Search for gravitational waves from twelve young supernova remnants with a hidden Markov model in Advanced LIGO’s second observing run

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Persistent gravitational waves from rapidly rotating neutron stars, such as those found in some young supernova remnants, may fall in the sensitivity band of the advanced Laser Interferometer Gravitational-wave Observatory (aLIGO). Searches for these signals are computationally challenging, as the frequency and frequency derivative are unknown and evolve rapidly due to the youth of the source. A hidden Markov model (HMM), combined with a maximum-likelihood matched filter, tracks rapid frequency evolution semi-coherently in a computationally efficient manner. We present the results of an HMM search targeting 12 young supernova remnants in data from Advanced LIGO’s second observing run. Six targets produce candidates that are above the search threshold and survive pre-defined data quality vetoes. However, follow-up analyses of these candidates show that they are all consistent with instrumental noise artefacts.

I. INTRODUCTION

Young supernova remnants (SNRs) hosting rotating neutron stars are promising candidates for the detection of continuous gravitational waves (GWs) by the advanced Laser Interferometric Gravitational-wave Observatory (aLIGO) [1–3]. Detection of transient GW events from mergers of compact binaries has now become routine [4]. Persistent, periodic GW signals have not yet been detected, but they are an attractive target, because the GW strain is proportional to the stellar ellipticity, which is determined partly by the nuclear equation of state [1]. Motivated by the opportunity to do fundamental nuclear physics experiments, several groups have conducted continuous wave searches covering the whole sky [5–7] and various specific targets, e.g. known pulsars [8, 9], the Galactic center [10, 11], and young SNRs [12–15], which are the subject of this paper.

Young neutron stars are especially likely to be non-axisymmetric, as any ellipticity produced during the violent birth of the star has had less time to relax by Ohmic, viscous, or tectonic processes [16–18]. Mass quadrupole emission (e.g. thermoelastic [19, 20] or magnetic [21–23] mountains) is expected to occur at the neutron star’s rotational frequency, $f_*$, or $2f_*$. Current quadrupole emission, e.g. from a pinned superfluid [24, 25] or r-modes [26], is expected to occur at $f_*$ or approximately $4/3f_*$ respectively.

Traditional searches are hampered by the computational cost of trialling a huge number of matched-filters, when the spin frequency and its evolution are rapid and unknown. The number of required templates scales as $\tau_{obs}^{n+1}$, where $n$ is the highest derivative $f_s^{(n)}$ in the phase model. This makes searches on long stretches of data with unknown frequency evolution computationally infeasible. Neutron stars are also subject to timing noise [27], which causes the signal to wander stochastically.

In this paper, we present the results of an HMM search for continuous waves first introduced by Suvorova et. al in 2016 [28], using open data from advanced LIGO’s second Observing Run [29, 30]. The HMM is both robust against spin wandering and computationally cheap.

The paper is organized as follows. In Sec. II A we give an overview of the methods used in previous searches for GWs from SNRs. In Sec. II B we introduce the HMM, and then in Sec. II C we describe how the HMM formalism is used in the search for continuous GWs. Section III explains the methodology for selecting the search parameters for each SNR. In Sec. IV A we go over the selection of SNR targets, and in Sec. IV B we introduce the methods for selecting a threshold for detection. Sec. V presents the results of our search, included the requirements for vetoing a potential candidate. We conclude in Sec. VI.

II. METHODOLOGICAL OVERVIEW

A. Previous SNR searches

Three searches for continuous GWs from SNRs were performed in data from initial LIGO [14, 31–33]. More recently, three searches have been performed for GW emission from young SNRs in Advanced LIGO’s first and second Observing runs (O1 and O2, respectively) [12, 13, 15]. No detections were reported, and upper limits were set on the maximum GW strain emitted by each target. Because O1 and O2 are more sensitive than Initial LIGO, [12, 15] significantly improve upon the upper limits set in Ref. [32].

Some of the previous searches [12, 15, 31, 32] used a coherent matched-filter test that was based on the maximum likelihood $F$-statistic [34]. The $F$-statistic models the continuous GW signal as a sinusoid with slow frequency evolution given by

$$f(t) = f_* + f_0(t - t_0) + \frac{1}{2} \dot{f}_0(t - t_0)^2,$$

where $t_0$ is the time at the start of the observing period. The $F$-statistic accounts for amplitude modulation arising from the movement of the Earth. However, it does
not account for stochastic spin wandering on time scales of days to weeks, known as timing noise [35–37], which represents a major challenge for traditional $F$-statistic searches. Additionally, the young neutron stars in this search may spin down so rapidly, that a template bank proportional to $\dot{f}_N$ must be kept in Eq. 1, leading to an unmanageable number of templates. Consequently, previous young SNR searches only use some of the available data. For example, O1 spanned 130 days, but the searched data in Ref. [12] only ranged from 3 to 44 days in the 15 targets [12]. The more recent $F$-statistic search in O2 data spanned 12 to 55 days depending on the target, and searched a frequency band of 150 to 150 Hz [15].

