

Early release of low-frequency atlas of continuous gravitational waves

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We present the public release of the low-frequency atlas of continuous gravitational waves, covering signals with frequencies from 20 Hz to 200 Hz and frequency derivatives from -5×10^{-11} to 5×10^{-11} Hz/s. Compared to the previous atlas releases, this version demonstrates significant improvements in sensitivity and sky resolution. In the most sensitive region, even the worst-case upper limits on gravitational wave strain are below 10^{-25} . The atlas data are being released ahead of the completion of the full follow-up analysis.

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I. INTRODUCTION

The first continuous gravitational wave atlas was released several years ago [1] and covered signals with frequencies between 500 and 1000 Hz and frequency derivatives from -5×10^{-11} to 5×10^{-11} Hz/s. Since then, we produced new atlases that progressively expanded parameter space coverage [1–3].

With this paper, we make the low-frequency atlas publicly available to improve coverage in the low-frequency regime. The sky resolution has been enhanced by a factor of 6 compared to Ref. [3], and the use of the full O3 data [4,5] combined with a longer coherence length has improved the sensitivity of the search. In fact, the worst-case all-sky upper limits have decreased by 30%, and for the first time are below 10^{-25} at the most sensitive frequencies (Fig. 1).

Our atlas provides upper limits on continuous gravitational waves based on measurements of power in LIGO [8] data. Additionally, we include signal-to-noise ratio (SNR) peaks and their associated parameters.

II. SIGNAL MODEL

Continuous gravitational waves are expected from rapidly rotating neutron stars with sustained nonaxisymmetric deformation ε . The intrinsic amplitude of the gravitational

wave signal at a distance d from the source is proportional to the deformation, increases with the square of the signal frequency f , and decreases with the inverse of the distance to the source d :

$$h_0 = \frac{4\pi^2 G I_{zz} f^2 \varepsilon}{c^4 d}, \quad (1)$$

where $I_{zz} = 10^{38}$ kg m² is the moment of inertia of the star with respect to the principal axis aligned with the rotation axis. Gravitational waves carry away energy, gradually slowing down the pulsar's rotation. Most known radio pulsars have frequency derivatives within $\pm 2.5 \times 10^{-11}$ Hz/s.

To compute the atlas data, we assume a source which emits gravitational waves with the following frequency evolution in the Solar System barycenter:

$$f(t) = f_0 + (t - t_0)f_1 + (t - t_0)^2 f_2 / 2. \quad (2)$$

Here, the source frequency f_0 covers frequencies from 20 to 200 Hz, the source frequency derivative is constrained by $|f_1| \leq 5 \times 10^{-11}$ Hz/s, and the source second frequency derivative is within $|f_2| \leq 10^{-20}$ Hz/s². We chose epoch $t_0 = 1253800000$ s GPS (2019 Sep 29 13:46:22 UTC), which is in the middle of our dataset.

Higher-order frequency derivatives are not explicitly searched over, instead relying on the intrinsic robustness of a search with a coherence length of 2 days and using one year of data. The signal model of Eq. (2) and the parameter space choice were optimized for isolated rotating neutron stars, but they apply more generally—in particular, to neutron stars in wide-period binary orbits [9,10] and to boson condensate sources [11–14].

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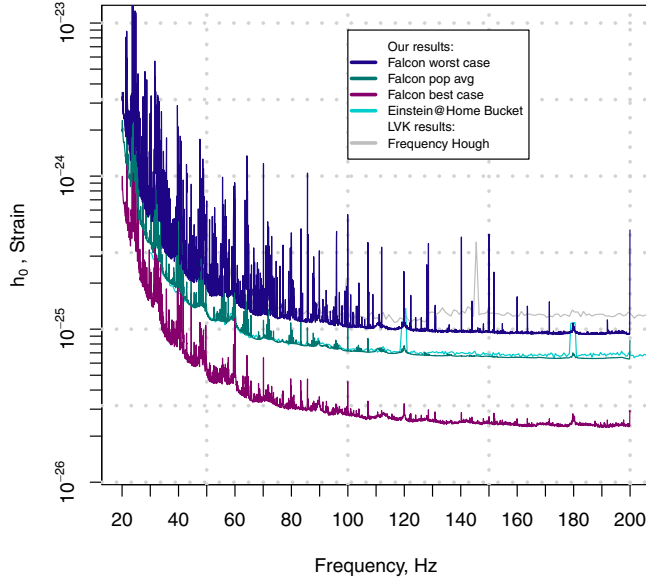


FIG. 1. Gravitational wave intrinsic amplitude h_0 upper limits at 95% confidence as a function of signal frequency. The upper limits reflect the sensitivity of the search. We also plot latest the LIGO/Virgo and Einstein@Home all-sky population average results [2,6,7] and the Falcon population average proxy $LL_{90\text{-sky}}$.

