Chapter 13
On the Epistemology of Observational Black Hole Astrophysics

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Abstract We discuss three philosophically interesting epistemic peculiarities of black hole astrophysics: (1) issues concerning whether and in what sense black holes do exist; (2) how to best approach multiplicity of available definitions of black holes; (3) short (i.e., accessible within an individual human lifespan) dynamical timescales present in many of the recent, as well as prospective, observations involving black holes. In each case we argue that the prospects for our epistemic situation are optimistic.

13.1 Introduction

Black holes are philosophically fascinating entities, but in many ways they are also philosophically troubling. Apart from existential questions about spacetime singularities and metaphysical questions about the fundamental theory of quantum gravity, there are epistemological issues to consider. How and what could we ever know about global regions of no escape swallowing every known type of matter? Since we are now entering a golden era of observations of black holes, it is appropriate to consider epistemology of observational black hole astrophysics.[1]

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[1] We should immediately point out here that this chapter has, by design, a limited scope. Because current empirical evidence does not establish quantum effects related to black holes, we only discuss black holes as seen from the point of view of classical general relativity, and we are only focusing on selected epistemic questions in observational black hole astrophysics. As a consequence, we ignore important issues related to black holes in the foundations of physics, such as the study of singular structure in the black hole interior (Earman 1995), their importance for numerous questions regarding the global structure of spacetime (such as determinism, see Doboszewski (2019), or existence of time machines, see Doboszewski (2022)), or a very closely related issue of the cosmic censorship conjectures (Landsman 2021). We are also setting aside

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N. Mills Boyd et al. (eds.), *Philosophy of Astrophysics*, Synthese Library 472,
https://doi.org/10.1007/978-3-031-26618-8_13

Multiple lines of astrophysical evidence strongly indicate the existence of black holes, and the future of such observations looks bright. Black holes provide the basis for the widely accepted theories of accretion and relativistic jet emission in active galactic nuclei (AGNs). AGNs are observed across most of the electromagnetic spectrum. Jets are measured with X-rays with facilities such as the Chandra X-ray Observatory. High resolution observations of some of them can be done in the optical and infrared part of the spectrum, using bright optical sources such as the star S2 near the center of the supermassive black hole (SMBH) candidate Sagittarius A* in the center of our galaxy,[2,3] and with short wavelength radio interferometry (in particular by recent imaging of multiple sources with the Event Horizon Telescope array and its planned extensions). Most gravitational wave detections with the LIGO-Virgo network of observatories also seem to be generated by collisions involving black holes. Further extensions to the LIGO-Virgo network are under construction, and third generation detectors (such as the Einstein Telescope, Cosmic Explorer, and the space detector LISA) are planned. Furthermore, high redshift evidence concerning formation of supermassive black holes is expected to soon be available from the James Webb Space Telescope.

The number of observations is also growing quickly. To give just two examples: in LIGO-Virgo detections of gravitational waves,[4] the first observational run O1 (in 2015–2016) had 3 events, run O2 (in 2016–2017) 8 events, while runs O3a had 44 and O3b 36 events, for a total of 80 combined in 2019–2020. Some important tests of fundamental physics have already been made with these observations; one example is a strong dis-confirmation of some modified gravity theories, in particular TeVeS, by GW170817.[5] The Earth-spanning EHT network of synchronized telescopes grew from three radio telescopes in 2009 to eight telescopes on six sites in 2017, with further three added in 2018–2020; it has set aside coordinated observational time for a week (typically in early April) every year. EHT images of the M87* (The

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issues of theory-ladenness, model independence, and robustness—all of which play prominent roles in establishing the reliability of particular lines of evidence for the existence of black holes.

[2] By a common convention the central region of Sagittarius A, M87 galaxy, etc. is denoted with an asterisk.

[3] Black holes come in different sizes, roughly subdivided into the following types. Stellar black holes are observed mostly using gravitational waves, and have masses from 2–5$M_\odot$ to 100–150$M_\odot$, with currently the highest known being the outcome of the merger event GW190521, of 163.9$M_\odot$. Intermediate size black holes are observed through ultraluminous X-ray sources, and have masses ranging from 100$M_\odot$ to 1000$M_\odot$, perhaps even up to $10^4 M_\odot$. Supermassive black holes are observed in the optical spectrum as well as with radio interferometry have masses of $10^4 M_\odot$ to $10^{10} M_\odot$. And, so far hypothetical, primordial black holes, which might have formed in the very early phase of the universe, and could lie anywhere between 10^{-8}kg to $10^5 M_\odot$.

[4] These passed one of the following thresholds for detection: at least 50% probability of being astrophysical in origin, or have a chance of being a false alarm below 1 for 3 years. For readability we will be omitting confidence intervals throughout this chapter.

[5] For confirmed events, the prefix GW stands for “gravitational wave”, with the numbers following it describing day, month, and the last two digits of the year. Gravitational wave astrophysics is discussed in much more detail in Lydia Patton’s and Jamee Elder’s chapters of this volume.

Event Horizon Telescope Collaboration et al. 2019) and SgrA* (The Event Horizon Telescope Collaboration et al. 2022) were constructed on the basis of data collected in 2017. As a part of its successor, the next generation Event Horizon Telescope, even more stations will be added in the forthcoming years, beginning with five stations in phase 1.

Black holes are in many ways unlike other astrophysical entities, so it is of quite some importance to consider black hole astrophysics' position within astrophysics more generally. Astrophysical tests of the more speculative aspects of black holes, such as the detection of Hawking radiation, remain out of reach for the foreseeable future.[6] But some philosophically interesting observations about the existence of black holes and the character of methodology used in search for them can already be made.

Here we will discuss three questions concerning epistemology:

- are our means of accessing black holes compatible with the belief that black holes exist in the same sense as other physical entities?
- are multiple alternative definitions of a "black hole" detrimental to our overall epistemological situation?
- are observations of black holes limited to effectively static snapshots and other trace-like forms of evidence?

In each case, we provide a cautiously optimistic assessment (in a sense similar to optimism about historical sciences of Currie (2018)) of our overall epistemic situation when it comes to black holes. In Sect. 13.2 we situate black hole astrophysics within considerations about realism, both generally and more specifically within philosophy of astrophysics; these are further exacerbated by the lack of direct access to black holes. However, we argue that the situation is not as problematic as it might seem: if considered jointly with a system coupled to it, there are many directly observable proxies for the geometry of a black hole. In Sect. 13.3 we consider some of the possible reactions to the fact that many different definitions of black holes are available, and argue that relationships between definitions are compatible with there being a substantial common core to the notion of a black hole, mediated by their appropriate behavior in the limiting case of an (idealized) exact solution. Finally, in Sect. 13.4 we point out that dynamical scales in black hole astrophysics are often short (accessible within an individual humans lifespan), and contrast black hole astrophysics with the effectively static snapshot character of many astrophysical lines of evidence, as well as with the view which sees astronomy as analogous to historical sciences. In these regards epistemology of black hole astrophysics is in a considerably better situation than many other branches of astrophysics.

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[6] See Alex Mathie's chapter in this volume for a discussion of analogue gravity models, which aim at confirming occurrence of these effects by investigating systems similar to black holes and yet available for laboratory manipulation (such as sonic holes in fluids).

