Chapter 15
Extragalactic Reality Revisited: Astrophysics and Entity Realism

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Abstract Astrophysics is a scientific field with a rich ontology of individual processes and general phenomena that occur in our universe. Despite its central role in our understanding of the physics of the universe, astrophysics has largely been ignored in the debate on scientific realism. As a notable exception, Hacking (Philos Sci 56(4):555–581, 1989) argues that the lack of experiments in astrophysics forces us to be anti-realist with respect to the entities which astrophysics claim inhabit the universe. In this paper, I investigate the viability of astrophysical realism about black holes, given other formulations of entity realism, specifically Cartwright's (How the Laws of Physics Lie. Oxford University Press, 1983), and Chakravartty's (A Metaphysics for Scientific Realism: Knowing the Unobervable. Cambridge University Press, 2007) versions of entity realism. I argue that on these accounts of entity realism, you cannot be a realist with respect to black holes, and likewise, if you want to be a realist about black holes, you cannot be an entity realist of these particular strands.

15.1 Introduction

Astrophysics is a scientific field with a rich methodological profile: it uses explanatory causal inferences, astronomical observation, complex modeling, data analysis, and simulations in order to generate theories about the individual processes and general phenomena that occur in our universe (Anderl 2015; Jacquart 2020). Scientific realism is a philosophical doctrine that seeks to carve out the specific conditions under which we may rationally believe that a scientific theory is true, or when its objects are real. Usually, realists are taken to hold that there is a mind independent world which terms in our best scientific theories successfully refer to, and that we can come to know what that world is really like. Astrophysics is a field

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in science which contain theories and claims about the nature of various processes and phenomena in the universe. The question is if the epistemological practices in astrophysics satisfy the realist criteria, and so, if we should be realist with respect to the entities which astrophysics take to inhabit the universe. Surprisingly, given the scope of astrophysics, few realists have engaged with this question.[1] A notable exception is Hacking's "Extragalactic Reality: The Case of Gravitational Lensing" in which his brand of realism—entity realism—regarding astrophysics as a whole is deemed unattainable:

> Astrophysics is almost the only human domain where we have profound, intricate knowledge, and in which we can be no more than what van Fraassen calls constructive empiricists. (Hacking 1989, 578)

Although Hacking's skeptic conclusion about astrophysical realism has been challenged (Shapere 1993; Sandell 2010; Anderl 2015), much remains to be said about the specific relation between entity realism and astrophysics. Hacking's entity realism premises belief in a certain entity on the possibility of causally manipulating that entity, which explains why he excludes both theoretical truth and realism about the majority of objects and processes found in astrophysics (as well as in cosmology and astronomy). Entity realism in this form, then, may be taken to exclude realism about astrophysical objects. The question arises as to what degree Hacking's astrophysical anti-realism can be taken to represent the broader entity realist project in the astrophysical context.

Like Hacking, Cartwright (1983) has advocated a form of entity realism which emphasizes the role played by causality in homing in on the proper objects of realism: the entities. For her, however, the connection between causation and realism is not modeled on the manipulation of entities by experimentalists. Instead, *causal explanation* is the epistemic route to realism. Causal explanations, she argues, only make sense if we take the causes described by the explanations to be real. In this sense, she permits ontology based on an *inference to the most likely cause*. That is, if we want to take the causal explanations offered by science seriously, we have to believe in the entities to which they refer. Or as Cartwright herself puts it: "In causal explanations truth is essential to explanatory success." (1983, 10) Prima facie, her view of realism as premised on causal explanations allows for a more permissive epistemology and consequently a richer ontology. Whether or not accepting causal inferences is sufficient to output realism about astrophysical entities is nevertheless opaque.

Yet another kind of entity realist account is *semi-realism*, defended by Chakravartty (2007). The epistemic aim in semi-realism is, like Cartwright's version, more ambitious than Hacking's entity realism. It introduces a spectrum

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[1] Although adjacent questions have been somewhat explored, for example cosmological realism (Merritt 2021), dark matter realism (Jacquart 2021; Allzén 2021; Martens 2022), String Theory realism (Dawid 2007, 2013), observation and simulation (Jacquart 2020), experimental limits in astrophysics (Evans and Thébault 2020), and simulation and modeling (Guala 2002; Morgan 2005; Parker 2009; Parke 2014).

of causal connection that correlates with degrees of belief. To this end, Chakravartty offers an epistemic distinction between *detection properties*, defined as "the causal properties one knows, or in other words, the properties in whose existence one most reasonably believes on the basis of our causal contact with the world." (Chakravartty 2007, 47), and *auxiliary properties*, defined as the properties which are attributed to objects by a theory. In this framework, auxiliary properties can become detection properties once new experiments and technology facilitates causal contact with them. This enables semi-realism to be firmly realist about empirically confirmed unobservables, and agnostic about unobservables posited for explanatory reasons.

