Theory-mediated detection of novel phenomena in astrophysics: the case of the photon ring

Jamee Elder

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Abstract

This paper examines the opportunities and pitfalls of theory-mediated measurement in astrophysics. I locate the main danger *not* in the use of models of the target phenomena, but rather in the methodological context where these models are deployed. To illustrate this, I zoom in on a recent controversy among astronomers concerning attempts to detect the photon ring. I provide an account of what went wrong in this "detection" in conversation with other cases of (attempted) theory-mediated detection of novel phenomena in astrophysics—in particular, the retracted gravitational-wave detection claim by BICEP2 and the successful gravitational-wave detection claim by LIGO-Virgo.

1 Introduction

In this paper I will examine the opportunities and pitfalls of theory-mediated measurement—especially model-based detections—in astrophysics. I will locate the main dangers of these approaches *not* in the use of models of the target phenomena, but rather in the methodological context where these models are deployed: in particular, methods that are sensitive to errors in modelling backgrounds are especially problematic. To illustrate this, I zoom in on a recent controversy among astronomers over an attempted detection of the photon ring.

In 2022, a group of astrophysicists claimed to have measured the photon ring of black hole candidate M87* (Broderick et al. 2022). This would have been an important step in measuring the properties of M87*, because the features of the photon ring are determined by the spacetime curvature itself. However, a follow-up paper with an overlapping author list argues against the conclusion of the first, showing that the method used in the Broderick et al. paper, "hybrid imaging", is susceptible to false positives (Tiede et al. 2022).[1]

In this paper I will analyze what went wrong in this theory-mediated measurement, in conversation with other cases of (attempted) theory-mediated detection of novel phenomena in astrophysics. In particular, I will compare this case with both the successful gravitational-wave detection claim by the LIGO-Virgo Collaboration and the retracted gravitational-wave detection claim by the BICEP2 Collaboration. I will argue (*pace* Tiede et al.) that mediation by theory (models of the photon ring) is *not* itself the problem with the hybrid imaging method.

Section 2 frames these issues in terms of both an older tradition of concern about the theory-ladenness of observation and a newer trend in the philosophy of measurement that takes model-mediated inference to be both characteristic of measurement and productive of high-quality empirical evidence. Section 3 presents the case study of the subsequently-discredited photon ring detection claim. Finally, section 4 diagnoses what went wrong with the purported photon ring detection, emphasising that it is the overall methodological context—especially the failure to establish discriminant validation—rather than the reliance on theory-motivated models that was ultimately to blame.

2 From theory-laden observation to theory-mediated measurement

In a tradition with roots in Hanson (1958) and Kuhn (1962/1970), philosophers of science have long worried about theory-laden observation. Although this worry comes in many flavours, the version relevant for my purposes concerns the theory-ladenness of measurement, or experiment (see, e.g., Franklin (2015)). The concern here is that theoretical assumptions built into a measurement procedure will bias the measurement

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[1] There are interesting sociological and social epistemological questions raised by scientists publishing papers with such sharply discordant theses over a four month period. However, I set aside these questions for the purposes of this paper.

results, such that it is difficult or impossible to obtain results in conflict with those assumptions—regardless of whether the theoretical assumptions are true.

However, an emerging tradition in the philosophy of measurement adopts a rather different viewpoint, taking model- and theory-mediated inference to be central to measurement. Leading this re-evaluation of the role of models in measurement is Eran Tal (e.g., Tal (2012, 2013)), who generically casts measurement as a model-mediated inference. Wendy Parker (e.g., Parker (2017)) draws on this conception of measurement to provide a taxonomy of kinds of measurements based on the different model-based inferences required to go from the raw data to a final measurement outcome. In a similar vein, Alisa Bokulich 2020 provides a taxonomy of the ways that data can be model-laden or model-filtered.

This body of work subverts the older tradition of viewing theory- or model-ladenness as a problem by showing how model-mediation in measurement settings can be a virtue, rather than a vice. Instead of fetishising unmediated raw data as the ideal, this work shows how models are effectively deployed by scientists both to correct biased data and to extend what can be learned from it.[2]

Some classic work in this new tradition is that of George Smith (and his collaborator, Raghav Seth), which argues that (at least in the cases they analyse) theory-mediated measurement is exemplary scientific practice. Smith (2014) considers the case of Newtonian solar system mechanics and argues that an iterative process of accommodating discordance between theoretical predictions and observations by introducing further physical effects—a process he calls “closing the loop”—provided high quality evidence for Newtonian mechanics. Smith and Seth (2020) further argue that Perrin’s famous measurements are an impressive example of theory-mediated measurements providing high-quality evidence.