An alternative to a fully coherent matched-filter search is to break the data into smaller segments and perform a semi-coherent analysis. A number of semi-coherent analyses have been used in LIGO and Virgo searches for continuous GWs [38–40]. In this paper we perform a semi-coherent search that uses an HMM to track the GW frequency. The HMM employs recursion to prune efficiently the exponentially large bank of templates required to capture rapid secular spin down or stochastic spin wandering.

B. HMM

A Markov chain describes a state $q(t)$ that wanders among a set of discrete states, $\{q_0, q_1, \ldots, q_{N_t}\}$, with state transitions happening at discrete time steps $\{t_0, t_1, \ldots, t_{N_t}\}$. A Markov chain is memoryless, so the state at time $t_i$ depends only on the state at the previous time step, $t_{i-1}$. The probability of a transition from one state to another is given by the transition probability

$$A_{q_iq_j} = P(q_j|q_i), \quad (2)$$

with $q_j = q(t_j)$.

An HMM relates a finite set of unobservable ("hidden") discrete state variables to a finite set of observables. The observable $o(t)$ occupies one of the discrete states $\{o_0, o_1, \ldots, o_{N_o}\}$. The observable state is related to the hidden state by an emission probability defined by

$$L_{o_iq_j} = P(o_i|q_j), \quad (3)$$

with $o_i = o(t_i)$.

Over some observation period we can find the most likely hidden state sequence, $Q^*$, given the observable state sequence, $O$ by maximizing

$$P(Q|O) = L_{o(t_{N_t})q(t_{N_t})} A_{q(t_{N_t})q(t_{N_t-1})} \times \ldots$$

$$\times L_{o(t_1)q(t_1)} A_{q(t_1)q(t_0)} L_{q(t_0)}, \quad (4)$$

with respect to $Q$. In Eq. 4, $\Pi_{q(t_0)}$ is the prior probability that the state started at $q_0$ at $t = t_0$. The maximization can be done with the Viterbi algorithm [41], which uses dynamic programming to sample the $N_{T_f}$ sequences $Q$ efficiently.

Having outlined the HMM formalism, we now discuss how it is implemented in GW searches in Sec. II C.

C. HMM search for GWs

As discussed in Section II A, fully coherent $F$-statistic searches are computationally expensive. One method to lighten the computational load is to perform a semi-coherent search: we divide the full stretch of data of length $T_{\text{obs}}$ into smaller segments of length $T_{\text{drift}}$, perform a coherent search in each segment, and combine the results of those searches.

Here we combine the HMM and $F$-statistic to perform a semi-coherent search. The framework for combining an HMM and the $F$-statistic to search for GWs from young SNRs was first introduced in [42]. The hidden state is the GW frequency, $f_0(t)$. The observable is the $F$-statistic, whose emission probability is given by [28]\(^1\)

$$L_{o(t)|q} \propto \exp \left[ \mathcal{F}(f_0) \right]. \quad (5)$$

We calculate $\mathcal{F}(f_0)$ for each segment of length $T_{\text{drift}}$, at a frequency resolution of $\Delta f = 1/(2T_{\text{drift}})$. The recipe for setting $T_{\text{drift}}$ is described in Section III.

To construct the transition probability, we assume that between time steps the frequency either stays in its current state ($q_i$), moves up one frequency bin ($q_{i+1}$), or moves down one frequency bin ($q_{i-1}$) with equal probability:

$$A_{q_iq_i} = A_{q_iq_{i+1}} = A_{q_iq_{i-1}} = \frac{1}{3}. \quad (6)$$

All other probabilities are equal to zero\(^1\). Analyzing the data in segments eliminates the need to explicitly search over $f_0$. The data segmentation also allows for a more flexible model of frequency evolution to account for stochastic spin wandering [43–46] and magnetic dipole braking simultaneously.

Finally, as we do not know $f_0(t_0)$, the prior is uniform:

$$\Pi_{q(t)} = \frac{1}{N_Q}. \quad (7)$$

Here $N_Q$ is the number of frequency bins.

III. PARAMETERS

In this section we again outline the procedure for setting the parameters for an SNR search, namely the frequency range and $T_{\text{drift}}$.