The current paper addresses the viability of entity realism in the case of black holes. Are the epistemic and methodological tools available to the astrophysicist sufficient to generate rational beliefs about the existence and properties of astrophysical black holes, and if so, can this result be recovered in entity realism?[2] Studies of black holes involve many instances of methodological practices found in astrophysics, and there is a fairly wide consensus about their existence. This allows for a comparison between the epistemic justification astrophysicists have for the existence and properties of black holes, and the ontologically committing causal reasoning of the considered forms of entity realism.

15.2 Entity Realism

Scientific realists believe that our best scientific theories can be taken at face value: their terms refer to a mind independent reality, and we can come to know what that reality is like by consulting science. In the early 1980s Laudan (1981) showed that many of our best scientific theories in the past were, *pace* realism, false. Laudan's historical gambit—the so called 'pessimistic meta-induction' (PMI)—targets the fact that scientific realists postulate a connection between empirical success and truth. By breaking this connection, Laudan showed that not only do we have reason to believe that past science was false, but, by induction, our current best science is as well. If there is a connection, we have inductive reasons to think that it is between empirical success and falsehood. Any realist that aims to be taken seriously had to find a way to deal with PMI. One of the strategic revisions to the realist position was to reduce its scope. Perhaps, realists thought, theoretical terms in past successful theories were empty, but the *entities* to which those terms were intended to refer may well have existed nonetheless. If so, that would mean that, under certain specified conditions, it is rational to believe that the 'corpuscles' that J.J. Thomson experimented with in his cathode-ray tubes and the electrons that

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[2] The idea of letting the particulars of scientific epistemology inform the standards according to which realism is viable is not unanimously accepted in the realist debate. Usually, realists take a principled approach to such standards and then decide on that basis if some particular scientific epistemology merits realism. This issue may be taken to arise as an upshot of the paper's current focus, so it will be alluded to in the concluding remarks.

are essential to the operation of an electron microscope are the same ontological entity, one which is constant through theoretical changes and advancements. It is the entities, not the theory, that realism ought to target, hence *entity realism*. This move is thought to bypass PMI because it does not commit the realist to the truth of any specific theoretical model, predictively successful though it might be, and so does not suffer from being forced to accept the truth of incorrect but predictively successful theories. Prima facie, entity realism sounds like a plausible route for astrophysical realism, given that much of astrophysical theory investigates the nature of entities and processes in the universe. Decoupling realist commitment from theoretical descriptions renders a more robust ontology, and an epistemically safer route to a defensible realism. There is, however, more than one way in which to design the selection criteria for an entity's eligibility for realist commitment. In order to evaluate the specific relation between entity realism and black holes, we will first need to review a representative sample of these different criteria.

15.2.1 Hacking's Manipulationist Account

One of the founders of, and primary advocates for, entity realism, Hacking (1983) suggests taking the *manipulation* of entities to be central to realist commitment:

> Experimenting on an entity does not commit you to believing that it exists. Only manipulating an entity, in order to experiment on something else, need do that. (Hacking 1983, 263)

In order to manipulate an entity, scientists must first establish a certain level of causal connection to it. The causal connection enables scientists to extract some of the causal properties of the entity in order to build devices that can manipulate it. The core premise for realism outlined by Hacking offers a significantly smaller but epistemically safer set of things to be realist about: we may not be licensed to believe in the truth of the Standard Model of particle physics or the theory of electromagnetism, but we are licensed to believe in the reality of the electron and some of its causal properties. Hacking is in a sense employing a methodological approach to realism: since experimentation by manipulation of electrons does not require a full theory of the nature of the electron, philosophers can take a leaf from the experimenter's book and be realist with respect to entities which function, to us, as tools. However, as Hacking himself points out in "Extragalactic Reality: The Case of Gravitational Lensing" (1989, 578), his manipulationist account of entity realism is not the route to astrophysical realism simply because we cannot manipulate astrophysical entities in the way necessary for his realist criteria to kick in. This result is striking because it renders an anti-realism about basically the whole universe, given that the manipulationist premise sets a boundary of accessibility that does not extend to objects outside of our solar system. It is perhaps possible to call Hacking a *qualitative* realist about the stuff in the universe, given that there is a sufficient level of local interaction with the kind of entities that comprise the universe globally. This qualitative realism, however, requires a reductionist programme where astrophysical macro objects can be reduced to their component parts, which are such that we can use them as tools. Alas, this route begs the question against Hacking's own realism, given its reliance on the fact that astrophysical theory is correct about the constitution of macro objects.