Overall, theory- and model-mediated measurement is increasingly viewed by philosophers of science as both standard and unconcerning. Models are instead understood as crucial to gaining empirical access to phenomena. Theory and models also play an important role in improving empirical data by correcting for confounding effects or biases.

Nonetheless, there remains an important question of establishing that the theories and models doing the mediating are reliable (or to use the terminology of Parker (2020)

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[2] On related “relational” and “enriched” views of data, see Leonelli (2016) and Boyd (2018b, 2018a) respectively.

and Bokulich and Parker (2021), "adequate-for-purpose"). If they are not, then this has the potential to undermine the measurement. Put another way, the traditional concerns about theory-ladenness are poised to make a comeback.

This issue looks to be particularly pressing in a science like astrophysics, where the epistemic resources may be limited by the distance to the phenomena being investigated (the 'target phenomena'). This is especially so when it comes to the detection of novel astrophysical phenomena—phenomena that have never been observed before. In such cases, theoretical support for the existence of the phenomena may be extremely high, but empirical evidence is not yet available. One might think that gaining genuinely empirical evidence for the phenomena, under these circumstances, means measuring the phenomena with as much independence as possible from theoretical presuppositions.

In the remainder of this paper, I zoom in on a particular case study of this kind, which on the surface seems to support this thesis about the need for independence from theory. It involves a theory-mediated measurement of the photon ring (Broderick et al. 2022) which was subsequently found to be unreliable (Tiede et al. 2022). The scientists who uncovered the faults in the measurement conceive of the problem as one of model-dependence, viewing the role of theoretical assumptions in detection as something to be wary of. However, I offer a different interpretation, which both draws on and contributes to the emerging, more optimistic literature on theory-mediated measurement.

3 Case study: detection of the photon ring

General relativity predicts that images of optically thin accretion around a black hole will contain a "photon ring", a nested series of increasingly sharp subrings from increasingly strongly lensed emission in the region (Johnson et al. 2020). These are indexed by the number n of half orbits around the black hole, so the $n = 0$ image is the primary 'direct' image (which may not form a ring) and $n = 1$ is the secondary image formed by photons that have completed a half orbit before reaching the observer. From there, each subsequent ring is both narrower and dimmer (see Figure 1). The features of the photon subrings ($n = 1$ onwards) are determined by the spacetime curvature. This means that measurements of the photon ring with the ngEHT could provide a clean probe of the target black hole's properties (mass and spin) and tests of the Kerr metric (Johnson et al. 2020). Detecting the photon ring, and measuring its properties, are therefore important scientific goals for observational black hole astrophysics (Falcke, Melia, and Agol 1999; Chael, Johnson, and Lupsasca 2021; Kurczynski et al. 2022).