III. ATLAS DATA

The atlas [15] partitions the parameter space by frequency and sky position. The frequency space is divided into 50 mHz frequency bands. For each frequency band, we

construct a grid of sky locations. The sky points are sufficiently dense that the upper limit values associated with the point hold for all sky positions in the Voronoi domain associated with the point. The Voronoi domain is constructed using the angular distance on the celestial sphere. The script `sky_grid_example1.R` provided with the atlas plots the centers of all Voronoi domains for any frequency band.

We set different types of upper limits, established based on different assumptions on the polarization of incoming signals. The worst-case upper limit is computed as maximum over all polarizations and is dominated by linearly polarized signals. Circularly polarized signals yield the most stringent upper limits (lower curve in Fig. 1), typically more than a factor of 2 lower than worst-case upper limits, because circularly polarized signals couple best with the detector. Upper limits for signals of arbitrary polarizations can be estimated using the sky-position-dependent coefficients provided in the atlas [16].

All upper limits are derived using the universal statistics algorithm [17] and are strict frequentist 95% confidence level upper limits. The 95% is actually a design target, and actual values are expected to have higher confidence depending on the underlying noise distribution.

The atlas has an SNR peak value per sky-grid point and per 50 mHz band. This value is the maximum SNR over the 50 mHz frequency band and over polarizations at that sky-grid point. We also provide the value of the frequency and the polarization of the highest SNR result. Table I

TABLE I. This table shows the frequency parameters of the hardware-injected continuous wave signals and how they appear in the atlas data. We show all the hardware injections within the 20–200 Hz range, including those outside of our search space, as indicated by the “In” column. We show our upper limit (UL) at the injection sky position and polarization parameter values, and how it compares with the injection amplitude h_0 : if the upper limits are correct, UL/h_0 has to be $> 100\%$. This is the case for all hardware injections “in range”—i.e., within the target parameter space of this search. h_0/LL shows the ratio of the signal strain to the lock level (LL), and we expect to detect signals when this ratio is $> 100\%$. We hence expect to identify the first two hardware-injected signals in range, but not the third. “To identify” here means that the SNR peak at the closest sky position to the signal has frequency and polarization parameters within the tolerances described in Sec. IV of the signal parameters. Hardware injection 11 is offset in frequency $|\Delta f| > 0.2$ mHz from the signal frequency, and is thus not recovered, consistently with the fact that its h_0 lies below the LL. In the nearby frequency region, there is a disturbance that produces a high-SNR event and a high upper limit. We use the reference time (GPS epoch) $t_0 = 1253800000$ s (2019 Sep 29 13:46:22 UTC). The script `spatial_index_example2.R` provided with the atlas shows how to obtain this data from the atlas.

	f	$\dot{f}$	SNR	UL/h_0	h_0/LL	Δf	In
#	Hz	Hz/s	(Atlas)	%	%	mHz	
3	108.85716	-1.46×10^{-17}	34.1	126.7	189.4	0.031	Yes
5	52.80832	-4.03×10^{-18}	259.9	135.2	364.6	-0.005	Yes
6	145.33976	-6.73×10^{-9}	8.2	19.8	638.0	-30.505	No
8	189.96498	-8.65×10^{-9}	8.3	58.8	215.0	0.832	No
10	26.33144	-8.5×10^{-11}	51.2	86.4	120.5	-23.734	No
11	31.42470	-5.07×10^{-13}	41.7	245.4	87.4	-10.257	Yes
12	37.70750	-6.25×10^{-9}	9.7	106.4	133.3	47.890	No