15.2.2 Cartwright's Causal-Explanatory Account

Despite being cautious regarding scientific realists' aim of recovering truth in science, Cartwright appears to share at least some of their optimistic spirit:

> I think that van Fraassen and Duhem eliminate more than they should. It is apparent from earlier essays that I share their anti-realism about theoretical laws. On the other hand, I believe in theoretical entities, and that is my main topic in this essay. (Cartwright 1983, 89)[3]

For Cartwright, like for Hacking, the core of a tenable scientific realism is causality and entities. What sets her account apart from Hacking is that she gravitates towards causal explanation, not manipulation, as the locus of causal interest. Causal explanations require a cause as an explanandum, which in turn strongly implies some entity or process that is the real world instantiation of the explanandum. Such explanations are in some sense isomorphic to the world in a way that other forms of explanation just aren't: "In causal explanations truth is essential to explanatory success" (1983, 10). Cartwright might seem to invoke an inference that is merely an instance, or a special case, of inference to the best explanation, but she argues that in causal explanations, truth is an internal part of the explanandum, whereas in other explananda truth is an external addition.[4] The argument is that while inference to the best explanation can be used with explanations that lack this external addition, thereby generating incorrect inferences to theoretical claims, inference to the most likely cause always involves an inference to a causing entity or object, the existence of which is not dependent on theories about it:

> I infer to the most probable cause, and that cause is a specific item, what we call a theoretical entity. But note that the electron is not an entity of any particular theory. In a related context van Fraassen asks if it is the Bohr electron, the Rutherford electron, the Lorenz electron or what. The answer is, it is the electron, about which we have a large number of incomplete and sometimes conflicting theories. (Cartwright 1983, 92)

Again, we can see that this form of realism is aiming at designing principles for realism with theory-invariance of some sort built in, at least with respect to physical theory. It also aims to provide a natural connection between entities and causal explanations.

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[3] Cartwright is referring to the constructive empiricism of van Fraassen (1980) and the instrumentalism of Duhem (1991). Both views shun a realism about theory and unobservable entities.

[4] An argument to this effect can be found in Psillos (2008).

15.2.3 Chakravartty's Semi-realism

Chakravartty's semi-realism is yet another attempt to protect realism against objections like the pessimistic meta-induction, underdetermination by data, and challenges to inference to the best explanation. His specific view aims to take the idea of selective scepticism—to not accept predictively successful theories wholesale—and pair it with the dictum that "a realist's degree of belief should reflect one's degree of causal contact, with mastery and manipulation at one end of the spectrum, and mere detection and weaker speculation at the other" (Chakravartty 2007, 47). It is clear that causality again plays the main role, setting the parameters for rational belief and mapping realist commitment about properties or entities to the level of causal contact we have with them. Chakravartty fleshes out his semi-realism by distinguishing between auxiliary properties and detection properties, where only the latter are candidates for rational belief. Auxiliary and detection properties are described, and distinguished, as follows:

> An auxiliary property is one attributed by a theory, but regarding which one has insufficient grounds, on the basis of our detections, to determine its status. (Chakravartty 2007, 47)

And;

> The realist requires a practical means of demarcating detection properties (and the structures associated with them) from auxiliary properties. Here is a suggestion. Detection properties are connected via causal processes to our instruments and other means of detection. (Chakravartty 2007, 48)

Causality does much (if not all) of the heavy lifting in order to provide an epistemically safe connection between the detection properties of scientific objects and us. Knowledge about these properties, and their relations, are then thought to constitute knowledge about concrete structures of the world—objects and entities—which then furnishes the ontology of particulars in semi-realism (Chakravartty 2007, 64).

