



Sub-torque-balance Upper Limits on Continuous Gravitational Waves from Scorpius X-1

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Received 2026 July 8; revised 2026 August 19; accepted 2026 August 22; published 2026 October 13

Abstract

We present the results of a search for continuous gravitational waves (GWs) from the low-mass X-ray binary Scorpius X-1 using LIGO data from the first part of the fourth LIGO–Virgo–KAGRA observing run. By applying the resampling version of the cross-correlation pipeline to search for signal frequencies f_0 between 25 and 200 Hz (corresponding to neutron star spin frequencies of 12.5–100 Hz for GWs due to triaxiality, or ~ 15 –20 to ~ 120 –150 Hz for GWs due to r -modes), we are able to achieve longer coherence times than before, and for the first time set upper limits below the standard torque balance level, independent of neutron star spin inclination, for 50 Hz $\lesssim f_0 \lesssim 200$ Hz. The most sensitive upper limits on the gravitational wave amplitude h_0 , at the upper end of the frequency band searched, approach 5×10^{-26} marginalized over inclination angle and 2×10^{-26} assuming the most favorable inclination. The marginalized upper limits correspond to a sensitivity depth of 70–75 Hz $^{-1/2}$, improving sensitivity considerably over previous searches. Expressed as constraints on the triaxial deformation of the neutron star, the limits correspond to an ellipticity of 3×10^{-5} if the GW frequency f_0 is 75 Hz and 3×10^{-6} if $f_0 = 200$ Hz, approaching deformations that could be supported by ordinary nuclear matter. Outliers from the search were ruled out as potential signals by a combination of hierarchical follow-up and analysis of additional data from later in the observing run.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Low-mass x-ray binary stars (939); Gravitational waves (678); Gravitational wave astronomy (675); LIGO (920)

1. Introduction

Neutron stars (NSs) in low-mass X-ray binaries (LMXBs) are prime targets for continuous gravitational wave (GW) searches with the network of current and near-future ground-based audio band detectors, because of arguments that they will soon be detectable (K. Riles 2023; B. J. Owen & B. Rajbhandari 2025; B. J. Owen 2026). In these systems, asymmetries in an NS’s mass distribution, sustained by elastic and magnetic stresses (G. Ushomirsky et al. 2000; M. Vigelius & A. Melatos 2009; M. Priymak et al. 2011; N. Singh et al. 2020; E. L. Osborne & D. I. Jones 2020; G. Pagliaro et al. 2026), can emit a persistent, quasimonochromatic GW signal as the NS rotates. Magnetically channeled accretion provides an additional mechanism to form such a mountain (A. Melatos & D. J. B. Payne 2005). Accretion can also spin the NS up to a point where gravitational radiation reaction may drive the growth of NS oscillations, such as r -modes (L. Lindblom et al. 1998; B. J. Owen et al. 1998; Y. Levin 1999; L. Rezzolla et al. 2000; W. Dong & A. Melatos 2025), which emit continuous GW signals (K. Riles 2023).

The GW torque may offer the solution to an astrophysical conundrum. There appears to be a sharp observed cutoff in the spin frequency (ν_s) distribution of NSs in LMXBs at $\nu_s \approx 750$ Hz (D. Chakrabarty et al. 2003; A. Patruno et al. 2017), significantly below the theoretical breakup frequency (G. B. Cook et al. 1994; B. Haskell et al. 2018). Although there are uncertainties when modeling the spin-up accretion torque (K. Glampedakis & A. G. Suvorov 2021; A. Patruno & A. L. Watts 2021), which may explain this observation (A. Patruno et al. 2012; Ü. Ertan & M. A. Alpar 2021), it has also been suggested that the spin-down GW torque leads to an

equilibrium at high frequencies, which naturally explains the observed ν_s distribution (J. Papaloizou & J. E. Pringle 1978; R. V. Wagoner 1984; L. Bildsten 1998), notably the clustering for 500 Hz $\lesssim \nu_s \lesssim 750$ Hz (A. Patruno et al. 2017; F. Gittins & N. Andersson 2019). In such a scenario, there is a natural correlation between the observed X-ray flux and GW strain, as a higher accretion rate exerts a stronger spin-up torque, which implies a higher GW torque at equilibrium.