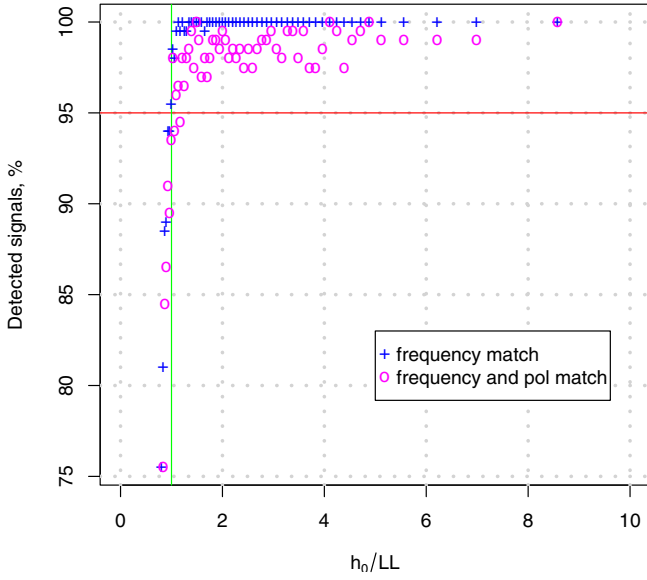


FIG. 2. Signal recovery as a function of signal strain. To highlight the consistency of our LL, we plot the signal strain as a ratio of signal strain to lock-level estimated on data with the test signals. The red line marks the 95% threshold. The blue crosses show the percentage of points where the SNR peak frequency was within 0.2 mHz of the injected value. Given the 50 mHz frequency band, there is a 0.4% chance of false coincidence. The magenta circles show the percentage of points where in addition to frequency constraint ι was within 0.7 of the injected value and ψ was also within $0.6/\sin(\iota)$ of the injected value modulo $\pi/2$. Such wide tolerances are due to shoulders in ι and ψ recovery (see Figs. 3 and 4).

shows an example of atlas data looked up for hardware-injected signals.

With this atlas, we also introduce an estimate of the signal strength necessary for our search to “lock on” to a signal from a given sky position—i.e., to detect the signal

and correctly estimate its frequency and polarization. This is the “location-specific polarization-average lock-level proxy.”

IV. POPULATION-AVERAGE PROXIES

The location-specific polarization-average lock-level proxy LL is defined as the signal strain level at which the frequency and polarization parameters of the SNR peak in the corresponding Voronoi domain (sky region around a sky-grid point and 50 mHz frequency band) are correctly reported in the atlas for 95% of signals. Specifically, the location-specific polarization-average lock-level proxy LL is the h_0 value such that 95% of signals with strain at or above LL, independently of their polarization, within that frequency band and within the Voronoi cell associated to that sky-point, would generate an SNR peak in the atlas with parameters consistent with the signal. That means at a frequency which is no more than 0.2 mHz away from the signal frequency, at an inclination angle ι within 0.7 of the signal ι_s and polarization ψ within $0.6/\sin(\iota_s)$ of the signal values, modulo $\pi/2$. In this sense, we call this a polarization-average proxy. The primary intended use for the proxy is to assess when a limited parameter-space follow-up of SNR-peak parameters has merit, or when the entire Voronoi domain needs to be reanalyzed with a more sensitive search in the given frequency band. For example, one can compare the LL with the gravitational wave signal amplitude estimated for a newly discovered pulsar.

Our location-specific polarization-average lock-level proxies are computed for each atlas entry from an estimate of the background noise and are insensitive to the presence of plausible strength signals. In our injection study, 99% of the test signals (of Fig. 2) change the lock level by less than 1%.

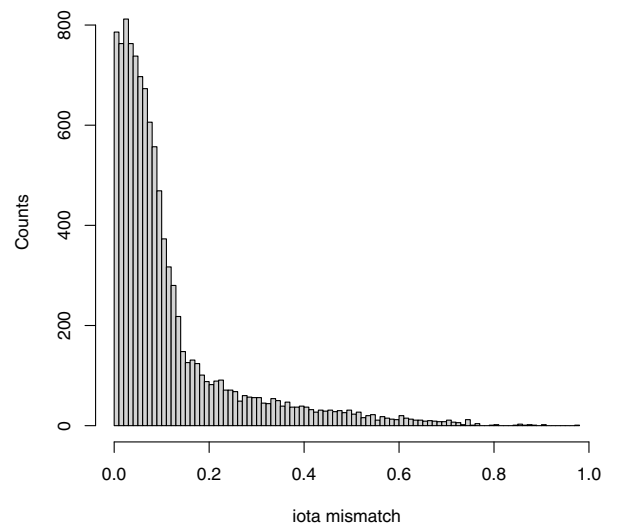
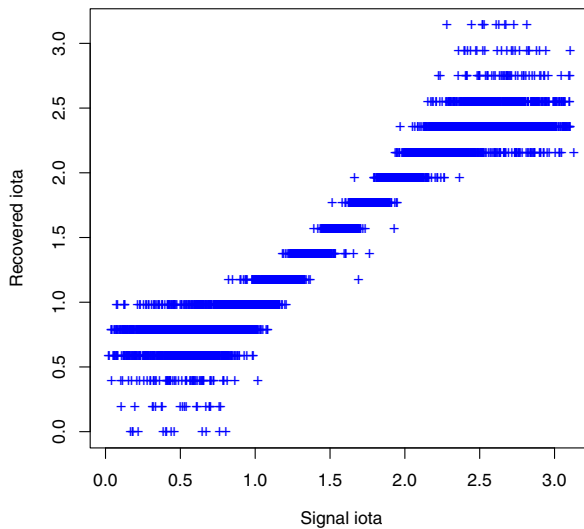