15.3 Astrophysical Black Holes

It is an understatement to say that attempting to provide a universally accepted definition of a black hole is hard. As Curiel (2019) shows, there are more than a few candidate definitions, where each field harbors a definition which suits their specific methodological needs, and in addition, many of them are inconsistent. The astrophysical picture of a black hole is centered around the notion that black holes are *objects* with properties, for example mass (and/or charge, spin, etc.), which can be connected with observational data. A couple of quotes from Curiel (2019) can, if not provide a precise definition, give a sense of the focal point for the conceptual understanding of an astrophysical black hole:

> A black hole is a compact body of mass greater than four solar masses – the physicists have shown us there is nothing else it can be. – Ramesh Narayan, astrophysicist (active galactic nuclei, accretion disk flow) (Curiel 2019, 30)

> [I]n practice we don't really care whether an object is 'precisely' a black hole. It is enough to know that it acts approximately like a black hole for some finite amount of time. . . . [This is] something that we can observe and test. – Don Marolf, theoretical physicist (semi-classical gravity, string theory, holography) (Curiel 2019, 31)

> Today 'black hole' means those objects we see in the sky, like for example Sagittarius A*. – Carlo Rovelli, theoretical physicist (classical general relativity, loop quantum gravity, cosmology, foundations of quantum mechanics) (Curiel 2019, 31)[5]

The definition(s) here clearly take a black hole to be an astrophysical system—a three dimensional object which persists through time and participates in dynamical behavior, such as black hole mergers or in binary systems—which is within the boundary of empirical study. This is the rough definition of a black hole that will be assumed in relation to the issues considered in this paper. Assuming this view means that (some of) the properties of a black hole can be accessed and studied, at least in principle.[6] Whether this in-principle epistemic access to black holes allows us to be realists about them in the philosophical sense, however, remains to be seen.

15.3.1 Discovery of Black Holes

The first black hole ever discovered is called Cygnus X-1. This discovery was not serendipitous, given that black holes would be virtually impossible to find if you don't know what to look for. The preceding work that made the discovery possible was both theoretical (Schwartzschild's solution of Einstein's field equations of GR in 1916) as well as empirical (the discovery of neutron stars in the 1960s). When the Uhuru X-Ray satellite in 1970 found an intensely flickering X-Ray source (later discovered to be part of a binary system) with a high mass in a small region, the once theoretical possibility of black holes took a leap towards becoming a reality.[7] Importantly, the methodology involved in this discovery involves an inference, theoretical background assumptions, and observational astronomy.

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[5] Sagittarius A* refers to the supermassive black hole at the centre of the Milky Way.

[6] Phenomena that occur in the interior of a black hole are in principle not accessible, given that the interior marks a causal boundary—an event horizon—which means that black holes are only partially in-principle accessible.

[7] In a panel discussion on the existence of black holes, physicist Werner Israel recalls being ridiculed for believing in the mere conceptual possibility of black holes existing: "the Director of the Institute remarked, 'Werner is going to be with us for a year. We should all talk to him and try to cure him of these silly notions he has about the possibility of black holes"' (Collmar et al. 1998, 487).

If we take the discovery of Cygnus X-1 to mark the first time the concept of a black hole was coupled with empirical evidence, we get some idea of the particular epistemology that is employed when detecting black holes. Given the rather strange nature of spacetime regions associated with black holes, the corresponding epistemology has its unique set of challenges:

> How would we know if there were a black hole? The fundamental obstacle to direct detection is, of course, blackness: a black hole will not itself give off any radiation [. . .]. But black holes will feature extremely strong gravitational fields, so we can hope to detect them indirectly by observing matter being influenced by these fields. As matter falls into a black hole, it will heat up and emit X-rays, which we can detect with satellite observatories. A large number of black-hole candidates have been detected by this method, and the case for real black holes in our universe is extremely strong. (Carroll 2019, 235)

Already, we may note that astronomical observation, both in the visible and X-ray range, is of crucial importance to obtain the data needed to make inferences about likely causes for the dynamical behavior of matter surrounding a specific region of spacetime. But to get a more fine-grained, and hopefully clearer, understanding of black hole epistemology, it will be useful to devote some space to the discovery and reasoning that supported the existence of black holes. Much of the following will be based on Celotti et al. (1999).

15.3.1.1 Stellar Black Holes

As already mentioned, Cygnus X-1 was the first observable source that was coupled with the theoretical understanding of a stellar black hole.[8] The earliest observations that detected discrete X-ray sources outside of our solar system were made in the early 1960s, using X-ray detectors which operated outside of the atmosphere. Nearly a decade later, up to twenty different X-ray sources had been identified this way. Optical observations later determined that there was a star-counterpart to one of the most intense X-ray sources, leading researchers to infer that given that the star could not itself be the source of the X-rays, the source was most likely very hot gas. The gas could only be that hot if it was being accreted from the optical star on to a compact undetected nearby binary object. In the following decade, the data improved with the launch of the X-ray satellite Uhuru, which enabled scientists to conclude that the X-ray source was in fact part of a binary system, most likely a black hole (Rothschild et al. 1974). In the mid 1980s, a detailed analysis of the Cygnus X-1 binary system combined over 55 astronomical observations, concluding that:

> Our results indicate that the mass of the X-ray source is much greater than the neutron star limit, which further strengthens its black hole candidacy. (Gies and Bolton 1986, 387)

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[8] Taking the mass range of stellar black holes to be $\approx 5M_{\odot} - 100M_{\odot}$.