Scorpius X-1 (Sco X-1), the most luminous LMXB, which is presumed to consist of an NS of mass $\approx 1.4 M_\odot$ in a binary orbit with a companion star of mass $\approx 0.4 M_\odot$ (D. Steeghs & J. Casares 2002), is therefore a promising potential source of GWs. In particular, the torque-balance model means that searches for GWs from Sco X-1 are now entering the realm where a detectable signal amplitude is not just possible but predicted.

Sco X-1 has been the target of numerous GW searches (B. Abbott et al. 2007a, 2007b; J. Abadie et al. 2011; J. Aasi et al. 2014, 2015a; B. P. Abbott et al. 2017a, 2019a, 2021; G. D. Meadors et al. 2017; A. G. Abac et al. 2025a; F. Amicucci et al. 2025) by various methods (P. Jaranowski et al. 1998; S. W. Ballmer 2006; C. Messenger & G. Woan 2007; E. Goetz & K. Riles 2011; L. Sammut et al. 2014; P. Leaci & R. Prix 2015; G. D. Meadors et al. 2016; A. Singhal et al. 2019; A. Mukherjee et al. 2023). The cross-correlation method (S. Dhurandhar et al. 2008; J. T. Whelan et al. 2015) used in the present work is an extension of the radiometer search (S. W. Ballmer 2006) to use the signal model of GWs from an LMXB such as Sco X-1 to correlate Fourier data at different times. It has previously been applied to Advanced LIGO data from the first, second, and third LIGO–Virgo–KAGRA (LVK) observing runs to set the strongest limits so far on GWs from Sco X-1 (B. P. Abbott et al. 2017b; Y. Zhang et al. 2021; B. P. Abbott et al. 2022a; J. T. Whelan et al. 2023). In particular, the resampling version of the pipeline defined in G. D. Meadors et al. (2018) speeds up the computation for signal frequencies below around 200 Hz, allowing a deeper search to be run with manageable computing resources. A complementary method of note is the so-called Viterbi search (S. Suvorova et al. 2016, 2017; A. Melatos et al. 2021), which uses a hidden

³³² Deceased, 2026 March.³³³ Deceased, 2024 September.³³⁴ Deceased, 2025 August.

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Table 1
Electromagnetically Measured Parameters of the LMXB Sco X-1

Parameter	Value
R. A. ^a	16 ^h 19 ^m 55 ^s .0850
decl. ^a	−15°38′24″.9
Distance (kpc)	2.8 ± 0.3
Orbital inclination i ^b	44° ± 6°
K_1 (km s ^{−1}) ^c	[40, 90]
t_{asc} (GPS s) ^d	1078153676 ± 33
Orbital period P_{orb} (s)	68023.919 ± 0.017

Notes. Uncertainties are 1σ unless otherwise stated.

^a The sky position (as quoted in B. Abbott et al. 2007a, derived from C. F. Bradshaw et al. 1999) is determined to the microarcsecond. It is treated as being known exactly in this Letter.

^b The inclination i of the orbit to the line of sight, from observations of radio jets by E. B. Fomalont et al. (2001), is not necessarily the same as the inclination angle ι of the NS’s spin axis, which determines the polarization of the GW in Equation (3), although accretion may drive the two angles toward each other.

^c The projected orbital velocity K_1 is estimated by Doppler tomography measurements and Monte Carlo simulations in L. Wang et al. (2018), which show K_1 to satisfy the weak constraint $40 \text{ km s}^{-1} \lesssim K_1 \lesssim 90 \text{ km s}^{-1}$.

^d The time of ascension t_{asc} , at which the NS crosses the ascending node (moving away from the observer), measured in the solar system barycenter, is given by T. L. Killestein et al. (2023). It corresponds to a time of 2014 March 6 15:07:40 UTC, and can be propagated to other epochs by adding an integer multiple of P_{orb} , which results in increased uncertainty in t_{asc} and correlations between P_{orb} and t_{asc} ; see Figure 2.

References. C. F. Bradshaw et al. (1999); E. B. Fomalont et al. (2001); L. Wang et al. (2018); T. L. Killestein et al. (2023).