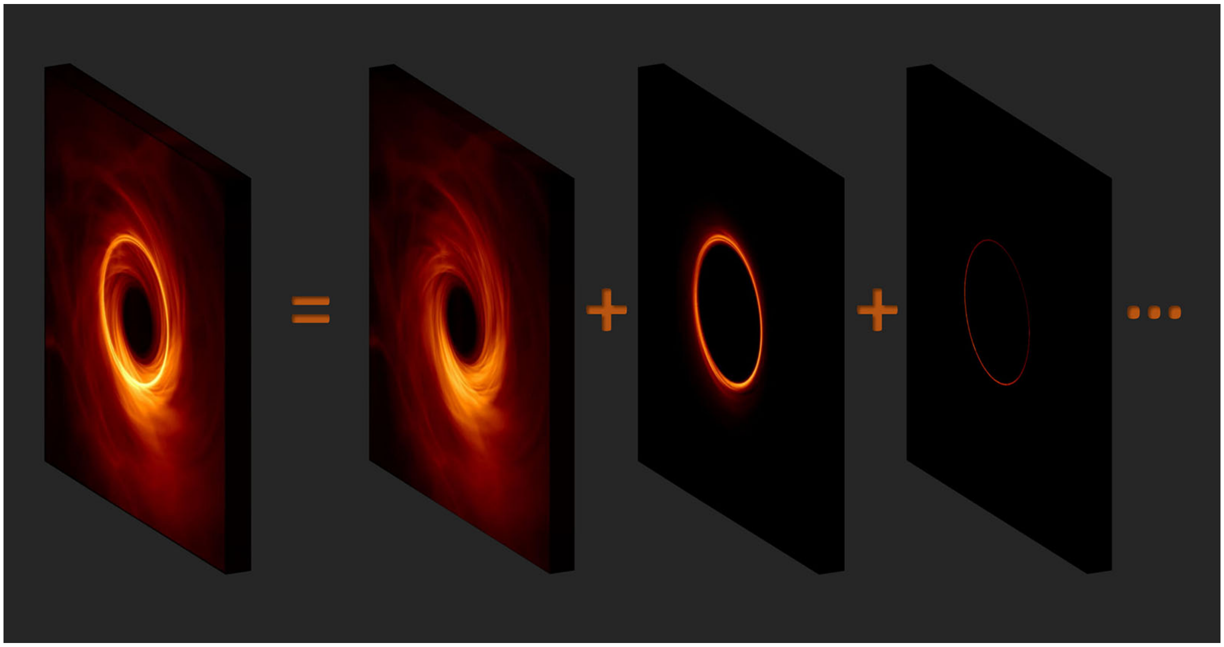

Figure 1: Nested subrings contribute to the overall image of a black hole. Photo credit: George Wong and Michael Johnson.

In 2022, Broderick et al. (2022) claimed to have measured the photon ring of supermassive black hole candidate M87*. They made this claim on the basis of applying a method called "hybrid imaging" to the M87* 2017 Event Horizon Telescope (EHT) dataset.[3] However, in a follow-up paper with an overlapping author list, Tiede et al. (2022) argue against the conclusion of the first, showing that hybrid imaging is susceptible to false positives.

"Hybrid imaging" is a form of theory-mediated measurement. It involves modelling source emission using a combination of a thin ring model and a flexible, unconstrained raster model (Broderick et al. 2020). The former is based on theoretical predictions of the photon ring, while the latter is aimed at capturing the remaining diffuse emission. Fitting these models with the data allows for measurement of the size of the ring (and, by extension, the mass of the black hole) as well as the proportion of the total flux

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[3] The EHT Collaboration uses an array of telescopes around the globe to produce images of supermassive black holes. See e.g., The Event Horizon Telescope Collaboration et al. (2019a, 2022). See Doboszewski and Elder (2024) for philosophical discussion of EHT methods.

coming from the ring. In a nutshell, this method is supposed to extract the $n = 1$ (and beyond) photon ring emission using a theory-motivated geometric ring model. The raster model represents what remains: the relatively unconstrained (and potentially time-variable) direct emission.

Broderick et al. (2022, p.3) report that they 'are able to isolate the $n = 1$ photon ring from the surrounding diffuse emission'. They claim that this amounts to a 'direct detection of the bright ring' (p.8), which they in turn associate with 'the strong gravitational lensing that produces the $n = 1$ photon ring' (p.12). They also claim that this detection provides the basis for a mass estimate for M87* with 'significantly reduced systematic uncertainties'.

However, Tiede et al. (2022) cast doubt on the photon ring detection claim made by Broderick et al. (2022) arguing that:

> [T]he results of hybrid imaging must be interpreted with extreme caution for both photon ring detection and measurement—hybrid imaging readily produces false positives for a photon ring, and its ring measurements do not directly correspond to the properties of the photon ring. (Tiede et al. 2022, p.1)

Tiede et al. (2022) show this by applying the hybrid imaging method to synthetic data, where the synthetic data are data generated using GRMHD simulations of M87*, processed and sampled based on models of realistic EHT and next generation EHT (ngEHT) arrays.[4] In other words, the synthetic data are a model of the data that would actually be produced by a VLBI array like the (ng)EHT, assuming source emission predicted by a GRMHD simulation. Crucially, using synthetic data allows for the addition or removal of features by hand. Tiede et al. (2022) generated multiple synthetic datasets, including one that includes a photon ring and one where it has been removed.[5] Their results are reported in Tiede et al. (2022, fig.4) and reproduced here in figure 2.