As we can see, this result, though based on observational data, rests on an important piece of reasoning from eliminating alternative possibilities. The only candidate objects compact enough to generate the observed phenomena were neutron stars and stellar black holes, which was precisely the underdetermination that Gies and Bolton (1986) were trying to break. Given that the mass limit for neutron stars was uncertain, Cygnus X-1 and other signature X-ray sources like it suffered from underdetermination: the data retrieved from X-ray sources was consistent with them being neutron stars. This uncertainty was a consequence of the fact that neutron stars are so dense that the equations of state for material go well beyond known nuclear physics, and therefore beyond well confirmed and understood physics for which there is experimental data. Whatever equations of state one determines are appropriate for neutron stars in turn determines the maximum masses they can have. Celotti et al. (1999) describes how Rhoades Jr and Ruffini (1974), based on better known low density equations of state, derived a fixed upper limit on the maximum mass of neutron stars: $M_{max} \backsimeq 3.2 M_{\odot}$. Based on this limit, one can estimate the likelihood of a compact object being a stellar black hole or a neutron star based on its mass. It is this upper limit that feeds the inference that the Cygnus X-1 X-ray source is *not* a neutron star, but a stellar black hole (this reasoning is well reflected in the above quote from Ramesh Narayan). The advancements of X-ray detection coupled with optical observations, models of neutron stars, and modeling of accretion flow are clearly methods needed when inferring the existence of a stellar black hole, all of which rely on a solid understanding of basic physical principles. It's interesting to note that the fact that Cygnus X-1 was part of a binary system turned out to be prototypical for discoveries of stellar black holes since "All the known stellar-mass black holes are members of X-ray binaries" (Frampton 2016, 1).

15.3.1.2 Supermassive Black Holes

If the detection, observation, and modeling of neutron stars are significant for the epistemology of stellar black holes, the same is true for quasars and supermassive black holes (SMBHs) which are black holes with masses $\geq 10^5 M_{\odot}$. Quasars, short for 'quasi-stellar radio sources', are, as the name suggests, a source of immense radiation, far exceeding the luminosity of the Milky Way.[9] In 1964 Edwin Salpeter and Yakov Zel'doviĉ proposed that the mechanism responsible for the radiation of quasars was accretion of gas onto a SMBH, and in 1971 Lyndon-Bell and Rees suggested that our own Milky Way may host a SMBH in its centre. The most compelling candidate objects for SMBHs then, reside in the centre of galaxies. The initial inference made by Salpeter, Zel'doviĉ, Lyndon-Bell, and Rees was one built on the observation that some massive compact object produced extreme levels of

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[9] Quasars are now often referred to as active galactic nuclei (AGN), since the abbreviation 'quasar' turned out to be misleading.

radiation in the centre of (many) galaxies. Again, the upper limit of mass for neutron stars was essential for eliminating alternatives, and the modeling of accretion around black holes provided a consistency test with known data. Interestingly, scarcity of alternative explanations for the radiation seems to have played a significant part in the acceptance of SMBHs:[10]

> Accretion onto a black hole was at that point the widely accepted model, to be sure, but the seemingly exotic nature of black holes left many astrophysicists with unease; there was, however, no other plausible candidate known. With upper possible mass limits on neutron stars worked out in the 1970s, and more and more observational evidence coming in through the 1980s that the objects at the centre of quasars had to be more massive than that, and compressed into an extremely small volume, more and more doubters were won over as theoretical models of no other kind of system could so well account for it all. (Curiel 2019, 28)

> The main characteristic feature of the AGN phenomenon is the inferred compactness of the sources: luminosities of the order of 10^{46} erg s^{-1} (more than 10^{12} times the luminosity of the Sun) are produced from regions less than a light year across ($\sim 10^{18}$ cm). [...] The most extreme constraint on the compactness comes from the high-energy (X-ray) radiation. [...] This high energy radiation, together with other spectral characteristics, including line emission from gas moving at speeds of thousands of km s^{-1}, cannot be satisfactorily ascribed to any stellar-related (quasi-thermal) process. (Celotti et al. 1999, A13)