FIG. 3. Recovery of the inclination angle ι . We plot only points corresponding to signals with strains at or above the population-average lock level. The higher uncertainty for nearly circular polarized signals results in wide shoulders in the histogram.

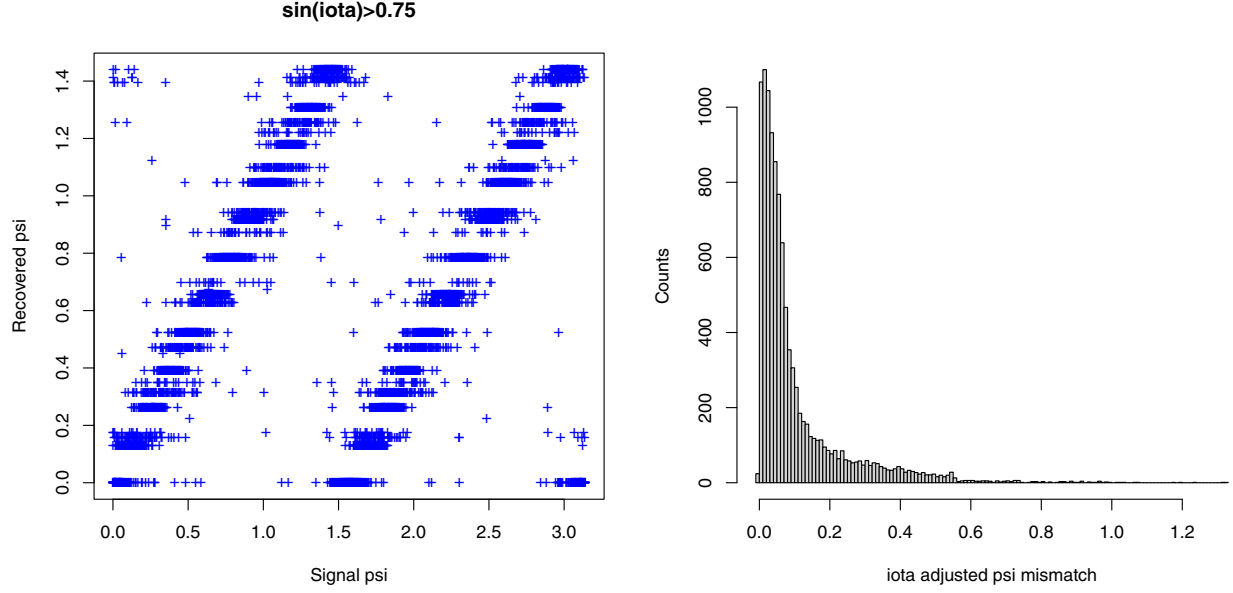


FIG. 4. Recovery of the polarization angle ψ from the SNR peaks. We plot only points corresponding to the injected strain at or above the polarization-average lock level. The left plot restricts data to nearly linearly polarized signals. The right plot includes all points, but multiplies the difference between injected and recovered ψ values (modulo $\pi/2$) by $\sin(i)$. This way, the mismatch in ψ is deweighted as i approaches circular polarizations 0 or π (the “poles” of the polarization sphere).