Essentially, it turns out that the ring-like nature of the diffuse emission means that hybrid imaging will "detect" a photon-ring even when (by construction) there is none.

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[4] GRMHD stands for "general-relativistic magnetohydrodynamic". GRMHD simulations are the state of the art in modelling black hole accretion and are used by the EHT in interpreting their images (see Doboszewski and Elder (in preparation) for philosophical discussion of this). The ngEHT is the planned extension of the existing EHT array, featuring new telescopes around the globe

[5] They also created a dataset with $n = 0$ removed and a dataset in which $n = 1$ was shrunk relative to $n = 0$.

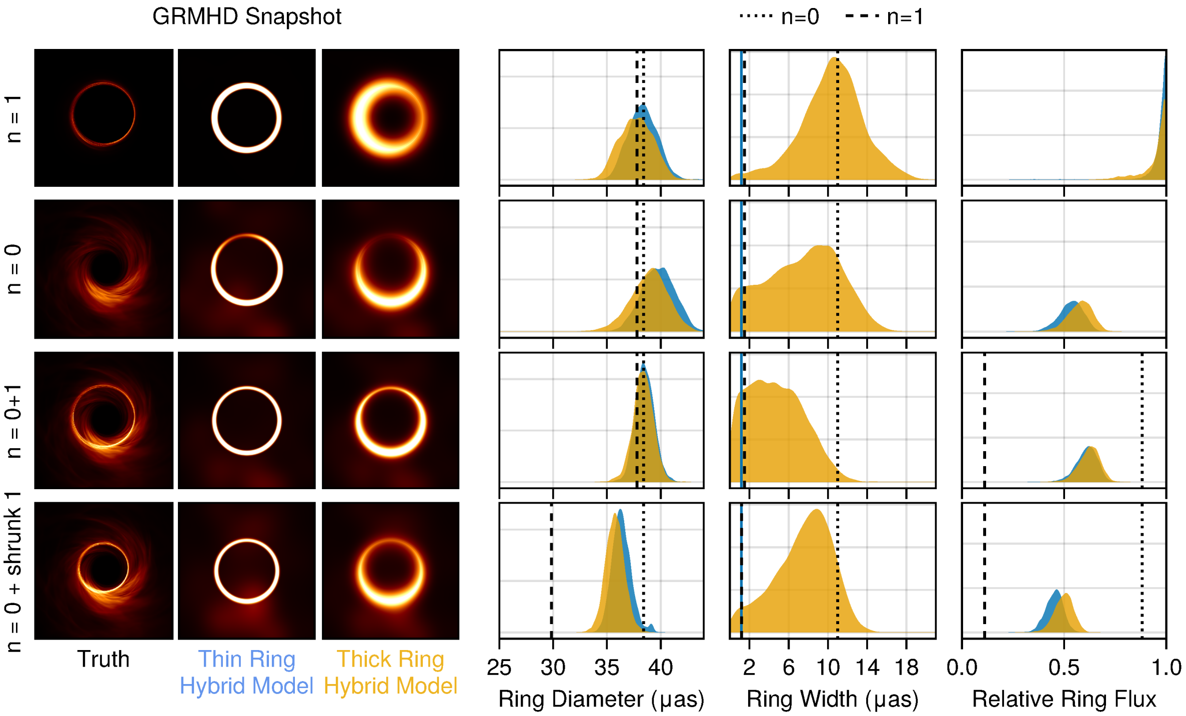

Figure 2: Key results from Tiede et al's application of hybrid imaging to synthetic data, reproduced from Tiede et al. (2022, fig.4)

Thus, hybrid imaging is an unreliable method for detection of the photon ring. Furthermore, measurements of the properties of the photon ring (and correspondingly, of the black hole) are systematically biased towards properties of the $n = 0$ emission. In particular, measurements of the ring diameter are biased towards the $n = 0$ emission diameter.