13.2 Epistemic Access to Black Holes

Two main issues concerning realism about black holes arise. The first is a general concern about the manipulability of astrophysical entities, the second is related to their indirect observability. If black holes cannot be manipulated, and if they are only indirectly accessible, shouldn't we remain neutral about claims concerning their existence and properties? As for the first clause of the antecedent, we we will argue that the criterion linking manipulability and existence of an entity is too strict, and in any case sufficient lines of evidence are available; as for the second clause, in a substantial sense direct access to black holes is possible (even if not yet realized by human astronomers).

13.2.1 No Interventions on Black Holes

In 1984, Ian Hacking argued that one's belief in the existence of an entity A posited by some theory is justified if and only if A can be used in manipulating and experimenting with some other phenomenon B. He went on to argue that according to this criterion, the existence of most astrophysical entities is doubtful, as they are too far away from us for us to use them in our manipulations. (Hacking's arguments apply to entities outside of the Solar System, as planets within our solar system have been used for gravity assist maneuvers and thus have been used in manipulating other objects, thus fulfilling Hacking's criterion for justified belief in them.) However, in the case of black holes we have good reason to believe that if they exist, then they are so far away from us that using them to manipulate on and experiment with black holes will likely remain beyond human reach, and so they don't fulfill Hacking's criterion for justified belief, as indeed Hacking himself has claimed.[7] It should be noted that the same applies to all stars on the night sky; none of them fulfills Hacking's criterion either, and one might well argue that this speaks against Hacking's criterion rather than against the existence of stars and thus against the possibility of observational astronomy to establish justified belief. Be that as it may; in the following we will argue that even if one accepts Hacking's criterion, the existence of black holes is now much *less* doubtful than it was even just 10 years ago.

First let us note that if a black hole were present anywhere near us, a number of manipulations and experiments using it *would be possible*, and it would thus fulfill Hacking's criterion. These would include extracting energy from a black hole using

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[7] See Hacking (1989, 561). One could argue that it is an open question whether Hacking's arguments apply to primordial black holes in a similar way, for they might well exist close to us and thus might be amenable to be used in interventions. But despite extensive searches (see Carr et al. 2021 for a recent overview), no trace of those has yet been found. Accordingly, we will ignore primordial black holes in what follows.

a Penrose process (Penrose and Floyd 1971), which would enable us to use that energy in manipulating other objects. It would also be possible to use the black hole to perform gravity assist maneuvers, i.e., to use it in the same way that the planets of the solar system have already been used to speed up a spacecraft in a slingshot maneuver. These manipulations utilising a black hole could be performed by human agents, despite the massive difference in scale between them and the black hole. The outcomes of such interventions can be precisely calculated. Some of these effects are universal general relativistic effects, which only become more apparent in the presence of a strong gravitational field. Some other effects (for example gravitational time dilation or frame dragging) have been experimentally confirmed on Earth, and the corresponding predictions carry over to black holes. Apart from not being readily available for our experimentation, black holes are not special in this regard.

Hacking could admit all this and even be excited about all the things one *could* do with black holes if they were nearby, and yet maintain that the fact remains that they are *not* near enough to do any of these things, so that his criterion for justified belief in their existence is not fulfilled. So let us next look at how far astrophysical objects that are candidates for being black holes actually are beyond human reach.

The location of the black hole nearest to Earth is somewhat uncertain,[8] covering a range between 470 pc to 1530 pc. How far away is this from what humans can reach? After 45 years of travel, Voyager 1 is the human made object farthest from us, at a meager approximately 0.0007 pc. Prospects for any kind of humanity's expedition reaching any of these black hole candidates are, then, even more meager. And so are any experimental interventions, either by using these sources to intervene on something, or on the sources itself. It is practically impossible.

But should we really think of our lack of ability to manipulate things by help of black holes as a fundamental problem, or merely a contingent one? One view is that our location in the cosmos is a highly contingent matter, and thus so is the lack of ability to manipulate with such entities.[9] Drawing conclusions about the existence of some type of physical entities on the basis of a contingent feature would elevate it to

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[8] To the point where candidates have changed at least three times during the writing of this paper: from HR 6819 and V723 Monocerotis (which seem to be stripped binaries, see Frost et al. 2022 and El-Badry et al. 2022b, respectively) to the gravitational lens which played a role in the microlensing event MOA-2011-BLG-191/OGLE-2011-BLG-0462 (which seems to be an isolated stellar mass black hole of $7.1 M_\odot$ (Sahu et al. 2022); this is highly remarkable, because it is the first ever, and so far the only, candidate for an isolated stellar mass black hole), to Gaia BH1 (El-Badry et al. 2022a).

[9] It is not clear whether Earth-like planets and life-as-we-know-it could thrive in the vicinity of a black hole. The so-called black sun hypothesis states that they can. If the hypothesis turns out to be false, then living far away from a supermassive black hole would in some sense be physically necessary for organisms with a biology similar to ours. The jury is still out on this hypothesis. It seems that so-called "blanets", a certain type of exoplanets, could form around some AGNs (Wada et al. 2021). Moreover, blanets might have a temperature (with the gradient provided by the flow of blueshifted flux of cosmic microwave background radiation onto the cold spot of a black hole) within the habitable range (Bakala et al. 2020). On the other hand, arguably (Forbes and Loeb

a privileged epistemic position, and as such would be anthropocentric. Furthermore, human spaceflight is now barely 61 years old. An optimistic outlook on human ability to cooperate would see uniting around a common goal (such as travel to a remote destination) as a possible option. From this perspective inaccessibility might not be an insurmountable difficulty, but a contingent feature of our epistemic position. In any case, it seems like an issue of practice, rather than an issue of principle.[10]

This relates to a point made by Shapere (1993), regarding Hacking's criterion. Remember that Hacking claimed that belief in the existence of A is justified if and only if A can be used in investigating some other phenomenon B. Shapere pointed out (see also Massimi 2004) that the term "use" in Hacking's criterion can be read in two different ways: as "manipulate" and as "employ" or "exploit". Entities posited in astrophysics can rarely be manipulated, but often are employed in mechanistic explanations of various phenomena.[11] Regarding black holes, this is now much more the case than when Hacking first applied his criterion to the question of whether black holes exist. Indeed, such mechanisms have now been probed and tested in various ways in black hole astrophysics. For example, black hole based waveforms have been employed in matching the patterns of gravitational waves detected by LIGO-Virgo. Furthermore, the observed shape of the central brightness depression in the EHT images of the two black hole candidates M87* and SgrA* have provided a good fit for the assumption that the exterior of these objects accords with the Kerr geometry, which in turn strengthens the plausibility that these objects are rotating black holes. (See, however, Bronzwaer and Falcke (2021) and Vincent et al. (2022) for some words of caution: size and shape of the black hole shadow are not unambiguous predictions of GR, but can be recovered from alternative models, and are sensitive not only to geometry of the source, but also to emission models; the photon ring, a strongly lensed thin feature of an image, is such a signature, but has not yet been resolved. This is also of relevance for assessing which of these features can provide direct evidence in the sense discussed in the next section.) Thirdly, the assumption that the respective active galactic nucleus (AGN) is a black hole is currently the only way to explain the bright output of the AGN, which is explained by the hot matter accreting onto a supermassive black hole assumed to be in the center. Finally, light emitted from high redshift quasars (whose high energy output is best explained as being powered by a black hole) has been used by Rauch et al. (2018) in setting up direction of polarization in quantum mechanical tests of

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2018) XUV irradiation emitted by the gas accreting onto a SMBH might increase loss of planetary atmospheres.