TABLE II. This table shows how signals are recovered in the 100–101 Hz frequency range. It is an illustrative spot check of the all-sky population-average upper limit estimate. In each band, we consider 200 test signals with strain equal to the all-sky population-average upper limit estimate and the other parameters distributed randomly in the search parameter space. We add each signal to the data and carry out the search. Columns 4 and 5 show the percentage of test signals for which the frequency (column 4) and frequency + polarization (column 5) are correctly recovered in the test-signal parameters Voronoi domain. For signals with arbitrary sky position, we expect both these numbers—and in particular, that of column 5—to be at least 90%, if the all-sky population-average upper limit estimate is correct. Indeed, we see that in most frequency bands this is the case. In the band containing a strong disturbance, such as the first band of the table, the SNR peak is due to the disturbance and not representative of a signal, so “signal lock” at the proxy level is not achieved as effectively (also see Fig. 5). Column 3 shows the highest SNR value from each band in the atlas results. Large values indicate a loud signal, astrophysical or not.

Band start	Band stop	SNR	Frequency	Frequency
Hz	Hz	all-sky	lock, % & pol lock, %	
100.003	100.054	98.2	64.0	61.0
100.053	100.104	17.8	99.0	96.5
100.103	100.154	10.6	99.5	98.0
100.153	100.204	10.3	99.5	94.0
100.203	100.254	10.2	99.0	98.0
100.253	100.304	12.3	99.5	97.5
100.303	100.354	11.3	99.5	98.0
100.353	100.404	10.9	99.5	97.0
100.403	100.454	10.3	100.0	97.5
100.453	100.504	10.5	97.0	92.5
100.503	100.554	10.4	98.0	91.5
100.553	100.604	10.3	99.0	97.0
100.603	100.654	10.4	99.5	95.5
100.653	100.704	10.6	99.0	97.0
100.703	100.754	10.5	100.0	95.0
100.753	100.804	10.6	99.5	95.5
100.803	100.854	13.5	97.5	93.0
100.853	100.904	10.5	99.5	95.5
100.903	100.954	10.4	98.0	96.0
100.953	101.004	10.7	100.0	96.0

We validate this proxy using test signals distributed uniformly on the sky and with frequencies in the 100–200 Hz band. For each test signal, we consider the parameters (frequency and polarization) of the SNR peak at the sky point closest to the position of the test signal and in the relevant 50 mHz frequency band. Figure 2 shows the percentage of signals with SNR peak frequency within 0.2 mHz of the actual value, as well as the percentage of signals with both frequency and polarization correctly recovered, as a function of signal strength. We verify that when the signal strength is at the lock level, the recovered fraction of signals across a population of signals with arbitrary polarization is at the 95% level. Figure 2 also shows that frequencies are recovered most accurately, while polarization recovery is less precise. This is because polarization reconstruction relies heavily on amplitude modulation, introducing significant degeneracy, especially for nearly circularly polarized signals (Figs. 3 and 4).

Location-specific lock-level proxies can be used to estimate the sensitivity of our search for a population of signals coming from any direction in the sky, and this can in turn be used to generate an estimate of the so-called population-average upper limits over the whole sky, in the absence of signals. This is useful because most all-sky searches [6,7,18,19] report results as population-average upper limits. These are conceptually simple to implement by simulating search results from populations of signals and comparing them with the observation results, until the

signal amplitude that yields the 95% quantile is identified. However, practical challenges may arise, and the computational cost of these estimates is generally not trivial. The Falcon searches, like the one presented here, and its predecessor the Powerflux search, have used a different approach, establishing upper limits for fixed polarizations using the universal statistics [17], which do not suffer from the same limitations. However, this can make comparison with the results of other pipelines more difficult.

With the lock-level proxies in hand, we provide an estimate of the population-average all-sky upper limits in the absence of signals by taking the 95% quantiles of the location-specific lock-level proxies, resulting in a 90% confidence level: 95% confidence level of the proxies $\times$ 95% quantile $\gtrsim$ 90% confidence. We indicate this quantity with $LL_{90\text{-sky}}$. The resulting curve is shown in Fig. 1, and it can be used for pipeline sensitivity comparisons. Its physical meaning should be interpreted as the level of strain at which 90% of signals are expected to have correct SNR peak parameters in the atlas, and not as actual upper limit results. Computationally expensive test-signal recovery simulations would be required to determine the actual confidence associated with the values in each band.