Markov model to track spin wandering and has also been applied to Advanced LIGO data from the first three LVK observing runs (B. P. Abbott et al. 2017c, 2019b, 2022b).

The fourth and most recent observing run of Advanced LIGO (J. Aasi et al. 2015b; E. Capote et al. 2025; S. Soni et al. 2025), Advanced Virgo (F. Acernese et al. 2015, 2023), and KAGRA (T. Akutsu et al. 2021), O4 for short, began on 2023 May 24 15:00:00 UTC (GPS 1368975618) and ended on 2025 November 18 16:00:00 UTC (GPS 1447516818). The portion before the commissioning break at 2024 January 16 16:00:00 UTC (GPS 1389456018) is named O4a (A. G. Abac et al. 2025b). In this Letter, we use O4a data from the two LIGO detectors, as Virgo and KAGRA data were offline during O4a. We use the calibrated data (L. Sun et al. 2020; LVK 2025), which are limited to times when a detector was in scientific observing mode (S. Soni et al. 2025). Transient instrumental glitches degrade the sensitivity, so we use the channels `H1:GDS-CALIB_STRAIN_CLEAN_GATED_G02` and `L1:GDS-CALIB_STRAIN_CLEAN_GATED_G02`, which have had the “self-gating” procedure (D. Davis et al. 2025) applied to remove such glitches.

Some of the parameters inferred from electromagnetic observations of Sco X-1 are summarized in Table 1. The orbital eccentricity is assumed to be small (D. Steeghs & J. Casares 2002; L. Wang et al. 2018; T. L. Killestein et al. 2023) and is neglected in the present analysis. A noncircular orbit would add two search parameters, namely the eccentricity and the argument of periape (C. Messenger 2011; P. Leaci & R. Prix 2015; N. K. Y. Low & A. Melatos 2025), the effects of which are estimated in the Appendix and discussed at the end of Section 3.

The remainder of the Letter is laid out as follows. Section 2 describes the modeled GW signal from Sco X-1. Section 3

defines the resampling cross-correlation search method used in this Letter and its relationship to the original search algorithm. Section 4 describes the identification and follow-up of potential signals. Section 5 sets upper limits on the GW amplitude from Sco X-1. The conclusions are in Section 6.

2. Model of Gravitational Waves from Sco X-1

The GW signal from a rotating NS can be modeled as “plus” and “cross” polarization components $h_+(t) = A_+ \cos[\Phi(t)]$ and $h_\times(t) = A_\times \sin[\Phi(t)]$. The signal received at a detector is (P. Jaranowski et al. 1998)

$$h(t) = F_+(t)h_+(t) + F_\times(t)h_\times(t), \quad (1)$$

where F_+ and $F_\times$ are antenna response functions for that detector in the preferred polarization basis associated with the source, constructed from amplitude modulation coefficients $a(t)$ and $b(t)$ (which are detector-specific and periodic over one sidereal day) and an unknown polarization angle ψ , which is specific to the orientation of the NS (P. Jaranowski et al. 1998; R. Prix & J. T. Whelan 2007).

If the NS can be modeled as a non-precessing rotating triaxial ellipsoid, so that the GWs are generated by the (no n-axisymmetric) equatorial ellipticity of the NS, the GW frequency will be twice the spin frequency. If the GWs are generated by r -modes, rotating current perturbations in the NS, the GW frequency is $\sim 1.39\text{--}1.64 \times$ the spin frequency (S. Ghosh et al. 2023), which includes relativistic effects along with equation of state corrections (A. Idrisy et al. 2015) to the approximate multiplicative factor of $4/3$ in J. Papaloizou & J. E. Pringle (1978). In the absence of spin evolution, a signal with frequency f_0 in the reference frame of the source has a phase at the detector of

$$\Phi(t) = 2\pi f_0 t(t) + \Phi_0, \quad (2)$$

where the relationship between the source frame time t and the detector time t is determined by the motion of the detector relative to the solar system barycenter (SSB) and the motion of the NS in its orbit. The two polarization amplitudes are³³⁵

$$A_+ = h_0 \frac{1 + \cos^2 \iota}{2} \quad \text{and} \quad A_\times = h_0 \cos \iota, \quad (3)$$

