17226/9840

Baade, W., & Zwicky, F. (1934). On super-novae. *Proceedings of the National Academy of Sciences, 20*(5), 254–259. https://doi.org/10.1073/pnas.20.5.254

Bahcall, J. N. (1989). *Neutrino astrophysics.* Cambridge, UK: Cambridge University Press.

Bailer-Jones, D. M. (2000). Modelling extended extragalactic radio sources. *Studies in History and Philosophy of Science Part B, 31*(1), 49–74. https://doi.org/10.1016/S1355-2198(99)00028-3

Beacom, J. F., & Vogel, P. (1999). Can a supernova be located by its neutrinos? *Physical Review D, 60*(3), 033037. https://doi.org/10.1103/PhysRevD.60.033007

Bionta, R. M., Blewitt, G., Bratton, C. B., Casper, D., Ciocio, A., Claus, R., … Wuest, C. (1987). Observation of a neutrino burst in coincidence with supernova 1987A in the Large

Magellanic Cloud. *Physical Review Letters, 58*(14), 1494–1496. https://doi.org/10.1103/PhysRevLett.58.1494

Bokulich, A., & Parker, W. (2021). Data models, representation and adequacy-for-purpose. *European Journal for Philosophy of Science, 11*(1), 31. https://doi.org/10.1007/s13194-020-00345-2

Bonolis, L., Lalli, R., & La Rana, A. (2025). Shaping a multi-messenger universe: Historical and epistemological perspectives on the changing skyscape of astronomical observation. *Centaurus, 67*(1), 9–27. https://dx.doi.org/10.1484/J.CNT.5.151942

Burrows, A., Klein, K., & Gandhi, R. (1992). The future of supernova neutrino detection. *Physical Review D, 45*(10), 3361–3385. https://doi.org/10.1103/PhysRevD.45.3361

Cenko, S. B., Whitelock, P. A., Cadonati, L., Connaughton, V., Davies, R., Fender, R., … Zhang, B. (2020). *International coordination of multi-messenger transient observations in the 2020s and beyond: Kavli-IAU white paper*. ArXiv. Retrieved from http://arxiv.org/abs/2007.05546

Close, F. (2012). *Neutrino*. Oxford, UK: Oxford University Press.

Colgate, S. A. (1968). Mass ejection from supernova. *The Astrophysical Journal, 153*, 335. https://doi.org/10.1086/149668

Colgate, S. A., & White, R. H. (1966). The hydrodynamic behavior of supernovae explosions. *The Astrophysical Journal, 143*, 626. https://doi.org/10.1086/148549

da Costa, N., & French, S. (2000). Models, theories, and structures: Thirty years on. *Philosophy of Science, 67*(S3), S116–S127. https://doi.org/10.1086/392813

European Southern Observatory. (2007, February 24). The light curve of SN1987A. *European Southern Observatory*. Retrieved from https://www.eso.org/public/images/eso0708c/

Frigg, R. (2022). *Models and theories: A philosophical inquiry*. New York, NY: Routledge.

Frigg, R., & Hartmann, S. (2020). Models in science. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Spring 2020 ed.). Standford, AA: Metaphysics Research Lab, Stanford University. Retrieved from https://plato.stanford.edu/archives/spr2020/entries/models-science/

Frigg, R., & Nguyen, J. (2016). The fiction view of models reloaded. *The Monist, 99*(3), 225–242. https://doi.org/10.1093/monist/onw002

Frigg, R., & Nguyen, J. (2020). The fiction view of models. In R. Frigg & J. Nguyen, *Modelling nature: An opinionated introduction to scientific representation* (pp. 105–135). Cham, Switzerland: Springer International. https://doi.org/10.1007/978-3-030-45153-0_6

Giere, R. N. (1985). Constructive realism. In P. M. Churchland & C. A. Hooker (Eds.), *Images of science: Essays on realism and empiricism* (pp. 75–98). Chicago, IL: University of Chicago Press.

Godfrey-Smith, P. (2009). Models and fictions in science. *Philosophical Studies, 143*(1), 101–116. https://doi.org/10.1007/s11098-008-9313-2

Guzzardi, L. (2024). Imaging a black hole shadow through the Event Horizon Telescope: A study in scientific collaboration and its epistemic constraints. *Science in Context, 37*(2), forthcoming.