[10] However, this argument is weakened by the fact that we do not have a convincing design for how a spacecraft capable of such a journey could be constructed, even if we had unlimited funding and global cooperation.

[11] This idea also plays well with the view which sees astrophysics as employing natural experiments provided by the universe in a Cosmic Laboratory, cf. Anderl (2016).

Bell inequalities (as an element of an attempt at limiting the so-called freedom of choice loophole).[12]

Thus, at the very least in a passive sense AGNs have already been used in manipulating elements of experiments. It follows that AGNs *do* fulfill Hacking's criterion: there *really are* extremely heavy objects in the center of the M87 galaxy, and in the center of our own Milky Way galaxy. One can still maintain the position that the AGNs in question *may* not be supermassive black holes, despite the fact that this assumption has become ever more fruitful in astrophysics. In other words, the existence of black holes may still be doubtful—but it is now much less doubtful than when Hacking wrote about them in 1984.

13.2.2 Indirect Observability of Black Holes

Hacking's criterion as discussed in the previous subsection required that in order for black holes to exist, we would have to be able to manipulate other objects by help of black holes. A weaker criterion for their existence would be to say that black holes exist if and only if they are observable. This criterion is more in line with van Fraassen than with Hacking, and it brings up the follow-up question of when something counts as observable, and whether it has to be directly or merely indirectly observable.

Recently, Eckart et al. (2017) have argued that "[super-massive black holes] are philosophically interesting entities given that they are only observable by indirect means." Eckart et al. do not define what they mean by "indirect" here, but we can draw on a precise characterization of directness due to Shapere (1982).[13] Shapere considers an entity or a source which undergoes some physical interaction (be it manipulation by a human observer, or some natural process), which leads to the emission of an information-carrying signal, recorded at the detector. According to Shapere's notion, an observation is direct if information received from the source is transmitted without interference to the detector. What constitutes emission, transmission, and interference depends on the theory of the source, the theory of transmission, and the theory of the detector; these, in turn, depend on the particular line of evidence.[14]

Assuming Shapere's notion of direct vs indirect observability, what side do black holes fall on? Eckart et al. (2017) point at the nature of evidence concerning black holes to justify their claims. If an astronomical source is a black hole, there can be

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[12] The same team has earlier performed similar Bell inequality tests using Milky Way stars, so a similar point could be made about other entities outside the Solar System.

[13] Later elaborated by Franklin (2017); see also Elder (2021) for a recent critical discussion.

[14] One could further make a distinction between a strict notion of directness, where the detector is that of a human sensory system, and a permissive one, which allows for the use of scientific instruments. We will be assuming a permissive notion, as the strict one rules out observation relying on scientific instrumentation.

no emission from the black hole itself; an isolated classical black hole, after all, is a perfect absorber.[15] It is only when that source is coupled with some second system, such as matter in the accretion disk or another black hole, that any signal from the near horizon region can be emitted and detected by a distant observer. Said matter might be used as a proxy for the source itself, but it provides only indirect evidence. The black hole on its own is, then, an in principle unobservable entity. This is in line with Hacking (1989), invoked by Eckart et al. (2017), who notes that "[a] black hole is as theoretical an entity as could be. Moreover, it is in principle unobservable. (…) At best we can interpret various phenomena as being due to the existence of black holes" (561). Evidence for the existence of black holes could then be seen as somehow less certain and less conclusive than the usual empirically collected data, which might be straightforwardly ascribed (through direct observations) to theoretical entities responsible for their production. This argument targets black holes in contrast to other phenomena astrophysics is concerned with, because most other objects are electromagnetic emitters.

Note that some lines of evidence are direct in Shapere's sense. The data collected, for example by LIGO-Virgo, might be a direct detection of gravitational waves (even if arguably only an indirect detection of binary black hole mergers, on the grounds of relying on models of the merger; see Elder 2021). However, interference of radio waves (in the EHT) or an optical signal (in adaptive optics measurements) with the Earth's atmosphere provides interference which could be interpreted as invalidating the "without interference" clause of Shapere's definition. On the other hand, the signal emitted by these sources is present in the data and can be reconstructed; and if it would be the issue of atmospheric noise that invalidates the clause, then the question of indirectness becomes contingent on the location of a telescope. Gravitational waves couple weakly to interstellar matter, and so the "without interference" clause is easier to establish in that case.

What could the signal emitted by a black hole be? If the black hole is truly isolated, then (again, apart from quantum effects such as Hawking radiation or superradiance) the prospects for detecting any signal originating from it are by definition impossible. But once it is coupled to either another black hole, or to hot matter in the accretion disk, the situation changes dramatically. The shape of emissions is sourced by the gravitational field of the black hole. Insofar as the theory describing emission involves the strength and shape of said field, that part of Shapere's notion of directness can be satisfied. This line of argument relies on having a black hole coupled to some other system, and so one could complain that it is that other system which is directly measured, and that the black hole is accessed only indirectly through it. However, one might answer that then everything is an indirect observation: we never observe the table itself but only the light reflected from the table.

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[15] One limitation of this line of argument is that, arguably, processes such as emission of Hawking radiation, or superradiance mechanisms involving black holes, do constitute a form of emission of energy from a black hole.

In order to judge whether black holes are indeed at best indirectly observable, we have to consider the distinction between the region external to the black hole, the region of no escape inside of the black hole, and a surface separating them, the event horizon. Of these three regions, the interior is merely in-principle observable: only an observer ready to jump inside can observe what happens in there (but not transmit that to the outside).[16] The exterior region, including regions arbitrarily close to the separating surface, *is* epistemically accessible in the same sense as any other region of spacetime.

One might say that no-one had ever claimed that the exterior *outside* a black hole is not directly observable; the question was about whether the black hole *itself* is (directly) observable! But here is the crux that makes black holes special, at least in this respect: if the exterior of a black hole candidate is found to accord with the Kerr geometry, then we can reliably conclude that the object in question is a rotating gravitational source like a star *or* a black hole.[17] If, in addition, the object does not emit any light but is supermassive and sufficiently compact, then arguably the best explanation, even the only available explanation, is that the object in question is a black hole.[18] It's not really different from observing the exterior of a table: you only have to really know how the table looks from the outside to conclude that the object in question is indeed a table.

So, can we make experiments or observations that would tell us that the exterior of a black hole candidate accords to the Kerr geometry and thus is, in all likelihood, the exterior *of a black hole*? Yes: coordinated observers could, for example, shoot lasers towards the black hole candidate and test whether their paths agree with the trajectories of null geodesics of the Kerr geometry. One could also test whether light is on the verge of being trapped in a certain region, how strongly a given region of spacetime lenses light, what the shape of this lensing region is, whether frame dragging effect occurs, and so on.

In less abstract astrophysical situations, luminous matter such as gas or plasma in the accretion disk of an AGN is used for establishing the geometry of the gravitational field. Instead of considering a black hole on its own, one is considering a coupled system of a black hole and luminous matter, which is sufficient to establish exterior geometries that would provide signatures for various kinds of black holes: rotating, charged, those compatible with modified gravity theories, horizon-less black hole mimickers, and so on. Recent work of the EHT measuring the shadow of a black hole is a good example: here the shape of bright emissions from the accretion

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[16] Again, apart from the possibility that the measurement results leave the interior of a black hole during the semi-classical evaporation process. It is, however, worth pointing out that some physical mechanisms, such as the blueshift heuristic underlying investigations of the cosmic censorship conjecture, do constrain properties of the deep interior on the basis of perturbations of matter in the exterior. See Chesler et al. (2019) and references therein for this line of investigations.