where h_0 is an intrinsic amplitude describing the strength of the signal when it reaches the solar system, and ι is the inclination of the NS’s spin to the line of sight. (For an NS in a binary, the spin inclination ι is not necessarily equal to the inclination i of the binary orbit; see note *b* in Table 1.) If $\iota = 0^\circ$ or 180° , one has $A_\times = \pm A_+$, and gravitational radiation is circularly polarized. If $\iota = 90^\circ$, one has $A_\times = 0$, and the radiation is linearly polarized. The general case, elliptical polarization, has $0 < |A_\times| < A_+$. Many search methods are sensitive to the combination

$$(h_0^{\text{eff}})^2 = \frac{A_+^2 + A_\times^2}{2} = h_0^2 \frac{[(1 + \cos^2 \iota)/2]^2 + [\cos \iota]^2}{2}, \quad (4)$$

which is equal to h_0^2 for circular polarization and $h_0^2/8$ for linear polarization (C. Messenger et al. 2015); this was the

³³⁵ This is the form when the GWs are driven by a triaxial deformation of the NS. As shown in B. J. Owen (2010), for GWs generated by r -modes, the roles of the plus and cross polarizations are interchanged, so quantities like h_0^{eff} defined in (4) remain the same.

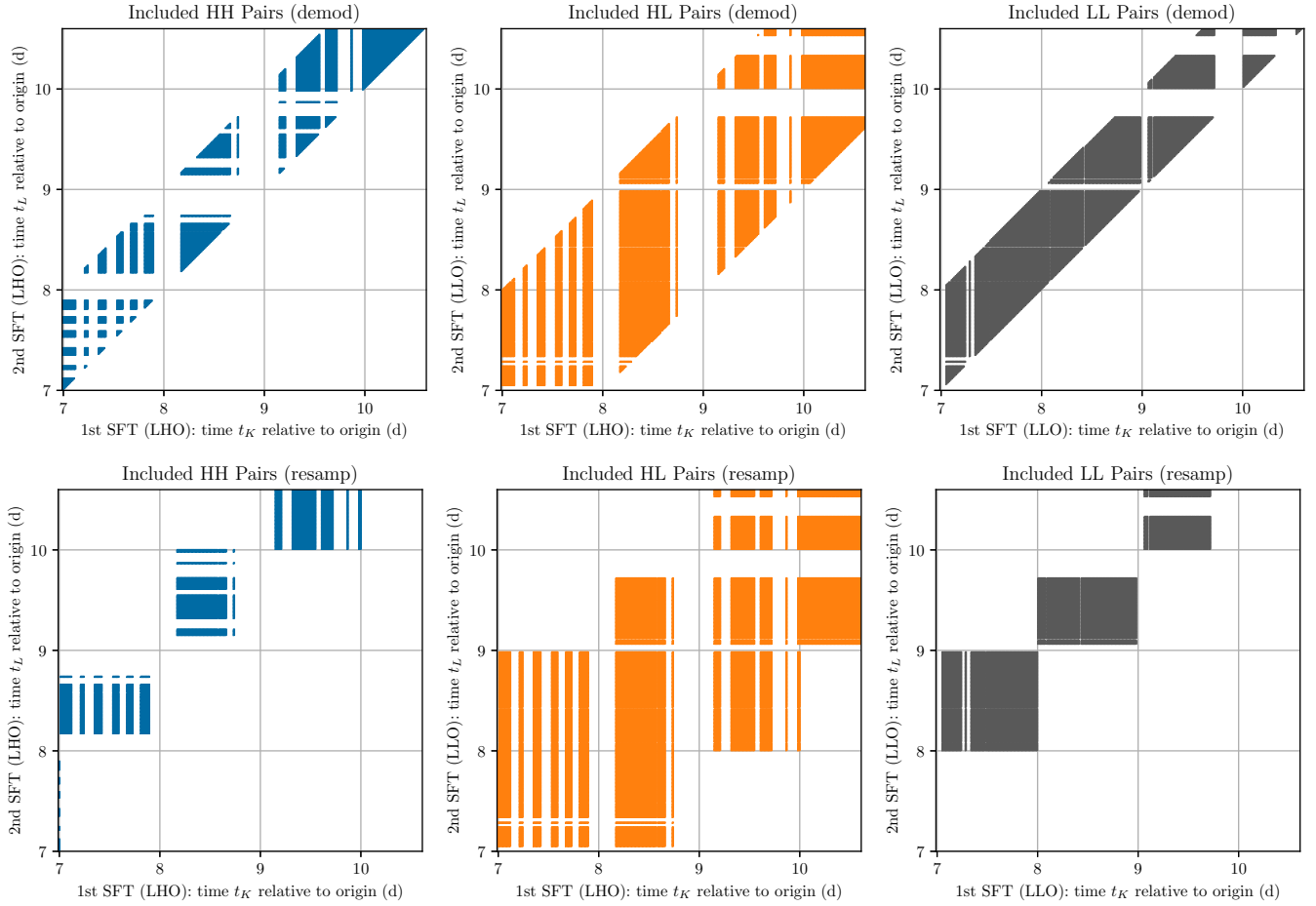


Figure 1. Representative illustrations of the SFT pairs used in constructing the cross-correlation statistics. The left column (“HH”) shows the times of pairs where both SFTs are from LIGO Hanford Observatory (LHO), the middle (“HL”) where the first is from LHO and the second is from LIGO Livingston Observatory (LLO), and the right (“LL”) where both are from LLO. Note that these plots only show a few days of data; the analysis included data from the entire O4a run. The horizontal and vertical gaps correspond to times where no science-quality data exist for that detector, and so no SFTs were made. The top row shows the original “demod” construction used in Equation (8): a pair of SFTs is included in the sum if the start times differ by $T_{\max}$ or less; in this case, $T_{\max} = 24$ hr. Each pair is only counted once, so for HH and LL pairs, we only include pairs with $t_K < t_L$. This was the setup used for the analyses in B. P. Abbott et al. (2017b, 2022a) and J. T. Whelan et al. (2023), albeit with