Though many in the scientific community were convinced by the strong theoretical reasoning, whatever doubt that remained dissipated with the later infrared observations and data-analysis which determined the density of the compact radio source, prompting the authors to state that “There is no stable configuration of normal stars, stellar remnants or substellar entities at that density” (Genzel et al. 1997, 219), referring to the SMBH Sagittarius A* in the Milky Way. The confidence in this conclusion is in part built on the observed orbital motions of stars in Sag A*, which requires modeling using stellar dynamics. Stellar dynamics is the description of systems containing $N \gg 10$ point masses where the mutual gravitational interaction of the point masses dictate their orbital motion, a description which is sensitive to modeling assumptions: “stars [...] behave basically like point masses in ballistic motion” (Celotti et al. 1999, A15).[11] As with its stellar counterpart, observation, inference, modeling, and eliminative reasoning all appear intrinsically coupled with SMBH epistemology.

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[10] One may note that on some accounts, the lack of alternatives may amount to confirmation. See Dawid et al. (2015), Dawid (2016) for the probabilistic strength of such an argument.

[11] See Celotti et al. (1999) for a full survey of the astrophysical evidence, and (Murdin 2001) for the equations and concepts involved in stellar dynamics.

15.4 Black Hole Realism?

15.4.1 Cartwright

Can the plurality of methodology displayed in astrophysics be analyzed in terms of causal explanations or detection properties so as go generate realism about black holes? Prima facie, this question is opaque at best, given the variety and complexity of astrophysical epistemology. One of the factors that muddies the waters is the application and use of background theory. One may plausibly claim that an inference to the most likely cause is at work when entertaining causes for extreme gravitational fields and their effects on surrounding systems which—for Cartwright—should entail being realist with respect to the black hole as an entity. However, as we have seen this inference is not only guided by, but dependent on, a multitude of background theories including general relativity; stellar dynamics; optics; accretion flow; et.c. One particularly salient aspect of the inference was that one could rule out neutron stars as a cause based on an upper mass limit, a limit which was determined using further theory:

> On the basis of Einstein's theory of relativity, the principle of causality, and Le Chatelier's principle, it is here established that the maximum mass of the equilibrium configuration of a neutron star cannot be larger than $3.2M_\odot$. (Rhoades Jr and Ruffini 1974, 324).[12]

To avoid any confusion, the 'principle of causality' is used in order to set limits on values in the equations of state so that it does not violate the speed of light. This seems to me to be a minimal requirement for something to count as a causal explanation, but not sufficient in order to categorize the upper mass limit for neutron stars as the kind of causal explanation that would merit realism for Cartwright:

> [W]hen do we have reasonable grounds for counting a causal account acceptable? The fact that the causal hypotheses are part of a generally satisfactory explanatory theory is not enough, since success at organizing, predicting, and classifying is never an argument for truth. Here, as I have been stressing, the idea of direct experimental testing is crucial. (Cartwright 1983, 98-9)

If direct experimental testing is crucial for truth or existence to emerge in Cartwright's account, then the existence of astrophysical black holes as inferred based on eliminating neutron stars as causes is beyond the limit of her entity realism. The lack of experiments was precisely the feature that led Hacking to the conclusion that we ought to be constructive empiricists about astrophysics. We cannot perform direct experimental tests on black holes, and the inference that guides reasoning in this case is so clearly coupled with the upper mass limit for neutron stars, as well as eliminative reasoning. Scientists cannot devise a direct experimental test for

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[12] Kalogera and Baym (1996) later used the same method to update the maximum mass of neutron stars to $2.9M_\odot$.

the mass limit,[13] and the eliminative reasoning can only be construed as a causal explanation in the most minimal sense. Indeed, it is unclear that the entity realist can even allow for a distinction of neutron stars and black holes at all on the basis of deriving an upper mass limit for neutron stars. The reason is that the distinction only makes sense on the basis of theory—GR. Applying Cartwright's stance on electrons, objects must *somehow* be theory-invariant to be eligible:

> [T]he electron is not an entity of any particular theory. In a related context van Fraassen asks if it is the Bohr electron, the Rutherford electron, the Lorenz electron or what. The answer is, it is the electron, about which we have a large number of incomplete and sometimes conflicting theories. (Cartwright 1983, 92)

Most descriptions of black holes, as well as the mass limit for neutron stars, are intrinsically linked to GR which limits the case for a Cartwright style entity realism about astrophysical black holes, unless direct experimental testing is available.[14] This last caveat may however be exploited by the entity realist by referring to multi-messenger astronomy.