[17] The same could be said if the exterior of the black hole candidate accords with the Schwarzschild geometry or the Reissner-Nordström geometry; however, all current observations are compatible with sources being Kerr, i.e., rotating bodies.

[18] Of course, Stanford's problem of unconceived alternatives always remains.

disk, measured at 230 GHz and 20μas resolution, can be used to rule out some of the shapes incompatible with the source being a black hole. In such situations direct experimental probing of structures and geometry close to the event horizon is possible, given enough time and resources. Even though a black hole is unlike other astrophysical entities,[19] the exterior of a black hole is accessible, and has such a distinctive signature that access to the exterior might be enough to conclude that it is the exterior *of* a black hole.

Finally, something should be said about the localization of a black hole. Hacking claimed that "we cannot with any confidence point to any region of the sky and say, there's one there" (Hacking 1989, 561). Indeed, the concept of a black hole event horizon is a global notion: one would need to know the whole history of spacetime in order to establish that an event horizon exists, and as such it cannot be localized to a finite region of spacetime observed for a short interval of time. In this sense, when taken at face value, it is not an epistemically accessible property of spacetime. But often global spacetime properties should not be taken at a face value: they rather express idealizations about the systems. We consider ourselves far enough from the source that for all practical purposes all light from it has reached us, and so, we can pretend we are observers located at future null infinity (Ellis (2002) even suggests that for a local group of galaxies the appropriate distance is 1.2 Mpc). In this sense a "black hole" as defined by "having an event horizon" *can* be localized (and the situation further improves if some quasi-local notion of a horizon is adopted).

To sum up: following Shapere's criterion, some means of direct access to black holes are possible. But, interestingly, even indirect observations can give us evidence strong enough that we can be quite sure what the object in question actually is; arguably as sure as in many cases of direct observation.

13.3 Interpreting Many Definitions of Black Holes

Issues of epistemic access are further exacerbated by the observation that a 'black hole' is a polysemic term: many definitions of a 'black hole' are available. One could be concerned: what do we even mean when talking about black holes? Do we have sufficient conceptual control over these notions? We will first survey various possible reactions to the occurrence of many definitions, and then argue for cautiously optimistic assessment of the situation: many of the definitions are compatible with each other.

Curiel (2019) recently surveyed some of the definitions of black holes used by practitioners of different sub-communities. These sub-communities include observational and theoretical astrophysicists, classical relativists, mathematical rela-

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[19] Arguably one can have direct access to the interior of e.g. the Sun by measuring neutrino flux generated within, or simply by entering it with a sufficiently sturdy spacecraft and come out again to tell the tale.

tivists, physicists working on semi-classical gravity, quantum gravity, and analogue gravity. He found at least twelve different ways of defining a “black hole” (see Figure 1 of Curiel (2019)). This includes the characterization as a physical object whose defining feature is that it is simply a very compact object that is incredibly massive, or one that is characterised by an event horizon, or, alternatively another geometric feature: an apparent horizon, or instead a trapped surface; that it is an object featuring a singularity; or instead a region of no escape for low energy modes; or that a black hole is a particular type of engine producing an enormous power output.[20]

13.3.1 Cluster Concepts, Perspectives, and Other Possible Reactions to the Many Definitions of Black Holes

How should we react to this plethora of definitions of black holes? First, we need to note that the fact that different sub-communities operate with these different definitions is crucial. One might say that given that different communities have different purposes, different definitions are not really a problem; a chemist has a different working definition of “molecule” than a quantum physicist. Still, the question remains if the different communities could come to an agreement about the notion of “molecule” or “black hole” that fits all their purposes and that they would accept as the underlying “proper” definition of the term in question—a set of necessary and sufficient conditions for something to be a “black hole” that can be agreed on across all communities. In the case of “black hole”, no such agreement on necessary and sufficient conditions has as of yet been found, and it is not clear at all that it ever will be found. Indeed, it is not even clear whether we should hope for such a set to be found, as many definitions for many purposes may well be seen as more flexible and fruitful for the conduct of further research on these objects.

Thus, we see six different options to react to the plethora of definitions of a “black hole” stemming from different sub-communities: (1) the classic hope of an “inner core” to all these definitions, i.e., a set of necessary and sufficient conditions for something to be a black hole; (2) that the different definitions form a Wittgensteinian family; (3) that a “black hole” is a cluster concept; (4) that the different definitions of a “black hole” correspond to different perspectives in the sense of perspectivism; (5) that the different definitions of a “black hole” are so disjoint that one is forced into semantic anti-realism; and (6) a kind of pragmatic pluralism about what a “black hole” signifies. We are going to elaborate on each of these options in the rest of this subsection. It will turn out that the question of which of these options is *actually* the most convincing will turn on how the different definitions of a “black hole”

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[20] Curiel’s list is non-exhaustive; for instance, a quasi-local horizon is one possibility, but there are many inequivalent candidate quasi-local horizon notions; see Booth (2005) for an accessible introduction, including unwelcome features of such notions.

are *actually* related to one another; a question that will be investigated in the next subsection.

But first let us look at the different possibilities. We have already looked at the first option, most familiar from analytical philosophy more generally: it is that there is, in the end, a set of necessary and sufficient conditions for something to be a black hole, and that we just have not yet found this set of conditions. The second option is that the different definitions of a "black hole" form a Wittgensteinian family, i.e., a set where any two family members have *something* in common, but where no trait or property is shared by *all* family members. The third option is that "black hole" is what Baker (2021) called a "cluster concept", i.e., a concept that cannot be captured by necessary and sufficient conditions but instead "can be satisfied in a variety of different ways by different entities falling under" the concept (S279). Baker sees the "best realizer" variant as the most plausible version of a cluster concept view: "only the (ideally unique) structure that best satisfies the criteria of the cluster concept counts as spacetime, even in cases where other structures also meet the criteria to a sufficient degree that they would count as spacetime if they existed alone" (Baker 2021, S290). Under this approach, a list of criteria for being a black hole should be produced (Baker provides just such a list of candidate criteria for a given structure to be a spacetime), and candidate definitions should be compared against it; the one which is a best fit to the criteria becomes the official definition.

At first sight, this looks rather similar to claiming that a given concept forms a "Wittgensteinian family" of definitions, but the idea is actually rather different. In such a cluster of definitions, in contrast to a Wittgensteinian family, there may well be two members of the set that don't have *anything* in common, precisely because the something can fall under the concept in question in "a variety of different ways". If a "black hole" is a cluster concept, then it would be possible to find a set of n conditions of which any $n - m$ conditions (with $n > m$) must be fulfilled in order for something to be a black hole. Of course, the task would be not only to find the set of n conditions but also to justify the number m.