lower $T_{\max}$ values, and is also used for the follow-up described in Section 4. For the resampling construction of G. D. Meadors et al. (2018), used in the present search, the SFT data are processed together (with gaps replaced by zeros) into time intervals of duration $T_{\max}$. As those are correlated with other such intervals that lie within $T_{\max}$, the effective set of SFT pairs is as shown in the bottom (“resamp”) row. One effect of this is that more HL SFT pairs are included in the calculation, so that the same nominal $T_{\max}$ value corresponds to a deeper search.

convention used in B. P. Abbott et al. (2017b) but differs by a factor of 2.5 from the definition of $(h_0^{\text{eff}})^2$ in J. T. Whelan et al. (2015).³³⁶

In order to understand the astrophysical relevance of the GW amplitudes we probe in this Letter, a useful benchmark is the torque-balance level. Suppose that Sco X-1 is in equilibrium, such that the spin-up torque N_A due to accretion is balanced by a spin-down GW torque (J. Papaloizou & J. E. Pringle 1978; R. V. Wagoner 1984; L. Bildsten 1998). Let us write approximately (J. E. Pringle & M. J. Rees 1972)

$$N_A = \dot{M} \sqrt{GMr}, \quad (5)$$

where $\dot{M}$ is the mass accretion rate onto the NS, which we infer from the X-ray flux F_X , M is the mass of the star, G is Newton’s gravitational constant, and r is the lever arm, i.e., the radius at which the accretion torque is applied. By balancing N_A with the GW torque, we infer the GW amplitude

(A. L. Watts et al. 2008; B. J. Owen 2010)

$$h_0 \approx 5.48 \times 10^{-27} \left(\frac{F_X}{10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}} \right)^{1/2} \left(\frac{f_0}{600 \text{ Hz}} \right)^{-1/2} \times \left(\frac{R_*}{10 \text{ km}} \right)^{1/2} \left(\frac{r}{10 \text{ km}} \right)^{1/4} \left(\frac{M}{1.4 M_\odot} \right)^{1/4}. \quad (6)$$

The usual torque-balance benchmark assumes $r = R_* = 10$ km, where R_* is the NS radius.³³⁷ For Sco X-1, assuming $r = R_*$, and using $F_X = 3.9 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}$ (A. L. Watts et al. 2008), we get

$$h_0 \approx 3.4 \times 10^{-26} \left(\frac{f_0}{600 \text{ Hz}} \right)^{-1/2} \quad (7)$$

for $f_0 = 2\nu_s$.