Tiede et al. (2022) actually use two different ring models in their hybrid-imaging analysis: a thin-ring hybrid model, which has been constrained to have a width of $1\mu as$ (similar to that used by Broderick et al. (2022)) and a thick-ring hybrid model where they fit for the thickness rather than forcing a particular value. It is interesting to note that Tiede et al. view these models as playing different roles in the overall empirical investigation, corresponding to the extent to which they build in theoretical assumptions about the photon ring:

> In our view, the two hybrid models serve different purposes, distinguished by their ability to fit all relevant ring parameters. The thick-ring hybrid model makes fewer assumptions about the fitted ring component, making it a useful basis for detecting a photon ring. The thin-ring hybrid model imposes more assumptions about the fitted ring component, making it a useful basis for measuring the remaining photon ring properties. (Tiede et al. 2022, pp.9-10)

Here, Tiede et al. distinguish between photon ring *detection* and *measurement*. On the one hand, I take detection here to be about showing that the photon ring is present. For the purposes of this epistemic goal Tiede et al. seem to say that a more agnostic approach is better; for a convincing detection claim, it is important to make as few theoretical assumptions as possible. On the other hand, I take measurement to concern the further analysis of the properties of the photon ring, on the assumption that it is present. For this epistemic goal Tiede et al. think that it appropriate to build in more theoretical assumptions about the phenomenon being investigated. Detection of a novel phenomenon, then, is conceived of as prior to measurement of its properties. Detection is also assumed to be more secure when less mediated by theoretical assumptions. Indeed, this stance is taken explicitly at the outset:

> [T]he most compelling detection might not require the assumption that general relativity (GR) is true, while a somewhat weaker claim of detection might test for the presence of this feature under the assumptions of GR. Likewise, methods could utilize models that assume the existence of the

> photon ring to make measurements of black hole parameters without needing to meet potentially more stringent criteria for an unambiguous detection of the same feature. (Tiede et al. 2022, p.1)

This is, I take it, an intuitive way of thinking about the role of theoretical assumptions in detecting novel phenomena. In addition to adopting a cautious stance toward epistemic risk—i.e., prioritising the avoidance of false positives—this way of thinking assumes that the incorporation of stronger theoretical assumptions reduces the security of the detection claim; the more theory-agnostic the detection method, the less likely it is to be susceptible to error scenarios, where the detection is undermined by a faulty theoretical assumption. This view of detection resonates with traditional concerns about the theory-ladenness of observation (or experiment).

In the remainder of this paper, I will show that this way of understanding the role of theoretical assumptions in detection is inadequate for properly understanding the case study at hand, and as such is inadequate as a general account of theory-mediated detection.

4 Detecting novel phenomena: the benefits (and dangers) of theory-mediation

One interpretation of the case study in section 3 is that making theoretical assumptions in the process of detection, at least of a novel phenomenon (one that has not previously been detected and as such lacks existing empirical support), weakens or even undermines the detection claim. On this interpretation, what went wrong with Broderick et al. (2022) "detection" was its reliance on general relativistic models in the process of isolating the photon ring. This interpretation seems to be what Tiede et al. (2022) have in mind when they say that the 'most compelling' detection would be the one that makes the weakest assumptions concerning general relativity. A model-based search for a signal which builds in theoretical assumptions is deemed inferior to a more agnostic search procedure.

However, this view is not supported by the case study at hand, and is false in other cases of novel detections in astrophysics. In this section, I will compare and contrast the case of Broderick et al. (2022)'s purported detection of the photon ring with both the successful detection of gravitational waves by the LIGO-Virgo Collaboration and the unsuccessful (retracted) detection of gravitational waves by BICEP2.

The 2015 detection of gravitational waves by the LIGO-Virgo Collaboration (Abbott et al. 2016c) was based on searches for coincident signals in data produced by two (spatially distant) gravitational-wave interferometers. These searches comprised modelled search pipelines and unmodelled (or, more carefully, 'minimally modelled') search pipelines (Abbott et al. 2016b). The modelled search pipelines use a method called 'matched filtering', which searches for correlations between a template (modelling a possible gravitational-wave signal) and the data, while the unmodelled searches look for excess power.[6] Although the modelled search makes stronger theoretical assumptions about the properties of the signal, based on a combination of numerical relativity simulations and other modelling approaches, it seems to be better than the unmodelled search for two key reasons. First, it is more efficient at extracting the signal from the noise. This means that it detects gravitational-wave signals with a higher signal-to-noise ratio (and higher statistical significance) than the unmodelled searches. Second, results of the unmodelled searches are more open to alternative interpretations. Indeed, these search pipelines are also used to detect glitches in the detector; when there is a "trigger" where the search reports an excessively high signal-to-noise ratio in one detector, this is used to exclude that data, on the understanding that it has been corrupted by a transient noise event.