\(^1\) Because young SNRs are expected to spin down rapidly [12, 42], another choice would be $A_{q_iq_i} = A_{q_iq_{i-1}} = \frac{\Delta f}{2}$. To maximize flexibility and robustness, we choose to use Eq. 6. The extra computational burden is minimal, as confirmed in previous studies [28, 42].
A. Frequency Range

The SNRs we are targeting in this paper do not contain electromagnetically observed pulsars, so \( f_0(t) \) is unknown. To search for electromagnetic braking, we must set the frequency range over a broad range of frequencies. To set the frequency range, we demand that the indirect, age-based, spin-down upper limit on the GW strain lies above the strain sensitivity of the search. For a neutron star of age \( a \) at a distance \( D \) that is spinning down purely due to GW radiation, the characteristic strain \( h_0 \) satisfies \( h_0 \leq h_0^{\text{max}} \) with [47]

\[
h_0^{\text{max}} = 1.26 \times 10^{-24} \left( \frac{3.3 \text{ kpc}}{D} \right) \sqrt{\frac{300 \text{ years}}{a}}. \tag{8}
\]

On the other hand, the 95% confidence upper limit on strain sensitivity for an incoherent search is analytically predicted to be (see Appendix E of [42])

\[
h_0^{95\%} = \Theta S_n(f)^{1/2} (T_{\text{obs}} T_{\text{drift}})^{-1/4}, \tag{9}
\]

where \( \Theta \approx 35 \) is an empirical statistical factor [32, 47], and \( S_n(f) \) is the one-sided noise spectral density. In this paper we search over all \( f_0 \) satisfying \( h_0^{95\%} > h_0^{95\%} \) from Eqs. (8) and (9).

B. \( T_{\text{drift}} \)

The segment length, \( T_{\text{drift}} \), is selected to minimize the mismatch in the \( F \)-statistic. The mismatch is the fractional loss of signal power caused by the discretization of the parameters in the template set [48–50]. Previous HMM searches for low-mass X-ray binaries set \( T_{\text{drift}} = 10 \) days, the fiducial autocorrelation time scale for stochastic spin wandering in accreting systems [51–53]. An HMM has also been used to search for GWs from a long-lived remnant of a binary neutron star merger [54], which used a much shorter \( T_{\text{drift}} = 1 \) second, as the remnant is possibly spinning down very rapidly. In young SNRs hosting a non-accreting neutron star, stochastic spin wandering with an autocorrelation time-scale of days to weeks, known as timing noise in radio pulsar astronomy [43, 55], must be weighed against rapid secular spin down.

As shown in detail in [42], for a neutron star with a spin-down rate of \( f_0 \), in order to keep the \( F \)-statistic mismatch below 0.2 we require \( T_{\text{drift}} \) to satisfy

\[
T_{\text{drift}} \leq \left( \frac{2}{f_0} \right)^{1/2}. \tag{10}
\]

Because the targets in this paper do not have visible pulsars, the spin-down rate \( f_0 \) is not known \( a \) priori. The range of \( f_0 \) to be used in this search can be found by considering the possible ranges of the braking index, \( n = f_0 f_0 / f_0^2 \). For a neutron star of characteristic age \( a = f_0 / [(n - 1) f_0] \), we have

\[
- \frac{f_0}{(n_{\text{min}} - 1) a} \leq f_0 \leq - \frac{f_0}{(n_{\text{max}} - 1) a} \tag{11}
\]

where \( n_{\text{min}} \) and \( n_{\text{max}} \) are the minimum and maximum braking indices respectively. Purely electromagnetic or gravitational braking implies \( n = 3 \) and \( n = 5 \) respectively. Current observations imply \( 2 \leq n \leq 7 \) [45, 56]. In this work we assume \( n = 2 \) conservatively to capture the widest possible range of signals, yielding from Eq. 10:

\[
T_{\text{drift}} = \left( \frac{a}{2 f_0} \right)^{1/2}. \tag{12}
\]

We note that Eq. 12 depends on \( f_0 \), which we do not know \( a \) priori. One option is to use a different \( T_{\text{drift}} \) for each frequency searched, but this adds computational costs as well as additional trials factors. In this work we use a single \( T_{\text{drift}} \) per SNR target, which is the \( T_{\text{drift}} \) that corresponds to the highest frequency where \( h_0^{\text{max}} > h_0^{95\%} \).