We have performed spot checks of the all-sky population-average upper limit estimates, the results of which are shown in Table II. Each frequency band was tested with 200 simulated signals having strain equal to all-sky population-average proxy and the rest of parameters

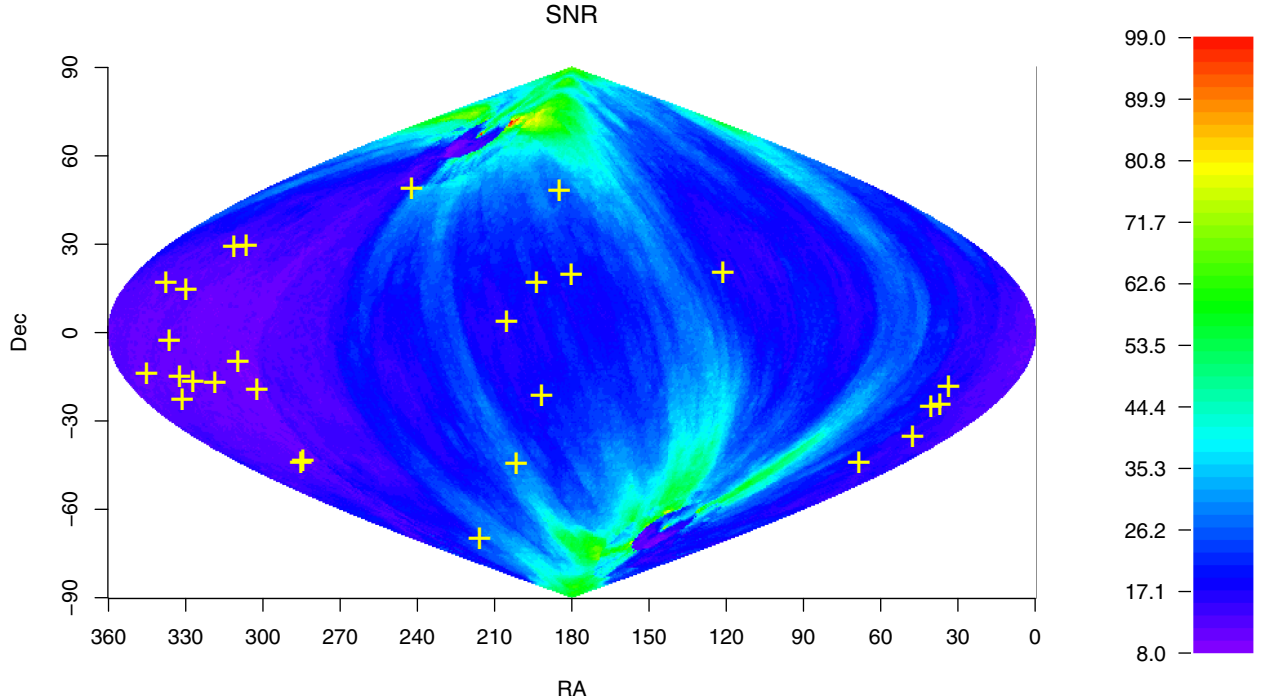


FIG. 5. This figure shows how SNR varies over sky position in the band 100.003–100.054 Hz. We observe strong contamination from instrumental artifacts near 100 Hz. The yellow plus signs denote locations of test injections with $|\cos(i)| < 0.5$ that were recovered with frequency lock. We see that they all come from areas with smaller SNR peaks and less severe contamination.

distributed randomly. We observe that lock rates are above the design value of 90% for all bands except 100.003–100.054 Hz, which is highly contaminated by detector artifacts (Fig. 5).

Figure 5 shows that nearly linearly polarized injections fail to achieve frequency lock in contaminated regions with high-SNR detector artifacts. This is expected behavior, because the lock level is a measure of background noise and is constructed to be insensitive to any signals in the band—whether astrophysical or technical.

More generally, there is a natural variation in detector sensitivity with sky position. Thus, the rate of test-signal recovery based on any population average proxy, regardless of how it is constructed, will vary with the position of the source in the sky. This again highlights the dependence of population average proxy on the population it was designed for, in contrast to frequentist upper limits designed with universal statistics [17], which apply to any subset of parameter space.

V. CONCLUSIONS

We have conducted a wide-band search of the full O3 data covering frequencies from 20 to 200 Hz, which is the

most sensitive all-sky search to date. The results have been compiled into an atlas, which we release while the final analysis is ongoing. We introduce population-average lock-level proxies for every sky location in the atlas data. The atlas includes several examples, written in R, that can be a starting point for future searches.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [15].

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