In the case of the LIGO-Virgo detection, we have a highly theory-mediated detection that is nonetheless highly compelling. Even though there is an alternative search pipeline capable of detecting gravitational waves, such detections are less secure than their modelled counterparts precisely because they make fewer assumptions about signal morphology. By building in fewer theoretical assumptions, the unmodelled searches are left open to "detecting" signals that are actually noise from terrestrial sources.

With the LIGO-Virgo case in mind, it is clear that Tiede et al. (2022)'s assessment of the hybrid imaging method is too quick. Greater independence from theoretical assumptions can also increase the potential for false positives, so it is not theory-agnosticism *per se* that makes a detection secure or 'compelling'. In assessing what went wrong with hybrid imaging, it is therefore misleading to blame the use of a theory-motivated ring model.

Both matched-filtering and hybrid imaging involve using a template model to extract the signal—representing the target phenomenon—from the 'background'. So why was the

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[6] See Elder (2023b, 2023a) for detailed philosophical discussion of the LIGO-Virgo gravitational-wave detections, including the role of matched filtering.

former detection successful when the latter was not? I see at least two key differences.

First, matched filtering works because the signal and background noise are uncorrelated. In contrast, hybrid imaging fails to reliably isolate the signal ($n = 1$ photon ring) from the background ($n = 0$ direct emission) because they *are* correlated; the direct emission can be sufficiently ring-like to be partly modelled by a simple geometric ring model.

Second, further features of the LIGO-Virgo methods guard against false positives for both the modelled and unmodelled search pipelines. In particular, the requirement of coincident (and matching) signals in (at least) two spatially distant detectors prevents transient noise sources in one detector being interpreted as a genuine gravitational-wave signal.[7] It is hard to see how to create a parallel of this setup for detection of the photon ring.

In contrast to the LIGO-Virgo case, the case of BICEP2 can be seen as a cautionary tale, representing the dangers of theory- or model-mediated detection. In 2014 the BICEP2 team announced the detection of gravitational waves (and evidence for cosmic inflation) through B-mode polarization of the cosmic microwave background (Ade et al. 2014). However, B-modes can be generated in a number of ways, and contributions from other sources including 1) dust, and 2) lensing from distant galaxies had to be subtracted to isolate the gravitational-wave contribution. It turned out that the BICEP2 modelling of the dust contribution was in inadequate, such that the entire purported signal could be accounted for by dust.[8]

Although the BICEP2 case illustrates the dangers of theory- or model-mediated measurement, it is important to note that the modelling of the signal was not the problem. Instead, the problem arose in the handling of backgrounds—the other contributions to B-mode polarization.

In astrophysics, this problem might seem to be particularly pressing because two of the main pathways to achieving this separation are (at least often) unavailable. Peter Galison (1987, pp.2-3) discusses three main strategies experiments have for separating signal from background: construction, measurement, and calculation. The first two are often unavailable in astrophysics. That is, astrophysicists generally cannot physically

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[7] Gravitational waves travel at the speed of light, which means that they should arrive in a second detector with a time lag of no more than the time taken for light to travel the distance between them. In contrast, there are no plausible noise sources that can mimic signals in *both* detectors within that time frame (Abbott et al. 2016a).

[8] For a detailed account of the BICEP2 affair, see Keating (2018).

shield the system they are investigating from background effects, since they are not *constructing* this system at all. It is also sometimes impossible *measure* the background effect independently of the target phenomenon. If the two effects always occur together, then measurement of one is always intertwined with the other, leaving the central problem of separating the two unresolved. What remains is *calculation*, sometimes called 'vicarious control', where the contributions of effects other than the target phenomenon need to be calculated and subtracted (or shown to be negligible). In both the BICEP2 case and the photon ring case the signal and background must be separated through this calculation strategy—i.e., through modelling—since other methods of control are not available. In both cases, the difficulty in isolating the target phenomenon is due to uncertainty in modelling of backgrounds.[9] For the photon ring case this uncertainty arises because the latter strongly depends on details of accretion, which are not well-constrained empirically.

Looking forward, the question is what *would* count as a successful detection of the photon ring? In other words, what are the appropriate detection criteria for this case and under what circumstances could such criteria plausibly be met?