The fourth option one could take in light of the multiple definitions of a "black hole" is perspectivism. Perspectivism (Giere 2010; Massimi 2018) associates the presence of many (possibly inconsistent) scientific models with multiple equally valid perspectives on a phenomenon. Taking many definitions as providing equally valid perspectives or aspects of the same entity may be tempting especially in contexts when these definitions are inconsistent with each other. For example, in non-stationary spherically symmetric spacetimes, the definition of a black hole relying on the presence of an event horizon picks up a different surface from the definition relying on the apparent horizon. (See figure 6 in Senovilla (2013) for a simple illustration of this incompatibility in Vaidya spacetimes.) Similarly, the so-called regular black hole spacetimes with non-singular interiors (see Berry et al. 2021 for an example construction) do not qualify as black holes for definitions relying on the presence of a spacetime singularity. On the other hand, Morrison (2011) argued that inconsistent models signal lack of theoretical understanding of the phenomenon in question. In such cases, she argues (Morrison 2011, 350) that perspectivism about models of the nucleus "amounts to endorsing a claim of the form: Taken as a classical system (...) the nucleus looks like X; as a quantum system it looks like Y, and so on for any given model we choose". Morrison finds this unsatisfactory, because "none of these 'perspectives' can be claimed to 'represent' the nucleus in even a quasi-realistic way since they all contradict each other on fundamental assumptions about dynamics and structure". An analogous point can be made about incompatible definitions of black holes.

The fifth option is a form of semantic anti-realism. Having established that the different definitions of a "black hole" have little in common, one could worry: what could a realist even be a realist about when it comes to black holes? This position has been suggested by Martens (2022) in the context of dark matter. However, arguably the situation of black holes is not so dire: in contrast to dark matter candidates there are consistent estimates for the masses of black holes—this is not the case for dark matter particles, whose mass varies over many orders of magnitude. There are also two commonly used theoretical models of a black hole, given by the Schwarzschild and (subextremal) Kerr geometries for the cases of non-rotating and rotating black holes, respectively. Again, this is not the case for dark matter, which could be accounted for using very different theoretical models, from primordial black holes through axions to entirely new species of particles.

The sixth option is the one that Curiel has argued for. It is a form of pragmatic pluralism: the many definitions of black holes are seen as something positive. Curiel concedes that "there is a rough, nebulous concept of a black hole shared across physics, that one can explicate that idea by articulating a more or less precise definition that captures in a clear way many important features of the nebulous idea, and that this can be done in many different ways, each appropriate for different theoretical, observational, and foundational contexts" (Curiel 2019, 33). He does not see this as a problem, but a virtue. A single precise definition, he argues, would likely be more constraining and less fruitful than the variety of tools provided by the many definitions of a "black hole".

Listing logical possibilities and options one could choose is all well and good, but which of these options we *should* choose will depend on the actual relations between the different black hole definitions. Semantic anti-realism with respect to black holes is only a viable option if the different definitions do indeed have little in common, and whether the definitions are better described as forming a Wittgensteinian family or a cluster concept likewise draws on what precise relationships can actually be found between the different definitions. Thus, we shall look at least at *some* black hole definitions in some detail, and investigate which relations hold between them.

13.3.2 Relationships Between Different Definitions of Black Holes

Curiel's analysis stops short of discussing relationships between more or less precise definitions used in different theoretical contexts. If one does, one finds that some of these definitions are not fully independent of each other; there are subtle relationships between them. The extent and precise nature of these relationships will determine which of the six options discussed in the previous subsection regarding how one could react to the many different definitions of a "black hole" is the most viable one. Here, we can only give a tentative foray into what these relationships are.

Since we are concerned with observational black hole astrophysics (where currently properties of classical black holes are at the frontier of investigations), we will conveniently restrict our attention to some of the definitions most useful in that context. In other words, we want to understand how the definitions of a black hole in terms of it being a compact object, an engine for enormous power output, an object that is characterised by an event horizon or an apparent horizon, or one that is characterised by a singularity are related to each other. By introducing this restriction we are making the task comparatively easy on ourselves: in the context of semi-classical gravity and quantum gravity relationships become more difficult to ascertain.

So what are some of the relationships between the different definitions of a "black hole"? At least two types of relationships can be found.

The first type of relationship obtaining between many definitions of black holes is restricted equivalence: two definitions may be equivalent in a restricted setting (but not in full generality). Consider the definition of a black hole in terms of it possessing an event horizon and the definition in terms of a foliation of spacetime by a sequence of apparent horizons. It turns out that even though in time-dependent spacetimes these definitions do pick out different surfaces, in static cases theses surfaces coincide; see fig. 5 and 6 of Senovilla (2013) for an illustration in the Schwarzschild spacetime and Vaidya spacetimes.[21] So these two notions are provably equivalent in a restricted setting, where the restriction in question is the condition of staticity.

The second possible relationship is one of reliable proxyhood. By this we mean a situation where in a particular theoretical context the fact that one definition holds strongly suggests (though not necessarily in the sense of a logical implication) that some other definition also holds. In that case, one notion of a black hole is a reliable proxy for another notion. Reliable proxies differ from restricted equivalences in two ways. First, the relationship may hold in typical cases (in a sense to be specified in a given context) only. Thus, it would not be appropriate to speak of an equivalence.

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[21] The stationary case remains open; see Carrasco and Mars (2013) for a summary of results suggesting that the answer will be positive.

Second, one definition may be a proxy for another even in cases where the regions of spacetime picked out by these two definitions fail to coincide. Nevertheless, by learning about the properties that the first definition relies on, we also learn about the properties that the second definition relies on. We will now give two examples of relationships between prominent definitions which illustrate these differences. In the first case, the proxy is located outside the surface of a black hole as characterized by most other definitions; in the second case, the proxy is located inside the surface of a black hole as characterized by some other definitions.

Astrophysical models of accretion and jet launching are usually constructed based on the assumption of a general relativistic background geometry. In this way, models are fitted to an exact solution (typically Schwarzschild or Kerr). The standard active galactic nuclei model strongly suggests that features of the AGNs, so characterizations of black holes in terms of "compact object" and an "engine for enormous power output" can plausibly be associated with the exterior of the object in question being characterised by the Kerr spacetime (and so its geometric structure, including its event horizons and apparent horizons). In this situation "engine for enormous power output" becomes an elliptic expression for "accretion onto a Kerr spacetime with large mass". Whether this proxy remains reliable can change—for instance, if observationally viable accretion models onto Exotic Compact Objects[22] are constructed, "engine for enormous power output" (or "compact object") might no longer be a reliable proxy for a spacetime region with a Kerr geometry. It is also not a scale-invariant characterization of a black hole: stellar mass black holes might not be definable in this way. If the microlensing event MOA-2011-BLG-191/OGLE-2011-BLG-0462 is indeed a black hole, it seems to have effectively zero energy output. In this situation the "engine for enormous power output" is not a universally reliable proxy for the Kerr geometry, despite it being a reliable proxy in the case of supermassive black holes (as long as no well-established alternative models for AGNs are available).

Another example of a reliable proxy are marginally outer trapped surfaces (MOTS). A marginally trapped surface is a closed 2-dimensional surface S such that outward future pointing null vectors have vanishing expansion. If there are many such surfaces, some contained inside others, then an apparent horizon is the outermost one; in other words, it is a MOTS which is not contained in any other MOTS. If the spacetime is asymptotically flat, has an event horizon, and the null energy condition holds, then an apparent horizon is located inside the event horizon (Wald 1984). In that setting, locating an apparent horizon is a reliable proxy for an event horizon. In the $3 + 1$ ADM approach to numerical relativity apparent horizons are easier and faster to find than event horizons (Thornburg 2007), because codes for finding MOTS' and apparent horizons can be run during the numerical construction

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[22] These are a large and very heterogeneous class of objects which have similar masses and sizes as black holes, but do not contain a horizon-like surface; see Cardoso and Pani (2019) for a recent overview of such models. Since by definition ECOs have surfaces instead of event horizons, such models can be constrained by an analysis of their luminosity (Lu et al. 2017).

of the spacetime. In contrast, event horizon finders have to be run as a separate step after the construction. However, as long as the appropriate background conditions are satisfied, a MOTS is located inside an event horizon. A definition of a black hole relying on a MOTS is thus a reliable proxy for the definition in terms of an event horizon.