C. Summary

The procedure for selecting \( T_{\text{drift}} \) and the frequency bounds \( (f_{\text{min}}, f_{\text{max}}) \) for each SNR target is as follows:

- Insert Eq. 12 into Eq. 9 to predict \( h_0^{95\%} \) for 10 Hz < \( f_0 < 4000 \) Hz, which is approximately the frequency band where LIGO is sensitive.
- Calculate the indirect upper limit \( h_0^{\text{max}} \) from Eq. 8.
- Find the highest frequency obeying \( h_0^{\text{max}} > h_0^{95\%} \), call it \( f_{\text{max}} \).
- Using Eq. 12, calculate \( T_{\text{drift}} \) for \( f_0 = f_{\text{max}} \).
- Insert \( T_{\text{drift}} \) back into Eq. 9 and find the minimum frequency obeying \( h_0^{\text{max}} > h_0^{95\%} \), call it \( f_{\text{min}} \). Fig. 1 shows a predicted sensitivity curve, and indirect \( h_0^{\text{max}} \) for one example SNR. The green curve shows Eq. 9 for the calculated \( T_{\text{drift}} \) of two hours. The blue line is the indirect upper limit from Eq. 8, and the red points indicate \( f_{\text{min}} \) and \( f_{\text{max}} \).

IV. IMPLEMENTATION

A. Target Selection

In this work, we follow up on SNRs that have been targeted previously in LIGO data [12, 32]. Recently, Ref. [12] searched O1 data for 15 young SNRs (as well as the neutron star Fomalhaut b). These SNRs were selected from the Green catalog [82]. Another recent search has followed up on a subset of these targets [15]. SNRs with central compact objects or small pulsar wind nebulae were are normally selected as they are likely hosts of neutron stars.

For each target, we select \( T_{\text{drift}}, f_{\text{min}}, \) and \( f_{\text{max}} \) as described in Section III B.
TABLE I. SNRs targeted in this search. For each target the table shows the astronomical parameters (RA, DEC, age, distance), and search parameters ($f_{\text{min}}$, $f_{\text{max}}$, $T_{\text{drift}}$, and number of sub-bands).

| SNR           | Age (kyr) | Distance (kpc) | $f_{\text{min}}$ (Hz) | $f_{\text{max}}$ (Hz) | $T_{\text{drift}}$ (Hrs) | RA (J2000)   | DEC (J2000) | Number of sub-bands | Duty cycle |
|---------------|-----------|----------------|------------------------|------------------------|--------------------------|--------------|-------------|---------------------|------------|
| G1.9+0.3 [57, 58] | 0.1       | 8.5            | 35                     | 122                    | 1.0                      | 174846.9     | -271016     | 61                  | 69%        |
| G18.9-1.1 [59, 60] | 4.4       | 2              | 34                     | 505                    | 3.3                      | 182913.1     | -125113     | 330                 | 77%        |
| G65.7+1.2 [61, 62] | 20        | 1.5            | 42                     | 335                    | 8.5                      | 195217.0     | 292553      | 205                 | 83%        |
| G93.3+6.9 [63, 64] | 5.0       | 1.7            | 32                     | 600                    | 3.1                      | 205214.0     | 551722      | 397                 | 77%        |
| G111.7-2.1 [65–67] | 0.3       | 3.3            | 28                     | 365                    | 1.0                      | 232327.9     | 584842      | 236                 | 69%        |
| G189.1+3.0 [68, 69] | 20        | 1.5            | 28                     | 853                    | 2.0                      | 61705.3      | 222127      | 577                 | 75%        |
| G266.2-1.2 [70, 71] | 5.1       | 0.9            | 18                     | 840                    | 1.0                      | 85201.4      | -461753     | 575                 | 69%        |
| G347.3-0.5 [76–78] | 1.6       | 0.9            | 23                     | 1747                   | 1.1                      | 171328.3     | -394953     | 1206                | 69%        |

FIG. 1. Example of the predicted 95% upper limit, $h_{95\%}$, from Eq. 9 (green), and the indirect upper limit, $h_{\text{max}}^0$, for the SNR G189.1+3.0. The red dots indicate $f_{\text{min}}$ and $f_{\text{max}}$.

We impose the requirement $T_{\text{drift}} \geq 1 \text{ hour}$, because the $F$-statistic ingests data in the form of 30-minute short Fourier transforms (SFTs), and requires at least two SFTs [83]. As a result, the predicted sensitivity for some targets from [12] cannot beat the indirect upper limit, i.e. those that are young and thus potentially spinning down rapidly. Furthermore, $f_{\text{max}}$ for some targets is bounded by the minimum $T_{\text{drift}}$ requirement rather than the sensitivity bounds in Sec. III B. The SNR targets and their respective search parameters are listed in Table I.