One option is simply to increase the angular resolution of the array used to observe supermassive black holes candidates. The expansion of the EHT array to form the ngEHT will not help with this, because resolution depends not on the number of stations but on the longest 'baseline' in the array—i.e., the longest distance between any two of its component telescopes, which will not increase for the ngEHT. However, the plan to adapt the array to observe at multiple frequencies by adding a 345GHz ($\sim 0.87mm$) will increase the resolution, since resolution improves with larger frequencies (smaller wavelengths). However, this would not bring the resolution of the array to that needed to observe the photon ring without some 'super-resolution' (i.e., building in modelling assumptions to go beyond the resolution of the instrument) Adding a space component such as the proposed 'Black Hole Explorer' mission (previously named 'Event Horizon Explorer') would also increase the resolution by increasing the longest baseline. A space-based component would allow astronomers to produce sharper images that resolve the photon ring (Kurczynski et al. 2022).

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[9] Particle physics (e.g., the ATLAS and CMS collaborations at the Large Hadron Collider) faces similar problems and as such could provide a valuable comparison case. However, due to space constraints, I leave development of this to future work (see also Doboszewski and Elder (2024) for a comparisons between the EHT and particle physics).

Other options involve utilising more theoretical results about accretion and/or the photon ring in order to distinguish between $n = 0$ and $n = 1$ emission. For example, Palumbo et al. (2023) make a case for detecting the photon ring using properties of the polarization of the photon ring. This would not be a measurement of the photon ring's other properties (its shape or diameter) but would establish that the photon ring was there. This is interesting, because it actually involves building in *more* theoretical assumptions in order to make a secure detection claim. This supports the idea that degree of theory-(in)dependence is not (*pace* Tiede et al. (2022)) a good measure of the reliability of a detection.

What else is needed for a successful theory-mediated detection? It is tempting to look at the case of LIGO-Virgo and think that strict detection criteria need to be worked out in advance. For the detection method described by Palumbo et al. (2023), this looks plausible. But for a detection more along the lines of the hybrid imaging approach, what would it take to be confident in the detection?

The answer, I think, lies in the methodology already employed by the EHT for detecting novel phenomena (specifically, the first observation of a black hole 'shadow' (The Event Horizon Telescope Collaboration et al. 2019b)). This detection did not rely on clear criteria established in advance. Instead, validation of the result took the form of a robustness argument, based on agreement across the results of multiple independent imaging pipelines (in particular, agreement about the size of the observed shadow feature) (Doboszewski and Elder 2024). Additionally, the use of synthetic data and imaging challenges established that these methods had the property of "discriminant validation"—they would not produce a ring/shadow feature if none was present in the source.[10] This latter feature, discriminant validation, is precisely what was lacking in the Broderick et al. (2022) "detection" since hybrid imaging turned out to be susceptible to false positives.

By using synthetic datasets to analyse how hybrid imaging performs for a range of (simulated) sources, including those where the photon ring was removed, Tiede et al. (2022) were following the methods used by the EHT in validating their first images of M87*. A model-mediated method like hybrid imaging could result in a compelling detection if it was able to pass a similar test. The prospects of passing such a test are (at best) unclear, but passing would likely mean building in *more* assumptions about the

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[10] See Doboszewski and Elder (2024) for detailed discussion of robustness and discriminant validation in the EHT case.

photon ring's features, in order to differentiate it from the $n = 0$ emission. Building in these further assumptions would not be concerning, or render it a less compelling detection. Rather, uncovering theoretical results that would allow such a method to achieve discriminant validation would be an enormous success for black hole astrophysics.

5 Conclusion

The case of the photon ring initially seems to highlight the risks of theory-mediated detection—in particular, model-mediated detection of novel phenomena in astrophysics. However, the dependence of hybrid imaging on theoretical assumptions about the target phenomena was ultimately not the problem with this method. Instead, the broader methodological context, including the modelling of backgrounds ($n = 0$ emission) and the lack of a test for discriminant validation explain why the detection claim didn't stick. In short, mediation by theory (models of the photon ring) is a virtue, rather than a vice, of the hybrid imaging method. Future detection by model-based methods can even be made *more* secure by making use of additional theoretical results the detection procedure. In showing this, I hope to have shed light on an interesting episode in recent black hole astrophysics; extended the scope of discussion of theory-mediated measurement; and ultimately contributed to a defence of theory-mediated measurement as a source of high-quality evidence.

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