13.3.3 Consequences of Relationships Between Many Definitions

At least some of the definitions of black holes are related to each other in interesting ways. This strengthens the hope that there might, after all, be a set of necessary and sufficient conditions to be found for something to be a black hole (option 1 from the previous subsection). But it is also entirely consistent with the idea that the different, yet related, definitions of a "black hole" form a Wittgenstein family (option 2) or a cluster concept (option 3). The relationships between definitions seem to weaken the perspectivism account (option 4), yet not rule it out, and also weaken the case for semantic anti-realism (option 5). The case for semantic pluralism (option 6) still stands strong, though the above has raised the question how much of a plurality of definitions there really will be in the end.

We should also note that the relationships between definitions, which we could only point to in this review, typically flow from the empirical and conceptual adequacy of an exact solution of Einstein's field equations, in particular the Kerr and Schwarzschild solutions of the Einstein's field equations. From these, many definitions are further derived, abstracted, or generalized. In this way the exact solution might provide a core concept of a black hole. Many of these definitions are formally or plausibly related under additional auxiliary assumptions (such as stationarity, asymptotic flatness, and the null energy condition), many of which, in turn, express idealizations, such as a system not varying over time, the system being isolated, or neglecting effects due to quantum nature of matter fields.

From this point of view, the plurality of definitions can be seen as resulting from an ongoing process of de-idealization and extension of a concept well understood in a particular limited domain to larger domains. It is then not surprising that many inequivalent definitions of a "black hole" are available. Indeed, one should expect that many definitions will appear: for any highly idealized notion, many ways of de-idealising are available. Depending on the particular context of investigation, different aspects of the object investigated are taken to the be of relevance. In any case, existence of many definitions does not have to constitute a worry for the epistemology of black hole astrophysics.

13.4 Short Dynamical Timescales

Accessible timescales influence available interpretative positions and the assessment of the overall epistemic situation, so it is appropriate to consider them here. Two particular aspects are worth discussing here, in some ways the epistemic situation of black hole astrophysics is richer than in many other areas.

First, astronomy and astrophysics are often seen as analogous to historical sciences such as archaeology, paleontology, or geology: the finite speed of propagation of light implies that the light reaching us from distant sources carries information about events that transpired, in some sense, long ago. Thus, epistemic access to dynamic processes occurring in these sources is limited to their downstream "traces", often sparse and partial, and impoverished in similar ways (see Anderl (2021) for an extended exposition of this view).

Second, in her recent analysis of epistemic roles played by astrophysical simulations, Jacquart has pointed out that astrophysics suffers from the fact that observed sources typically vary very slowly, remaining unchanged over thousands and more years. Access to signals emitted by such sources is effectively confined to an "observational 'snapshot'—a single time-slice of the object under investigation" (Jacquart 2020, p. 4).

Interestingly, a wide range of observations in black hole astrophysics deal with dynamical signals changing on timescales (much) shorter than the average human lifespan. Jacquart concedes that some astrophysical phenomena[23] change during the observation. However, she sees these as "by far the minority", as "[m]ost objects or phenomena of study in astrophysics take place over cosmic time scales of millions of years" (p. 4), which are too large to be observable for humans. Jacquart uses this observation in pointing out an amplifying role of astrophysical simulations, which provide stand-ins for the dynamical evolution of the source. However, notably, in black hole astrophysics short dynamic timescales are present much more commonly than in gravitational wave observations. They are the norm, and snapshots are an exception. This has a further consequence: if observable "traces" carry information about dynamical processes, then the commonly accepted analogy with historical sciences is weakened. Historical traces are in important respects unlike highly dynamical signals carrying information about black holes. We will now discuss some of the examples of the plurality of dynamical timescales present in the current main observational lines of evidence and in their prospective generalizations.

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[23] Such as supernova explosions and black hole mergers; but one could also point to pulsars, fast radio bursts, gamma ray bursts, etc.

13.4.1 Timescales in Black Hole Astrophysics

Although black holes seem to come in different sizes, the timescale of variability is not a function of the mass of a black hole. It rather relates to the source's immediate environment, distance from Earth to particular sources, and to particular ways of accessing them.

As already noted by Jacquart, current observations of gravitational waves are among the most striking examples of short dynamical timescales in astrophysics. The current generation of gravitational waves detectors is tuned towards very fast transients: those of 2–500 seconds are considered long. Events in LIGO-Virgo observational runs O1-O2 varied from 0.2 seconds (GW150914) to 100 seconds (neutron star-neutron star merger GW170817); the latter, however, is the only long one. But there are many intermediate timescales between these transients and effectively static snapshots.

An increasingly important line of evidence comes from short radio wavelength observations performed using Very Long Baseline Interferometry techniques utilising the Earth-spanning Event Horizon Telescope array. Here, time variability differs between sources and radio frequencies measured. The main targets of these observations are the central object in the Messier 87 galaxy M87* (the subject of the famous first image of a black hole from 2019) and SgrA* in the center of the Milky Way. A number of secondary targets, such as Centaurus A, 3C 279, supermassive black hole binary candidate OJ 287, and others, have also been observed. A natural variability timescale is set by the period of the innermost stable circular orbit, which in turn depends on the mass and spin of the source. In SgrA* this range is between 4 and 30 minutes (The Event Horizon Telescope Collaboration et al. 2022), while for M87* it ranges from 5 to 30 days. This intra-hour variability in the emitted flux leads to the possibility of producing not just single black hole images, but black hole movies, as SgrA* changes its state during a single observing night. However, even here other timescales occur: one example are bright flares, occurring daily, and observable in the near-infrared and X-ray spectrum. Such flares might be interpreted as hotspots generated in the accretion flow (Tiede et al. 2020) and used to map the surrounding spacetime region as a function of the hotspot passing through various near-to-far horizon scales. The M87* variability timescale is of the order of a month. But using the total 2009–2017 data set, the 2019 image as a prior, and under a simplifying assumption that the set of alternatives is limited (to asymmetric ring and a Gaussian), the evolution of the shape of the source over time can be constrained, with the asymmetric ring being preferred (Wielgus et al. 2020). In the case of another source, 3C279, its jet exhibits day-to-day variability (Kim et al. 2020). RadioAstron orbiting VLBI observations from 2014 suggest the presence of helical threads, or filaments, in the jet; this will soon be followed by analysis of 3C279 with the EHT data from 2017 onward, from which time variability of the filaments can be estimated. Finally, OJ 287 is a supermassive black hole binary candidate in which an elliptical orbit of the less massive component takes nearly 11.6 years to complete (Shi et al. 2007). For more than 22 years it has been monitored long term, occasionally with a daily cadence. In the case of this source, periodic flares can be predicted to occur on a particular day; Laine et al. (2020) find[24] that the 2019 flare arrived within 4 hours of the predicted time. In all of these examples multiple short timescales, varying from minutes to years, are accessible to the astronomers.