³³⁶ Note that $(h_0^{\text{eff}})^2 = H_0^2/2$, where H_0 is the wave amplitude used in the five-vector literature such as P. Astone et al. (2010) and F. Amicucci et al. (2025).

³³⁷ If, instead, we take the lever arm to be the Alfvén radius ($r = r_A$), as in the case where the magnetic field truncates the accretion disk above the surface, the h_0 implied by Equation (6) is larger (e.g., Y. Zhang et al. 2021, B. P. Abbott et al. 2022b).

Table 2
Parameters Used for the Cross-Correlation Search

Parameter	Range
f_0 (Hz)	[25, 200]
$a \sin i$ (lt-s) ^a	[1.44, 3.25]
t'_{asc} (GPS s) ^b	$1379295565 \pm 3 \times 82$
$\tilde{P}$ (s) ^c	$68023.919 \pm 3.3 \times 0.006$

Notes.

^a The range for the projected semimajor axis $a \sin i = K_1 P_{\text{orb}} / (2\pi)$ in light-seconds was taken from the constraint $K_1 \in [40, 90] \text{ km s}^{-1}$.

^b This value for the time of ascension t'_{asc} , defined in Equation (10), has been propagated forward by 4427 orbits from the value of t_{asc} in Table 1, and corresponds to a time of 2023 September 21 01:39:07 UTC, near the middle of the O4a run. The increase in uncertainty is due to the uncertainty in P_{orb} .

^c This is the “sheared” period defined in Equation (11); note that the uncertainty in $\tilde{P}$ has been reduced compared to the marginal uncertainty in P_{orb} by the same factor by which the uncertainty in t'_{asc} has been increased relative to that for t_{asc} , as described in K. J. Wagner et al. (2022).

Equation (7) is an order-of-magnitude estimate, which we use as a benchmark to understand if a search probes astrophysically pertinent portions of the parameter domain. Much of the physics entering N_A is highly uncertain and depends on the unknown topology of the stellar magnetic field, the disk-field coupling, viscous heating in the disk, efficiency of X-ray emission, or radiation pressure in the disk (N. Andersson et al. 2005; A. Patruno et al. 2012; B. Haskell et al. 2015; K. Glampedakis & A. G. Suvorov 2021; A. Melatos et al. 2023). The amplitude as a function of frequency is the same whether the GW emission mechanism is triaxiality or r -modes (B. J. Owen 2010).

3. Resampling Cross-correlation Search

The cross-correlation (CrossCorr) search method (S. Dhurandhar et al. 2008; J. T. Whelan et al. 2015), used to search for GWs from Sco X-1 in LIGO data from the first three observing runs of Advanced LIGO, Advanced Virgo, and KAGRA (B. P. Abbott et al. 2017b; Y. Zhang et al. 2021; B. P. Abbott et al. 2022a; J. T. Whelan et al. 2023), uses the signal model described in Section 2 to construct an appropriately weighted statistic ρ including correlations between data separated by up to a coherence time T_{max} . A reorganization of the algorithm developed in G. D. Meadors et al. (2018) leverages resampling techniques (converting the data into a time series evenly sampled in the reference frame of the neutron star) to speed up the calculation and allow longer coherence times. This is primarily effective at lower signal frequencies, and was used in Y. Zhang et al. (2021) to carry out a search with $T_{\text{max}} = 19 \text{ hr}$ for $f_0 \in [40, 180] \text{ Hz}$. In this work, we search for $f_0 \in [25, 200] \text{ Hz}$, with the upper end of the range set by the computational considerations detailed in G. D. Meadors et al. (2018).