The parameter space of many targets span decades in Hz, so we split the search into sub-bands to facilitate data handling as in previous work [51, 52]. In this work we search over sub-bands of 2 Hz. This is wider than the sub-bands used previously (ranging from 0.606 Hz to 1.0 Hz) because rapid spin-down means the signal could transverse an entire sub-band during an interval of length $T_{\text{obs}}$ if we use a width of 1 Hz or less. That is, there would be a high chance the signal would wander out of one sub-band, thus decreasing the sensitivity of the search. The sub-bands overlap, so that when a Viterbi path does straddle two sub-bands it is completely contained in one of the two.

B. Detection statistic and threshold

Previous HMM searches used the Viterbi score [51, 52] as the detection statistic. The Viterbi score is the number of standard deviations that the log-likelihood of a path deviates from the average of all the other paths in a given sub-band. The Viterbi score ceases to be useful when the number of frequency bins, $N_Q$, becomes comparable to the number of time steps, $N_T$. To understand why, consider how the Viterbi algorithm finds the optimal path. By the principle of optimality [84], given an optimal path over $N_T$ time steps that ends in frequency bin $f_i$, the optimal path that ends in frequency bin $f_{i-1}$ (or $f_{i+1}$) is identical up to time step $N_T-1$. More generally, two paths terminating $j$ frequency bins apart have the same optimal subpath for time-steps $1 \leq k \leq N_T-1$. For $N_Q \gg N_T$, we have $N_T-j < 0$ for most paths, so most of the sub-optimal paths do not overlap. For $N_Q \approx N_T$ however, many of the final paths converge onto the same sub-optimal path. If this path is a loud signal, it increases the mean of the log-likelihoods of all paths, thereby artificially decreasing the Viterbi score.

In short, in situations with $N_Q \gg N_T$, the Viterbi score for a true signal counterintuitively gets worse for longer observation times. For this reason in this work we use the log-likelihood of the optimal path ending in each frequency bin as our detection statistic, unnormalized by the log-likelihoods of the neighboring paths. We denote the log-likelihood as $L$. The probability distribution function of $L$ of the op-
The optimal path is not known analytically; see Section III C of [28] for details. As verified empirically in Gaussian noise, the mean and standard deviation of $L$ depend only on $N_T$ and scale in a well behaved manner. Fig. 2 shows the mean and standard deviation of the distribution of log-likelihoods in 100 realizations of Gaussian noise versus $N_T$ for $500 \leq N_T \leq 5000$, relevant to the SNRs in this paper. We find that the mean of $L$ scales $\propto N_T$, and the standard deviation of $L$ scales $\propto \sqrt{N_T}$.  

![Graph showing the mean (top) and standard deviation (bottom) of $L$ of the optimal path in Gaussian noise versus the number of time steps $N_T$. The blue points are the empirical results. The orange curve is the best fit to those points.](image)

We use the scalings in Fig. 2 to set the $L$ threshold, $L_{th}$. In this study we demand an overall false alarm probability of $\alpha_N = 0.01$ for each target across all of the relevant sub-bands, the standard used in previous HMM searches [51, 52]. For each sub-band the desired false alarm probability $\alpha$ satisfies

$$\alpha_N = 1 - (1 - \alpha)^N$$  \hspace{1cm} (13)$$

where $N$ is the number of sub-bands multiplied by $N_Q$.

The thresholds obtained from the above procedure are shown in Table II. The threshold range is $5761 \leq L_{th} \leq 47783$. The threshold scales with the age of the SNR, so that targets of similar age have similar $L_{th}$, though targets with many sub-bands incur more trials, thus increasing $L_{th}$.

### Table II. Threshold and the number of outliers above that threshold before and after applying the data quality vetoes.

| SNR         | $L_{th}$ | (pre-veto) Outliers | (post-veto) Outliers |
|-------------|----------|---------------------|----------------------|
| G1.9+0.3    | 47752    | 32                  | 0                    |
| G18.9-1.1   | 14830    | 100                 | 2                    |
| G65.7+1.2   | 5761     | 45                  | 4                    |
| G93.3+6.9   | 15156    | 125                 | 1                    |
| G111.7-2.1  | 47771    | 51                  | 0                    |
| G189.1+3.0  | 23227    | 115                 | 3                    |
| G266.2-1.2  | 47783    | 124                 | 3                    |
| G291.0-0.1  | 27243    | 65                  | 0                    |
| G330.2+1.0  | 23346    | 32                  | 0                    |
| G347.3-0.5  | 45290    | 227                 | 5                    |
| G350.1-0.03 | 47774    | 58                  | 0                    |
| G354.4+0.0  | 47753    | 38                  | 0                    |

C. Data

In this work, we search data from LIGO’s second observing run, spanning 270 calendar days from November 2016 to August 2017. A third detector, Virgo, joined O2 for the last month. Due to the short duration of the Virgo run and its lower sensitivity, we analyze only data from the two LIGO detectors, Hanford and Livingston in this paper. The strain data for O2 is publicly available from the Gravitational-wave Open Science Center [29, 30, 85].