Timescales accessible within an individual human lifespan are also available in the optical part of the spectrum. One example is Cygnus X-1, where the primary star HDE 226868 is orbiting around an unseen companion, with a period of 5.6 days.[25] Other bright tracers of candidate black holes are utilized; perhaps the most important one is the bright star S2 with an orbit of approximately 16 years. It has been monitored for 26 years (as of data published in 2018) by the ongoing GRAVITY collaboration (Abuter et al. 2018) observations of the center of the Milky Way, and also by the UCLA group (Do et al. 2019) independently observing the same region. The outcomes are consistent with the hypothesis that the central region SgrA* is a single highly concentrated mass. The star S2 is just one of many tracers, and multiple other similar objects are monitored. Multiple observations of objects on such orbits can be made within the lifetime of an individual observer.

Not all prospective observations of black holes are so dynamic: some are likely to be very long and slowly varying, even while supplementing other observations at shorter timescales. One example (following section 7 of Abbott et al. (2016)) are black hole binaries such as GW150914. These binaries emit gravitational waves in the frequency range of space detectors such as (e)LISA, plausibly 0.1–10 mHz; it is scheduled to launch in the 2030s. It takes approximately 1000 years to evolve from 2 to 3 mHz emission to the merger phase. The dynamics of such a system would be a time-varying signal (and so not a static snapshot), which could be monitored during a time interval much longer than an individual human lifespan.

Examples of snapshots can also be expected. Numerous mechanisms for formation and growth of SMBHs have been proposed; these include light seeds ($<10^3 M_\odot$), heavy seeds (10^4–$10^6 M_\odot$), and other intermediate pathways, and it remains an open question what proportion of these mechanisms can explain which proportion of the SMBHs population. Light seeds are likely to be too faint to be seen by the James Webb Space Telescope (JWST), but the possibility that heavy seeds at up to very high redshift $z \sim 15$ might be seen with the JWST (which at the moment of writing started releasing first images) is of relevance here. That evidence is likely to consist of snapshots, but (e)LISA and third generation gravitational wave detectors (Cosmic Explorer and Einstein Telescope) might be able to detect mergers at $z > 10$, and such supplementing evidence would again have a dynamical character. Pointers for a discussion of these mechanisms as well as other possible lines of evidence can be found in Chen et al. (2022).

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[24] Using the Spitzer Space Telescope rather than VLBI; but dynamics of OJ287 is also observed using VLBI methods, see Sawada-Satoh et al. (2015).

[25] Lack of emission from the companion counts among the lines of evidence for the existence of black holes.

There is a clear sense in which—JWST observations notwithstanding—evidence in observational black hole astrophysics is not confined to effectively static snapshots. It rather concerns a wide range of dynamic processes across different timescales, with the duration of a process typically accessible within an individual human lifespan. In cases of some particular sources (like the SMBH candidate Sagittarius A*) various timescales are accessible simultaneously.

13.4.2 Consequences of Short Dynamical Timescales

Short dynamical timescales provide more information than snapshots. The dynamics of the source accessed through snapshots needs to be inferred from the single trace only. But with short timescales accessible in black hole astrophysics it is not only a single state of the system that can be observed; its change over time can be recorded as well. The character of such downstream traces is different: they are dynamically rich records of the evolution of the black hole and its surroundings. In this way, epistemic access to black holes can be seen as more informative than in many other astrophysical contexts (dominated by effectively static snapshots).

In this way, the analogy with historical sciences is weakened: transient events and other observations associated with black holes in an important sense are unlike trace fossils or geological layers. In some—EHT sources—though not all—transients observed with the current generation of LIGO-Virgo detectors—cases, a dynamically evolving source is available for further sampling with subsequent observations, because the source can be monitored over extended periods of time.

An additional constructive perspective concerns transient observations which cannot be re-sampled at will. Recall that LIGO-Virgo made 91 detections until the end of observational run O3. Out of these 91 detections, black holes seem to be responsible for the vast majority of events: only 2 are classified as neutron star-neutron star collisions, 4 as black hole-neutron star collisions, and a further 2 as involving a black hole and an uncertain object. Plausibly, these proportions will remain similar in the future observational runs. If so, population studies will provide more immediate and more reliable constraints on evolution, production mechanisms, and statistical properties of the population of stellar black holes than on neutron star mergers. From this point of view, black hole astrophysics is in a comparatively better epistemic situation than astrophysics of many less “exotic” entities.

13.5 Conclusions

We have surveyed four problems which are *prima* facie detrimental to the epistemic situation of observations of black holes. The first one concerned lack of manipulability; we diagnosed this as a contingent feature, and pointed out that

AGNs have been used in setting up some experiments. The second concerned alleged lack of direct access; we have argued that under a particular notion direct access is possible (even though not yet realized in practice). The third concerned multiple available definitions of black holes; we have classified possible reactions, proposed two types of relationships between definitions, and suggested the sense in which exact solutions of general relativity might provide a core concept of a black hole. Finally, we have explored the consequences of empirical access to dynamical processes involving black holes. The overall conclusions are optimistic: the future of observations of black holes is bright, and so are prospects for the corresponding philosophical analysis.

Acknowledgments We are grateful to two anonymous reviewers, Nurida Boddenberg, Erik Curiel, Jamee Elder, Sophia Haude, Niels Martens, Jan Potters, Aleksandra Samonek, and Noah Stemeroff for their feedback on previous versions of this article, and to Nora Boyd for her patience. We would also like to thank the Volkswagen Foundation for its support in providing the funds to create the Lichtenberg Group for History and Philosophy of Physics at the University of Bonn.

References

Abbott, B.P., et al. 2016. Astrophysical implications of the binary black hole merger GW150914. *The Astrophysical Journal Letters* 818 (2): L22.

Abuter, R., et al. 2018. Detection of the gravitational redshift in the orbit of the star S2 near the galactic centre massive black hole. *Astronomy & Astrophysics* 615: L15.

Anderl, S. 2016. Astronomy and astrophysics. In *The Oxford handbook of philosophy of science*, ed. P. Humphreys. Oxford University Press.

Anderl, S. 2021. Evidence in astrophysics. In *The Routledge companion to philosophy of physics*, 744–752. Routledge.

Bakala, P., J. Dočekal, and Z. Turoňová. 2020. Habitable zones around almost extremely spinning black holes (black sun revisited). *The Astrophysical Journal* 889(1): 41.

Baker, D.J. 2021. Knox's inertial spacetime functionalism (and a better alternative). *Synthese* 199(2): 277–298.

Berry, T., A. Simpson, and M. Visser. 2021. General class of "quantum deformed" regular black holes. Preprint. arXiv:2102.02471.

Booth, I. 2005. Black-hole boundaries. *Canadian Journal of Physics* 83(11): 1073–1099.

Bronzwaer, T., and H. Falcke. 2021. The nature of black hole shadows. *The Astrophysical Journal* 920(2): 155.

Cardoso, V., and P. Pani. 2019. Testing the nature of dark compact objects: a status report. *Living Reviews in Relativity* 22(1): 1–104.

Carr, B., K. Kohri, Y. Sendouda, and J. Yokoyama. 2021. Constraints on primordial black holes. *Reports on Progress in Physics* 84(11): 116902.

Carrasco, A., and M. Mars. 2013. On uniqueness results for static, asymptotically flat initial data containing mots. In *Black holes: New horizons*, ed. S. Hayward, 55–92. World Scientific.