15.4.1.1 Multi-Messenger Astronomy

The advent of gravitational wave astronomy has made it possible to cross check detection of dynamical events like black hole or neutron star mergers. The basic idea is that gravitational signals received in gravitational wave observatories (LIGO, VIRGO and KAGRA) provide the basis for an assessment of what kind of event, and what kind of objects, are the cause of the signals. One may then direct electromagnetic telescopes to the location in order to receive electromagnetic signals from the same event. The types of hypothesized events that are violent enough to create detectable gravitational waves are black hole mergers, neutron star mergers, and black hole neutron star mergers. The entity realist could then claim that this method can be used to decouple the concepts of neutron stars and black holes. The claim is grounded in the fact that the prediction of neutron star merger gravitational signals by GR can be corroborated by following up with electromagnetic observations in the entire EM spectrum (gamma-ray, X-ray, ultraviolet, optical, infrared, and radio wave). This novel kind of observation in multiple regimes was first deployed in the neutron star merger GW170817A on August 17, 2017. Gravitational waves were detected at the two US LIGO locations (coupled with a weaker "blindspot" signal at Virgo) followed by a brief gamma-ray burst detection in the Fermi space telescope seconds later. The GW signal detected

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[13] "[. . .] the EOS at $\rho \gtrsim \rho_0$ cannot be reproduced in laboratory, and it cannot be calculated exactly because of the lack of the precise relativistic many-body theory of strongly interacting particles. Instead of the exact theory, there are many theoretical models. The reliability of these models decreases with growing ρ" (Haensel et al. 2007, 14).

[14] There are exceptions: see Kehagias and Sfetsos (2009) for solutions to black holes in non-relativistic gravity.

in LIGO and Virgo was not the short "chirp" associated with GW detection of a black hole merger, but a 100 second long signal. The difference of the signals coupled with the electromagnetic counterpart—the gamma-ray burst—were telling signs of a neutron star binary merger. The detections triggered scientists to do a follow up observation with the Hubble telescope to localize the source of the gamma-ray burst: a bright object in NGC 4993, a lenticular galaxy some 130 million light years away. The particularly striking part of GW170817 is the amount of data gathered by the following EM observations of the object. Over 70 observatories and telescopes were directed at the object, which radiated in all the frequencies of the EM spectrum. Had the binary system been a black hole merger, no such radiation would have been expected.

So, can the entity realist use this event, the first ever detected by multi-messenger techniques, in order to decouple neutron stars from black holes? Perhaps not. While the event may be used in order to allow for the existence of neutron stars (and other astrophysics, like the production of heavy elements like gold and platinum), the issue still boils down to *eliminative reasoning*. Since multi messenger astronomy cannot be used in order to directly detect black hole mergers (since they don't radiate), the only way to infer their existence is to eliminate the possibility that objects detected by gravitational waves are neutron stars. Even in such a well observed event as GW170817, this is a non-trivial matter:

> Gravitational-wave observations alone are able to measure the masses of the two objects and set a lower limit on their compactness, but the results presented here do not exclude objects more compact than neutron stars such as quark stars, black holes, or more exotic objects. The detection of GRB 170817A and subsequent electromagnetic emission demonstrates the presence of matter. (Abbott et al. 2017, 161101-2)

Given that the maximum mass estimates for neutron stars are uncertain and deeply theory driven, the existence of black holes are inferred because there are no other alternatives consistent with background theory, i.e. GR. While this inference is fine as an inference to the best (only?) explanation, it lacks the experimental flavor of causal inference that is central to Cartwright's account.

15.4.2 Chakravartty

For Chakravartty, the issue is whether black holes are "connected via causal processes to our instruments and other means of detection" (2007, 48).[15] X-rays, in the sense of being radiation, may fulfill this sort of relation, but that the detected X-ray *sources* are the product of accretion, either in the X-ray binary case for stellar black holes or in the AGN phenomena for SMBHs, is not detectable in the relevant sense. This is to say in the sense that we detect some phenomena over and

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[15] In more recent work, Chakravartty (2017) develops his account further and connects it to metaphysical inference and dispositional realism, but the core of his 2007 remains intact.

above the radiation itself. That would be an additional, interpretative, step which requires modeling and theory informed inference. It would be a further step still to say that the X-ray sources should be coupled, again in the semi-realist sense of connected to our instruments, with black holes. The chain of inferences here may be taken to go from detection of X-ray radiation to accretion to black holes, where the only candidate step in the chain pertaining to the causal relation presented by Chakravartty is the first. Prima facie, black hole detection is not well suited to take place in the kind of realist account on offer. However, since semi-realists primarily speak of *properties*, rather than *objects* (even though the latter are coupled with the former), we may switch the target system of realism from black holes qua object and instead focus on its associated properties in order to see if those can be recovered in semi-realism. To do this would better reflect the purpose and metaphysical spirit of semi-realism. In such an analysis, it makes sense to use Chakravartty's spectrum of strength of causal interactions mapping to degrees of belief as a basis for determining the level of commitment that a semi-realist should have towards the properties of black holes. Here, Chakravartty provides a brief statement of the connection:

