PROCEEDINGS OF SCIENCE

Experimentally, How Dark Are Black Hole Mergers?

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The first Advanced LIGO observing run detected two black hole merger events and likely a third. Many groups organized to followup the events in the optical even though there is a strong theoretical prior that no optical emission should be seen. We carry through the logic of this by asking about the experimental upper limits to an optical signal from Advanced LIGO black hole merger events. We inventory the published optical searches for transient events associated with the black hole mergers. We describe the factors that go into a formal limit on the visibility of an event (sky area coverage, the coverage factor of the camera, the fraction of sky not covered by intervening objects), and list what is known from the literature of the followup teams quantitative assessment of each factor. Where possible we calculate the total probability from each group that the source was imaged. The calculation of confidence level is reviewed for the case of no background. We find that an experimental 95% upper limit on the magnitude of a black hole requires the sum of the total probabilities over all events to be more than 3. In the first Advanced LIGO observing run we were far from reaching that threshold.

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1. Are black hole mergers dark?

There is a strong theoretical prior that the black hole mergers detected by Advanced LIGO [1] should be invisible. The expected progenitor systems lack the massive accretion disks that feed into the jets to make gamma-ray bursts and AGN so visible. Solar-mass scale accretion disks are, however, at least a logical possibility (e.g., [2], [3]) and even without them black holes in astrophysical environments are merely dim, not invisible (e.g., [4, 5, 6]). Furthermore, there are exotic compact objects that can have the redshift-spheres of black holes but which may or may not posses an event horizon (e.g., boson stars, dark matter stars, dark energy stars) see [7]); whether or not these have optical signatures different than black holes is a research topic. We are led to ask the question: experimentally, how certain are we that there is no optical signature from the Advanced LIGO black hole merger events?

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2. The event inventory and optical searches

The LIGO Science Collaboration discovered 3 black hole mergers in their first observing run; see table 1 (data from [1]). They confidently detected two merging systems, and likely detected a third. Only confidently detected events were transmitted to the electromagnetic followup teams.

	distance	final mass	1^{st} mass	2^{nd} mass	90% sky area	significance
	Mpc	$M_\odot$	$M_\odot$	$M_\odot$	deg^2	σ
GW150914	420^{+150}_{-180}	$62.3^{+3.7}_{-3.1}$	$36.2^{+5.2}_{-3.8}$	$29.1^{+3.7}_{-4.4}$	230	> 5.3
GW151226	440^{+180}_{-190}	$20.8^{+6.1}_{-1.7}$	$14.2^{+8.3}_{-3.7}$	$7.5^{+2.3}_{-2.3}$	850	> 5.3
LVT 151012	1000^{+500}_{-500}	35^{+14}_{-4}	23^{+18}_{-6}	13^{+4}_{-5}	1600	1.7

Table 1: Measurements of the three most significant events: median values with 90% credible intervals.

As of this writing (September 2016) there have been 10 papers describing followup in the optical. More reports of observations have been sent to GCN (see the list in [8]); we will put these aside, as we will the non-optical followup.

The optical followup breaks into two deep wide-field searches, two shallow very wide-field searches, and two searches based on nearby galaxies, The deep wide-field searches are from the DESGW and Pan-STARRS. Our DESGW group produced two papers on GW150914 [9, 10]and one on GW151226 [11]; two describing the search for the events and one describing a search for failed supernovae. The group using Pan-STARRS produced two papers, the first [12] describing in detail the search for GW150914, the second briefly describing the search for GW151226 [13] (and mentioning ATLAS telescope data); these papers also described extensive transient followup observations (i.e, spectroscopy and further photometry) of candidates. The shallow very wide field searches were by the collaboration operating the MASTER Global Robotic Network of 6 telescopes [14], and by the Japanese collaboration for gravitational wave electromagnetic followup (J-GEM) which uses 17 telescopes [15]. The groups using nearby galaxies to choose where to point their telescopes were the TOROS collaboration [16] and the group using the iPTF [17].