Habig, A., & Scholberg, K. (2020). The Supernova Early Warning System. *Nature Reviews Physics, 2*(9), 458–460. https://doi.org/10.1038/s42254-020-0221-5

Hacking, I. (1989). Extragalactic reality: The case of gravitational lensing. *Philosophy of Science, 56*(4), 555–581. https://doi.org/10.1086/289514

Handy, T., Plewa, T., & Odrzywołek, A. (2014). Toward connecting core-collapse supernova theory with observations. I. Shock revival in a 15 M⊙ blue supergiant progenitor with SN 1987A energetics. *The Astrophysical Journal, 783*(2), 125. https://doi.org/10.1088/0004-637X/783/2/125

Hillebrandt, W. (1987). Stellar collapse and supernova explosions. In F. Pacini (Ed.), *High energy phenomena around collapsed stars* (pp. 73–104). Dordrecht, The Netherlands: Springer. https://doi.org/10.1007/978-94-009-3823-6_4

Hirata, K., Kajita, T., Koshiba, M., Nakahata, M., Oyama, Y., Sato, N., … Cortez, B. G. (1987). Observation of a neutrino burst from the supernova SN 1987A. *Physical Review Letters, 58*(14), 1490–1493. https://doi.org/10.1103/PhysRevLett.58.1490

Holoien, T. W.-S., Vallely, P. J., Auchettl, K., Stanek, K. Z., Kochanek, C. S., French, K. D., … Strader, J. (2019). Discovery and early evolution of ASASSN-19bt, the first TDE detected by TESS. *The Astrophysical Journal, 883*(2), 111. https://doi.org/10.3847/1538-4357/ab3c66

José, J. (2016). *Stellar explosions: Hydrodynamics and nucleosynthesis*. Boca Raton, FL: CRC Press. Retrieved from https://www.taylorfrancis.com/books/e/9781439853085

Kafka, F. (1919). Eine kaiserliche Botschaft. In F. Kafka, *The complete stories* (p. 4; W. Muir & E. Muir, Trans.). New York, NY: Schocken Books.

Kitcher, P. (1995). *The advancement of science: Science without legend, objectivity without illusions*. Oxford, UK: Oxford University Press.

Kleiser, I. K. W., Poznanski, D., Kasen, D., Young, T. R., Chornock, R., Filippenko, A. V., … Silverman, J. M. (2011). Peculiar Type II supernovae from blue supergiants: Peculiar SNeII from blue supergiants. *Monthly Notices of the Royal Astronomical Society, 415*(1), 372–382. https://doi.org/10.1111/j.1365-2966.2011.18708.x

La Rana, A. (2022). EUROGRAV 1986–1989: The first attempts for a European interferometric gravitational wave observatory. *The European Physical Journal H, 47*(1), 3. https://doi.org/10.1140/epjh/s13129-022-00036-x

La Rana, A., Bonolis, L., & Lalli, R. (2025). The Emergence of Multi-Messenger Astronomy, Part I: Supernovae as Epistemic Laboratories. *Centaurus, 67*(1), 53–83. https://dx.doi.org/10.1484/J.CNT.5.151943

Leonelli, S. (2019). What distinguishes data from models? *European Journal for Philosophy of Science, 9*(2), 22. https://doi.org/10.1007/s13194-018-0246-0

Marsden, B. G. (1987, February 24). International Astronomical Union circular 4316. *Central Bureau for Astronomical Telegrams*. Retrieved from http://www.cbat.eps.harvard.edu/iauc/04300/04316.html

Massimi, M. (2022). *Perspectival realism* (1st ed.). New York, NY: Oxford University Press. https://doi.org/10.1093/oso/9780197555620.001.0001

Mészáros, P., Fox, D. B., Hanna, C., & Murase, K. (2019). Multi-messenger astrophysics. *Nature Reviews Physics, 1*(10), 585–599. https://doi.org/10.1038/s42254-019-0101-z

Mezzacappa, A. (2005). Ascertaining the core-collapse supernova mechanism: The state of the art and the road ahead. *Annual Review of Nuclear and Particle Science, 55*(1), 467–515. https://doi.org/10.1146/annurev.nucl.55.090704.151608