During O2 the detectors had periods of down-time. There were two commissioning breaks during the run: an approximately two week period between December and January, and a break in May lasting 19 days for Livingston, and 31 days for Hanford. In addition to these longer breaks, there were shorter periods of down time due to maintenance or environmental factors that brought the detectors out of lock. As described in the previous section, the SFT data products require at least 30 minutes of data, so stretches of data shorter than this are not used in the analysis. Furthermore, times in which the detector is known to not be properly operating in its nominal state are removed from the analysis [86, 87]. Because the $T_{\text{drift}}$ length periods used in this search are relatively short, there are sometimes $T_{\text{drift}}$ length periods where there is no analyzable data. When this occurs, we fill in this period with a constant log-likelihood, as done in previous HMM searches [52]. Accounting for missing SFTs, the effective duty cycles for each SNR are listed in Table I.
V. RESULTS

All 12 of the targets in Table I return Viterbi scores above the threshold defined in Sec. IV B. \( \lambda \) is plotted against the terminating frequency of the associated Viterbi path, with points color coded by their corresponding target (see legend at right). Top: Candidates before vetoes. Bottom: Survivors after the known line veto (circles), and remaining candidates after the single IFO veto (crosses).

**A. Vetoes**

Here we describe the vetoes in two categories. The motivating logic and implementation details for the vetoes are presented in Refs. [51, 52].

- **Instrumental noise lines.** Narrowband instrumental noise artefacts known as “lines” are present in LIGO data at both interferometer sites [88]. They are caused by suspensions vibrations, and the electrical power grid among other things. We veto any candidate whose Viterbi path crosses the catalog of known instrumental lines [29].

- **Single Interferometer Veto.** An instrumental noise artefact that is present in one detector but not the other can artificially lift \( \lambda \) from both detectors combined, \( \lambda_{2ifo} \), above the threshold \( \lambda_{th} \). To identify these false alarms, we rerun the search for each outlying sub-band in each interferometer separately. If \( \lambda \) in either interferometer (but not both) exceeds \( \lambda_{2ifo} \), we veto that candidate as an instrumental artefact. If neither of the single-interferometer log-likelihoods exceeds \( \lambda_{2ifo} \), the candidate survives.

Previous HMM searches have included a veto category in which the search is re-run, dividing the data into two segments. A real signal should be significant in both segments and not turn on or off, although one can imagine exceptions, e.g. a transient r-mode [26]. Previous searches however used the Viterbi score as a detection statistic [51, 52], which (when meeting the requirements described in Sec. IV B) is independent of \( T_{obs} \). Since our detection statistic depends on \( T_{obs} \), we do not use this veto.

**B. Survivors**

The fourth column of Table III lists the veto survivors. There are 18 spread across six SNRs. We report the terminating frequency of the Viterbi path, \( \lambda \) of the original candidate, \( \lambda \) of the single interferometer runs, and \( \lambda \) of an off-source search.

The off-source search is an additional follow-up procedure. For all 18 outliers, we shift the right ascension by 10° while keeping all other search parameters fixed. If the candidate is a true astrophysical signal, the resulting log likelihood should be consistent with Gaussian noise, with probability \( 1 - \alpha \) of falling below \( \lambda \) threshold. If the off-source search exceeds \( \lambda_{th} \), there is likely to be an instrumental noise artefact in that band. \( \lambda \) for the single interferometer runs is included to show whether the candidate is much stronger in one detector than the other. A candidate with a large asymmetry in the reported log-likelihoods from single interferometers can still be indicative of an instrumental noise artefact, even if neither log-likelihood exceeds \( \lambda_{2ifo} \) as described in Section V A. In particular, we note that \( \lambda \) is mostly higher in the Hanford detector than the Livingston detector. A real signal should not show this behavior, because in O2 Livingston was more sensitive than Hanford [4].