Chen, H.-Y., A. Ricarte, and F. Pacucci. 2022. Prospects to explore high-redshift black hole formation with multi-band gravitational waves observatories. Preprint. arXiv:2202.04764.

Chesler, P.M., E. Curiel, and R. Narayan. 2019. Numerical evolution of shocks in the interior of Kerr black holes. *Physical Review D* 99(8): 084033.

Curiel, E. 2019. The many definitions of a black hole. *Nature Astronomy* 3(1): 27.

Currie, A. 2018. *Rock, bone, and ruin: An optimist's guide to the historical sciences*. MIT Press.

Do, T., et al. 2019. Relativistic redshift of the star S0-2 orbiting the galactic center supermassive black hole. *Science* 365(6454): 664–668.

Doboszewski, J. 2019. Interpreting cosmic no hair theorems: Is fatalism about the far future of expanding cosmological models unavoidable? *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 66: 170–179.

Doboszewski, J. 2022. Rotating black holes as time machines: An interim report. In *The foundations of spacetime physics*, 133–152. Routledge.

Earman, J. 1995. *Bangs, crunches, whimpers, and shrieks: singularities and acausalities in relativistic spacetimes*. New York: Oxford University Press.

Eckart, A., A. Hüttemann, C. Kiefer, S. Britzen, M. Zajaček, C. Lämmerzahl, M. Stöckler, M. Valencia-S, V. Karas, and M. García-Marín. 2017. The Milky Way's supermassive black hole: How good a case is it? *Foundations of Physics* 47(5):553–624.

El-Badry, K., H.-W. Rix, E. Quataert, A.W. Howard, H. Isaacson, J. Fuller, K. Hawkins, K. Breivik, K.W. Wong, A.C. Rodriguez, et al. 2022a. A sun-like star orbiting a black hole. *Monthly Notices of the Royal Astronomical Society* 518(1): 1057–1085.

El-Badry, K., R. Seeburger, T. Jayasinghe, H.-W. Rix, S. Almada, C. Conroy, A.M. Price-Whelan, and K. Burdge. 2022b. Unicorns and giraffes in the binary zoo: stripped giants with subgiant companions. *Monthly Notices of the Royal Astronomical Society* 512 (4): 5620–5641.

Elder, J. 2021. On the "direct detection" of gravitational waves. *draft*.

Ellis, G.F. 2002. Cosmology and local physics. *New Astronomy Reviews* 46 (11): 645–657.

Forbes, J.C. and A. Loeb. 2018. Evaporation of planetary atmospheres due to XUV illumination by quasars. *Monthly Notices of the Royal Astronomical Society* 479(1): 171–182.

Franklin, A.D. 2017. Is seeing believing?: Observation in physics. *Physics in Perspective* 19(4): 321–423.

Frost, A.J. et al. 2022. HR 6819 is a binary system with no black hole - revisiting the source with infrared interferometry and optical integral field spectroscopy. *A&A* 659: L3.

Giere, R.N. 2010. Scientific perspectivism. In *Scientific perspectivism*. University of Chicago press.

Hacking, I. 1984. Experimentation and scientific realism. In *Science and the quest for reality*, 162–181. Springer.

Hacking, I. 1989. Extragalactic reality: The case of gravitational lensing. *Philosophy of Science* 56(4): 555–581.

Jacquart, M. 2020. Observations, simulations, and reasoning in astrophysics. *Philosophy of Science* 87(5): 1209–1220.

Kim, J.-Y. et al. 2020. Event Horizon Telescope imaging of the archetypal blazar 3C 279 at an extreme 20 microarcsecond resolution. *Astronomy & Astrophysics* 640: A69.

Laine, S. et al. 2020. Spitzer observations of the predicted Eddington Flare from Blazar OJ 287. *The Astrophysical Journal Letters* 894(1): L1.

Landsman, K. 2021. Singularities, black holes, and cosmic censorship: A tribute to Roger Penrose. *Foundations of Physics* 51(2): 1–38.

Lu, W., P. Kumar, and R. Narayan. 2017. Stellar disruption events support the existence of the black hole event horizon. *Monthly Notices of the Royal Astronomical Society* 468(1): 910–919.

Martens, N. 2022. Dark matter realism. *Foundations of Physics* 52(1): 1–19.

Massimi, M. 2004. Non-defensible middle ground for experimental realism: Why we are justified to believe in colored quarks. *Philosophy of Science* 71(1): 36–60.

Massimi, M. 2018. Perspectival modeling. *Philosophy of Science* 85(3): 335–359.

Morrison, M. 2011. One phenomenon, many models: Inconsistency and complementarity. *Studies in History and Philosophy of Science Part A* 42(2): 342–351.

Penrose, R. and R. Floyd. 1971. Extraction of rotational energy from a black hole. *Nature Physical Science* 229(6): 177–179.

Rauch, D., et al. 2018. Cosmic Bell test using random measurement settings from high-redshift quasars. *Physical Review Letters* 121(8): 080403.

Sahu, K.C., et al. 2022. An isolated stellar-mass black hole detected through astrometric microlensing. Preprint. arXiv:2201.13296.

Sawada-Satoh, S., et al. 2015. Apparent inward motion of the parsec-scale jet in the BL Lac object OJ287 during the 2011–2012 γ-ray flares. *Publications of The Korean Astronomical Society* 30(2): 429–432.

Senovilla, J.M. 2013. Trapped surfaces. In *Black holes: New horizons*, 203–234. World Scientific.

Shapere, D. 1982. The concept of observation in science and philosophy. *Philosophy of Science* 49(4): 485–525.

Shapere, D. 1993. Astronomy and antirealism. *Philosophy of Science* 60(1): 134–150.

Shi, W., X. Liu, and H. Song. 2007. A new model for the periodic outbursts of the BL Lac object OJ287. *Astrophysics and Space Science* 310(1): 59–63.

The Event Horizon Telescope Collaboration, et al. 2019. First M87 Event Horizon Telescope results. I. the shadow of the supermassive black hole. *The Astrophysical Journal Letters* 875(1): L1.

The Event Horizon Telescope Collaboration, et al. 2022. First Sagittarius A* Event Horizon Telescope results. I. the shadow of the supermassive black hole in the center of the Milky Way. *The Astrophysical Journal Letters* 930(2): L12.

Thornburg, J. 2007. Event and apparent horizon finders for 3+1 numerical relativity. *Living Reviews in Relativity* 10(1): 1–68.

Tiede, P., H.-Y. Pu, A.E. Broderick, R. Gold, M. Karami, and J.A. Preciado-López. 2020. Spacetime tomography using the Event Horizon Telescope. *The Astrophysical Journal* 892(2): 132.

Vincent, F., S. Gralla, A. Lupsasca, and M. Wielgus. 2022. Images and photon ring signatures of thick disks around black holes. *Astronomy & Astrophysics* 667: A170.

Wada, K., Y. Tsukamoto, and E. Kokubo. 2021. Formation of "blanets" from dust grains around the supermassive black holes in galaxies. *The Astrophysical Journal* 909(1): 96.

Wald, R. 1984. *General relativity*. University of Chicago Press.

Wielgus, M., et al. 2020. Monitoring the morphology of M87* in 2009–2017 with the Event Horizon Telescope. *The Astrophysical Journal* 901(1): 67.