Mostafá, M. (2020). The astrophysical multi-messenger observatory network. *Nature Reviews Physics, 2*(9), 446–448. https://doi.org/10.1038/s42254-020-0205-5

Müller, B. (2020). Hydrodynamics of core-collapse supernovae and their progenitors. *Living Reviews in Computational Astrophysics, 6*(1), 3. https://doi.org/10.1007/s41115-020-0008-5

Nguyen, J., & Frigg, R. (2022). *Scientific representation* (1st ed.). Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/9781009003575

Ostriker, J. P. (2000). Historical reflections on the role of numerical modeling in astrophysics. *Reviews in Modern Astronomy, 13*, 1.

Salis, F. (2021). The new fiction view of models. *The British Journal for the Philosophy of Science, 72*(3), 717–742. https://doi.org/10.1093/bjps/axz015

Suárez, M. (2013). Fictions, conditionals, and stellar astrophysics. *International Studies in the Philosophy of Science, 27*(3), 235–252. https://doi.org/10.1080/02698595.2013.825499

Suárez, M. (2023). Stellar structure models revisited: Evidence and data in asteroseismology. In N. Mills Boyd, S. De Baerdemaeker, K. Heng, & V. Matarese (Eds.), *Philosophy of astrophysics: Stars, simulations, and the struggle to determine what is out there* (pp. 111–129). Cham, Switzerland: Springer International. https://doi.org/10.1007/978-3-031-26618-8_7

Sundberg, M. (2010). Cultures of simulations vs. cultures of calculations? The development of simulation practices in meteorology and astrophysics. *Studies in History and Philosophy of Science Part B, 41*(3), 273–281. https://doi.org/10.1016/j.shpsb.2010.07.004

Suppes, P. (1960). A comparison of the meaning and uses of models in mathematics and the empirical sciences. *Synthese, 12*(2–3), 287–301. https://doi.org/10.1007/BF00485107

Suppes, P. (1962). Models of data. In E. Nagel, P. Suppes, & A. Tarski (Eds.), *Logic, methodology, and philosophy of science: Proceedings of the 1960 international congress* (pp. 252–261). Stanford, CA: Stanford University Press. https://doi.org/10.1007/978-94-017-3173-7_2

Suzuki, A., & Koshiba, M. (2009). History of neutrino telescope/astronomy. *Experimental Astronomy, 25*(1–3), 209–224. https://doi.org/10.1007/s10686-009-9162-9

The IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, … Sivakoff, G. (2018). Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science, 361*(6398), eaat1378. https://doi.org/10.1126/science.aat1378

Thompson, P. (1983). The structure of evolutionary theory: A semantic approach. *Studies in History and Philosophy of Science Part A, 14*(3), 215–229. https://doi.org/10.1016/0039-3681(83)90013-4

Thompson, P. (1986). The interaction of theories and the semantic conception of evolutionary theory. *Philosophica, 37*(1), 73–86. https://doi.org/10.21825/philosophica.82524

Thompson, P. (2007). Formalisations of evolutionary biology. In M. Matthen &C. Stephens (Eds.), *Philosophy of biology* (pp. 485–523). Amsterdam, The Netherlands: Elsevier. https://doi.org/10.1016/B978-044451543-8/50023-X

Van Fraassen, B. C. (1980). *The scientific image* (1st ed.). Oxford, UK: Oxford University Press. https://doi.org/10.1093/0198244274.001.0001

Van Fraassen, B. C. (2008). *Scientific representation: Paradoxes of perspective*. Oxford, UK: Oxford University Press.

Wilson, J. R. (1971). A numerical study of gravitational stellar collapse. *The Astrophysical Journal, 163*, 209. https://doi.org/10.1086/150759

Woosley, S. E., & Weaver, T. A. (1986). The physics of supernova explosions. *Annual Review of Astronomy and Astrophysics*, *24*(1), 205–253. https://doi.org/10.1146/annurev.aa.24.090186.001225

Zel'dovich, Y. B., & Guseinov, O. K. (1965). Neutron conversion of matter and neutrino spectrum in stellar collapse. *Soviet Physics Doklady*, *10*, 524.