Several of the surviving outliers are close to known instrumental lines, even though outliers of similar frequency are vetoed via the known lines veto in one or more of the other targets. As the \( F \)-statistic accounts for annual and diurnal Doppler modulation, lines that are stationary in the detector frame appear sinusoidal (with
TABLE III. Veto survivors. The second through sixth columns list: the Gaussian threshold log-likelihood, the terminating frequency of the Viterbi path, the dual-interferometer $L$ from Hanford and Livingston only, and $L$ of an off-source search. An asterisk indicates that the event is much more significant in one interferometer than the other, and a dagger indicates that the off-source search also produces a candidate above the Gaussian threshold. There are two survivors that are not marked with either a dagger or asterisk, one in G266.2-1.2 and one in G347.3-0.5. The terminating frequencies of these candidates are similar (445.677 and 446.703), which suggests that these survivors are due to a common noise artefact.

| SNR          | $L_{th}$ | Frequency (Hz) | $\log L_{H1}$ | $\log L_{L1}$ | $\log L_{\text{off-source}}$
|--------------|----------|----------------|---------------|---------------|------------------|
| G18.9-1.1    | 14830    | 323.994        | 16224         | 12342*        | 8479             | 14319           |
|              | -        | 462.986        | 17321         | 14363*        | 8467             | 16113†          |
| G65.7+1.2    | 5761     | 68.469         | 18848         | 6377          | 13890*           | 12964†          |
|              | -        | 69.997         | 12818         | 6412          | 5925             | 6474†           |
|              | -        | 71.996         | 6440          | 3972          | 4337             | 4907            |
|              | -        | 323.977        | 6403          | 3898          | 3726             | 6100†           |
| G93.3+6.9    | 15156    | 463.092        | 20483         | 18235*        | 9585             | 20489†          |
| G189.1+30    | 23227    | 451.503        | 43430         | 28129*        | 12165            | 24844†          |
|              | -        | 491.896        | 103623        | 65832*        | 12212            | 61207†          |
|              | -        | 521.749        | 26651         | 25177*        | 13404            | 26056†          |
| G266.2-1.2   | 47783    | 19.650         | 36351         | 372352        | 372352           | 2516600†        |
|              | -        | 446.677        | 49189         | 28319         | 22357            | 35833           |
|              | -        | 494.676        | 79622         | 47087         | 47087            | 100219†         |
| G347.3-0.5   | 45290    | 446.703        | 45571         | 26376         | 21285            | 33325           |
|              | -        | 451.551        | 89539         | 59024*        | 21161            | 51912†          |
|              | -        | 501.859        | 6465100       | 37762400      | 3492760          | 26757600†       |
|              | -        | 956.293        | 67043         | 63642*        | 21132            | 62908†          |
|              | -        | 1519.930       | 48015         | 43218*        | 22481            | 44627†          |

Next we briefly discuss all survivors.

1. **G18.9-1.1**

G18.9-1.1 has two candidates that survive the vetoes. Both show up more strongly in Hanford than Livingston.

The candidate at 462.99 Hz has a log-likelihood of 12342 in H1, versus 8479 in L1. This candidate also resurfaces as a significant outlier in the off-target search, indicating that it is not of astrophysical origin.

The candidate at 323.99 Hz is very close to an instrumental line, and similar candidates were vetoed for other targets. Therefore we believe this outlier is caused by a noise artefact.

The Viterbi paths for these two outliers are shown in Fig. 5.

2. **G65.7+1.2**

There are four veto survivors in G65.7+1.2. Three of the candidates surpass $L_{th}$ in the off-source search, and a period of a year) after passing through the $F$-statistic. Fig. 4 shows the recovered Viterbi path for an outlier in SNR G111.7-2.1. Overlaid on the Viterbi path is the predicted Doppler modulation of a stationary noise line as processed by the $F$-statistic. The agreement is very good.

Next we briefly discuss all survivors.
one is much more significant in the Livingston detector than the Hanford detector.

The candidate with a Viterbi path terminating at 71.996 Hz does not appear as an outlier in the off-source search, or as much more significant in one detector as compared to the other. However, comparing the Viterbi path of this candidate to that of the candidate with a terminating frequency of 69.996 Hz, as shown in the middle two panels of Fig. 6, we see that both paths exhibit similar behavior suggesting a common source. Overlaying the predicted Doppler modulation of a stationary noise line processed by the $F$-statistic, we see a strong overlap with the Viterbi path as shown in Fig. 7. Hence we believe this survivor is from an instrumental noise artefact.

The Viterbi paths of all survivors are shown in Fig. 6.

3. **G93.3+6.9**

G93.3+6.9 has one survivor, which is much more significant in Hanford than Livingston (18235 versus 9585), and very significant in the off-source search. Thus, we do not believe it to be a real GW signal.

The Viterbi path of the outlier is shown in Fig. 8.

4. **G189.1+3.0**

There are three veto survivors in G189.1+3.0, with frequencies of approximately 451.50 Hz, 491.90 Hz, and 521.75 Hz. All three are more significant in Hanford than in Livingston, and show up as significant candidates in the off-source search. They are consistent with noise artefacts.