> In addition to a negative charge, [. . .] scientists associated many different properties with electrons. Enter semirealism, first and foremost a realism about well-detected properties. This refinement illuminates certain discriminations that are otherwise glossed over: they all believed in negative charge, and certain relations involving negative charge and particulars having it, but many of the other properties they associated with these particulars changed dramatically over the years as subatomic physics developed. And since on this view the realist understands properties in terms of dispositions for relations, there is no question of separating a knowledge of one from a knowledge of the other. A knowledge of entities and their relations is intimately connected here.(Chakravartty 2007, 58-9)

The charitable sentiment may be that while knowledge of entities and their relations cannot be separated, black hole realism may still be recovered if their properties in some sense can stand in a suitable causal relation to our instruments. However, the candidate properties of black holes most likely to be measurable—spin, mass, and charge—are not measurable in the way that Chakravartty needs them to be. Mass estimates use the dynamics of objects in the gravitational field of a black hole to derive a value, and spin is measured by using the hot X-ray gas at the heart of accretion disks. Both methods are dependent on theory in a way unsuitable to satisfy the causal connection condition, at least in way that would license realist commitment. Recall that "the greater the extent to which one seems able to interact with something—at best, manipulating it so as to bring about desired outcomes—the greater the warrant for one's belief in it" (Chakravartty 2007, 59).

Another property of black holes which is strongly endorsed by scientists is Hawking radiation, the eponymous thermodynamic glow theorized by Stephen Hawking (and Jacob Bekenstein). What, for present purposes, is most interesting about Hawking radiation is the level of acceptance it has despite the fact that it is decoupled from any empirical testing:[16]

> [Black Hole Thermodynamics] itself relies almost entirely on theoretical arguments, and its most celebrated result—Hawking's argument that black holes emit radiation—has no direct empirical support and little prospect of getting any. (Wallace 2018, 52)

Wallace argues that despite its disconnect with empirical data, there are good reasons to believe that black holes are thermodynamic systems. For semi-realism, however, this line of evidential reasoning regarding astrophysical black holes will fall far from the mark of realism, given its reliance on theoretical argument. The detection of Hawking radiation, by virtue of its extreme redshift, is not particularly likely to happen, so will be located at the very speculative end of Chakravartty's spectrum of causal contact cum belief (if eligible at all). The epistemological practices of astrophysics appears to greatly outstrip the semi-realist position, leading the latter to an anti-realism about a well established class of astrophysical objects—black holes—and their properties.

15.5 Concluding Remarks

For scientific realism, one of the core questions is what we can be realist about. Different varieties of realism have constructed different criteria for how we can arrive at an answer for this question. The debate over these criteria has for the most part consisted in anti-realists presenting counter examples to proposed accounts, to which realists have responded in kind. Realists have focused on recovering the right verdict with respect to cases either in history of science or in specific scientific areas, for example in particle physics. Curiously, they have neglected astrophysics, cosmology, and astronomy (Hacking excepted). Curious, since these fields jointly encompass the quantitatively (and arguably qualitatively) dominant part of our universe. An unforeseen consequence of this neglect is that the realist criteria have been shaped to square with a specific set of cases, and their extension to astrophysics was far from obvious. Here, I have attempted to ameliorate the opaqueness of this extension, arriving at the conclusion that the criteria for realism forwarded by entity realists are not a promising route for astrophysical realism. Perhaps this result is

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[16] There may be other epistemic paths to knowledge about Hawking radiation, although it is unclear to what extent it would amount to detection. One class of such paths are analogue experiments with dumb holes in which certain black hole properties, in particular Hawking radiation, are disclosed or inferred by their analogue counterpart: "Our first core claim is that whether a theory regarding certain phenomena can be well supported or established by experiment is not constrained by the requirement that the target system displaying these phenomena be manipulable or accessible, either in principle or practice." (Evans and Thébault 2020, 2) This claim would be able to provide support for realism beyond causal detection as specified by semi-realism, but would of course also violate or alter its conceptual core.

a bullet realists think is worth biting, as Hacking thought. If it is not, realists may have to consider a formulation of their realist criteria based on the contemporary epistemic practices of science.

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