The cross-correlation construction defined in J. T. Whelan et al. (2015), referred to here as the “demod” pipeline, was performed using short Fourier transforms (SFTs) of length T_{sft} . If the SFTs are labeled by an index K, L , etc., which encode the detector and time of the SFT, and z_K (defined in Equations (2.1), (2.9), (2.19), and (2.23) of J. T. Whelan et al. 2015) is an appropriately normalized combination of the Fourier data at

the frequency of interest, the statistic ρ can be written as

$$\rho = \sum_{KL \in P} (W_{KL} z_K^* z_L + W_{KL}^* z_K z_L^*), \quad (8)$$

where P is the set of all pairs of SFTs whose start times differ by T_{max} or less, as shown in the top row of Figure 1. The complex weighting factor

$$W_{KL} \propto (\hat{a}_K \hat{a}_L + \hat{b}_K \hat{b}_L) e^{i(\Phi_K - \Phi_L)} \quad (9)$$

uses the signal model to determine the expected signal phase $\Phi_K = \Phi(t_K)$ at the midpoint t_K of SFT K ; $\hat{a}_K$ and $\hat{b}_K$ are noise-weighted antenna patterns appropriate to the time and detector encoded in K , derived from the amplitude modulation coefficients $a(t)$ and $b(t)$ introduced in Section 2 (R. Prix 2011; J. T. Whelan et al. 2015).

The resampling technique of G. D. Meadors et al. (2018), which we apply in this work, reorganizes the sum in Equation (8) into a double sum including quantities like $\hat{a}_K z_K e^{-i\Phi_K}$ and $\hat{b}_K z_K e^{-i\Phi_K}$. Since z_K is a combination of Fourier components, the sum over SFTs can be written as an integral over time of $a(t)x(t)e^{-i\Phi(t)}$ or $b(t)x(t)e^{-i\Phi(t)}$. Since the signal phase [Equation (2)] $\Phi(t)$ is periodic in the source frame time $t(t)$, resampling (i.e., reconstructing a time series that is evenly sampled in the source frame time t) turns the time integral within each SFT and the sum over SFTs into a Fourier transform, which also replaces the loop over signal frequency f_0 . Since the SFT durations are limited by Doppler acceleration, the calculation is made more efficient by changing the time baseline for this computation from T_{sft} to T_{max} (after resampling and accounting for the time dependence of the antenna patterns). This means that the data from each instrument are divided into intervals of duration T_{max} , and all data lying in intervals separated by T_{max} or less are combined in the calculation of the statistic, as illustrated in the bottom row of Figure 1.

Unlike in the O1 and O3 analyses of B. P. Abbott et al. (2017b, 2022a) and J. T. Whelan et al. (2023), which used a range of T_{max} values from 240 to 25,920 s to tune sensitivity against computing cost, the current search uses a fixed value of $T_{\text{max}} = 24 \text{ hr} = 86,400 \text{ s}$, just as the resampling search of Y. Zhang et al. (2021) used a T_{max} of 19 hr = 68,400 s. The SFT duration T_{sft} is limited by the Doppler acceleration of the orbit of Sco X-1, which would otherwise cause the GW signal to depart from the monochromatic assumption during an SFT. Optimal choices for T_{sft} as a function of signal frequency f_0 were determined in J. T. Whelan et al. (2015) and used in B. P. Abbott et al. (2017b, 2022a) and J. T. Whelan et al. (2023). However, in preparation for the present analysis, two errors were discovered in Figure 4 of J. T. Whelan et al. (2015). Most significantly, the assumed projected orbital velocity K_1 was taken from the estimates of $a \sin i = K_1 P_{\text{orb}} / (2\pi)$ appearing in, e.g., B. Abbott et al. (2007a) and A. L. Watts et al. (2008), which assumed a one-sigma uncertainty of $a \sin i = 1.44 \pm 0.18 \text{ lt-s}$ rather than the broader range of $a \sin i \in [1.44, 3.25] \text{ lt-s}$ (L. Wang et al. 2018; T. L. Killestein et al. 2023) shown in Table 2. A computational error in the opposite direction somewhat mitigated this, but the end result is that slightly shorter SFTs are appropriate. The T_{sft} values used in this search are shown in Table 3.³³⁸

³³⁸ We do not believe this introduced serious flaws in previous analyses, based on their success in recovering injected simulated signals.