The Viterbi paths for these candidates are shown in Fig. 9.

5. **G266.2-1.2**

G266.2-1.2 has three survivors. Two of these, at frequencies of 19.65 Hz and 494.68 Hz, are also significant.
in the off-source search. They are consistent with noise artefacts.

The third candidate is around 446.677 Hz. The single interferometer and off-source log-likelihoods do not show anything that immediately indicates a noise artefact. However, the target G347.3-0.5 independently generates a candidate at a very similar frequency (446.703 Hz). As there is no reason to believe two different SNRs emit GWs at the same frequency, the signal is unlikely to be astrophysical in origin.

The Viterbi paths for these candidates are shown in Fig. 10.

6. G347.3-0.5

G347.3-0.5 has five survivors. Four of them show up more strongly in Hanford and/or have significant outliers in the off-source search.

As mentioned above, the survivor at 446.703 Hz is very close in frequency to a survivor in the independent SNR G266.2-1.2. Both are consistent with noise artefacts.

The Viterbi paths for these candidates are shown in Fig. 11.

VI. CONCLUSION

In this work we present a search for continuous GWs from 12 young SNRs using an HMM combined with the maximum-likelihood $F$-statistic. This is one of the first searches for these targets in the LIGO O2 data set. The semi-coherent nature of the HMM search confers computational savings, allowing us to use the entire stretch of O2 data. It also ensures that the search is robust to stochastic spin wandering on time-scales longer than $T_{\text{drift}}$, with $1 \text{ hour} \leq T_{\text{drift}} \leq 8.5 \text{ hours}$.

For each target, we select the frequency band to be searched and coherent analysis time, $T_{\text{drift}}$, to maximize the GW discovery potential. After performing data quality vetoes, we find surviving candidates in six SNR targets. Off-source searches and manual follow-up of these survivors indicates that all of them are due to instrumental noise artefacts, and not GWs.

Just before submitting this manuscript, we became aware of a search for young SNRs by Lindblom and Owen [15]. The two searches are similar in some ways,
but there are four important differences:

1. They are directed at overlapping but distinct sets of targets. Specifically, targets searched in [15] but not in this work are G15.9+0.2, G39.2-0.3, and G353.6-0.7. Not included in [15] are searches for the targets G111.7-2.1, G266.2-1.2, and G347.3-0.5 (though these targets were searched in [13]).

2. They search different bands. The search presented in [15] examines the band between 15 and 150 Hz for all targets in order to accommodate a fixed computational cost. In this work the frequency band varies by target (see Table I). The narrowest frequency band searched is 35 to 122 Hz for G1.9+0.3, and the widest band is 23 to 1747 Hz for G347.3-0.5. With two exceptions (G1.9+0.3 and G354.4+0.0), the bands in this search are wider.

3. They analyze different volumes of data. The search presented in [15] uses a different observation time for each target. The range of these observation

FIG. 10. HMM frequency tracks for the outliers in G266.2-1.2.

FIG. 11. HMM frequency tracks for the outliers in G347.3-0.5.
times is 12 to 55.9 days. The search presented in this paper uses all available O2 data, as outlined in Sec. IV C.

4. The HMM search is semi-coherent and robust against spin wandering, whereas the work presented in [15] uses a coherent matched-filter.

For all these reasons, the two analyses are complementary without being easily comparable. A comparative study of the sensitivities, even within their common band, is a tricky exercise to be attempted in future work.

LIGO is currently in its third observing run, O3, and is expected to improve its sensitivity relative to O2. More data at higher sensitivity increases our chances of making a detection of periodic GWs. The HMM search can also be improved for rapidly spinning down SNR targets by tracking $f_0$ as well as $f_0$ [42].

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Appendix: Hardware injections

To validate data analysis pipelines and calibration, simulated signals can be added to the LIGO detectors. These are commonly called hardware injections. In O2, injections were added to simulate GW signals from isolated rotating neutron stars [29, 89]. One such hardware injection is picked up by our search for the SNR target G330.2+1.0. The Viterbi path for this candidate, along with the frequency evolution of the hardware injection are shown in Fig. 12. $\mathcal{L}$ for the candidate, the single interferometer runs, and the off-source run are shown in Table IV. We include the results to illustrate how a true GW signal would behave.

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| SNR | $L_{th}$ | Frequency (Hz) | logL | logL | logL |
|-----|---------|----------------|------|------|------|
| G330.2+1.0 | 23346 | 145.794 | 23452 | 17350 | 16344 | 12112 |

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