Event	Experiment	Magnitude	$\Sigma_{spatial}$	ε_{camera}	ε_{sky}	P_{total}
GW150914	Master 2x0.4m	18.4-19.9 O	49%	1.0		
	DESGW 4.0m Blanco, DECam	22.1 i	11%	$0.8 \cdot 0.34$ †	0.8	.024
	PanSTARRS 1.8m	19.7 i	4.2%	1.0 ††	0.5 ‡	.021
	iPTF 1.1m Oschint, CFH12K	20.6 R	0.2%	1.0 §		
	JGEM 1.1m Kiso, KWFC	19.0 i	0.1%			
	TOROS 1.5m EABA	21.7 r	galaxy	1.0		
GW151226	ATLAS 0.5m	19.0 o	36%			
	PanSTARRS 1.8m	20.5 i	26.5%	1.0 ††	0.5 ‡	.133
	DESGW 4.0m Blanco, DECam	22.1 i	2%	0.8	0.8	.013

Table 2: Published optical followup data on Advanced LIGO black hole mergers, showing the basic information needed to place an upper limit. The probability that we observed the location of the black hole merger is P_{total}.
† Template coverage.
†† Assuming the dither pattern covers the entire area.
‡ Sky fraction is mixed with, and dominated by, limiting magnitude.
§ The iPTF reported only the area after taking into account ε_{camera}.

3. Limits on optical signatures from black hole mergers

What is the probability of detecting a light source above a certain magnitude? Start with the probability P that an imaging element was able to measure a source:

$$P = \Sigma_{spatial} \cdot \varepsilon_{camera} \cdot \varepsilon_{area} \,. \tag{3.1}$$

Table 2 tabulates the information from the literature, where:

- $\Sigma_{spatial}$ is the summed probability inside the Advanced LIGO spatial localization map covered by the bounding box of images taken.

- ε_{camera} is the fraction of the camera that is live: the DECam, for example has an imaging area of $\approx \pi$ deg^2, but only 80% of it is filled with useful silicon; the rest are gaps between the CCDs, dead CCDs, or glowing edge regions around the perimeter of the CCDs that we remove from the analysis. DESGW and iPTF reported this number; PanSTARRS did not, perhaps because they covered the area multiple times (which has the effect of $\varepsilon_{camera} \rightarrow 1$).

- ε_{sky} is the fraction of the area imaged that a source would have been visible in. The DESGW, iPTF, and PanSTARRS analysis used fake objects injected into the images and recovered to measure this. Unfortunately, both iPTF and PanSTARRS used the measurement to establish limiting magnitude by locating the magnitude at which 50% of the fakes were found; it would be better to separate the two ideas.

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Next ask whether we imaged the precise sky location of at least one merger: the probability that we would cover at least one merger is 1 minus the probability of missing all events:

$$P_{one} = 1 - \prod_i (1 - P_i) \tag{3.2}$$

where P_i denotes P_{total} for the i^{th} event. After 6 events, assuming P_{total} = 50% for all, $P_{one} = 0.984$; after 10, $P_{one} = 0.999$

Finally, ask about the upper limit one can place. Assuming no background and a non-zero uniform prior, the cumulative posterior PDF is:

$$F(s|0) = \int_0^s \frac{t^n e^{-t}}{n!} \mathrm{d}t = 1 - e^{-s} \tag{3.3}$$

where s is the $\sum P_{tot}$ (accounting for sky overlaps; please let's put Healpix maps into GraceDB!). If one wants to place a 95% confidence limit at a given magnitude, one needs $s \geq 3$. The result of optical followup of the first Advanced LIGO as presented in Table 2 has $s = 0.19$. This could be raised by a factor of 2-3 by determining the ε_{sky} for the MASTER and ATLAS data and completing the template set for DESGW.

Experimentally we have no constraint on the optical emission from a black hole merger. A reasonable confidence level upper limit should be one of the primary aims of the optical followup to Advanced LIGO observing run 2.

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