Table 3
Summary of Numbers of Templates and Candidates

f_0 (Hz)						Candidates at Follow-up Level				
25	50	1140	7.2	4.12×10^{11}	0.1	68	46	34	18	6
50	100	780	7.3	3.24×10^{12}	0.5	103	89	84	51	15
100	150	660	7.5	1.25×10^{13}	0.4	106	92	89	52	14
150	200	600	7.6	3.16×10^{13}	0.5	134	115	111	70	16

Notes. For each range of GW frequencies, this table shows the SFT duration T_{sft} , the threshold in signal-to-noise ratio (S/N) ρ used for follow-up, the total number of templates, and the number of candidates at various stages of the process. (See Section 4 for detailed description of the follow-up procedure.)

^a This is the threshold for initiating follow-up.

^b This is the total number of candidates that would be expected in this band due to Gaussian noise, given the number of templates and the follow-up threshold.

^c This is the actual number of candidates (after clustering) that crossed the S/N threshold and were followed up.

^d This is the actual number of candidates remaining after the “level 0” targeted follow-up. All of the candidates “missing” at this stage were vetoed because their S/Ns in the targeted search were < 1.645 .

^e This is the number of candidates remaining after refinement. All of the candidates “missing” at this stage have been removed by the single-detector veto for unknown lines, defined in Section 4.

^f This is the number of candidates remaining after each has been followed up with a $T_{\text{max}} = 4$ days, $4 \times$ the T_{max} of the level 1 search. (True signals should approximately double their S/N; any candidates whose S/N goes down have been dropped.) All of the signals present at this stage are shown in Figure 4, which also shows the behavior of the search on simulated signals injected in software.

^g This is the number of candidates remaining after T_{max} has been increased to 16 day.

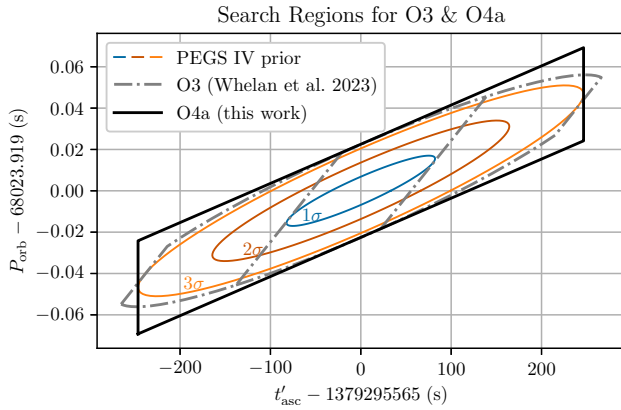


Figure 2. The search region (black parallelogram) for the present analysis, defined by t'_{asc} [Equation (10)] and $\tilde{P}$ [Equation (11)] ranges given in Table 2, expressed in terms of time of ascension t'_{asc} and orbital period P_{orb} . For comparison, the colored ellipses show the (correlated) uncertainties associated with the PEGS IV ephemeris (T. L. Killestein et al. 2023), corresponding to 1σ , 2σ , and 3σ (containing 39.3%, 86.5%, and 98.9% of the prior probability, respectively). The dashed boundaries show the truncated elliptical search region of the O3 cross-correlation analysis in J. T. Whelan et al. (2023), which also used the PEGS IV ephemeris. Note the dashed diagonal boundaries, which are not vertical, because the t'_{asc} definition used to specify them was appropriate for the middle of the O3 run (2019) rather than the O4a run (2023).

The resampling procedure allows the computation of detection statistics for multiple frequencies at once, but must be repeated for different values of the binary orbital parameters that determine the orbital Doppler shift. Each combination of orbital parameters and signal frequency defines a “search template.” The range of signal parameters covered by the search is summarized in Table 2. The projected semimajor axis of the orbit is assumed to lie in the range $a \sin i \in [1.44, 3.25]$ lt-s, corresponding to a range in projected orbital velocity of $[40, 90]$ km s $^{-1}$. The time of ascension t_{asc} from Table 1 is propagated 4427 orbits (i.e., from 2014 to 2023) to bring it to roughly the middle of O4a, defining

$$t'_{\text{asc}} = t_{\text{asc}} + 4427 \times P_{\text{orb}}. \quad (10)$$

The most likely t'_{asc} is 2023–Sep–21 01:39:07 UTC (GPS 1379295565), and the search covered a range of $\pm 3 \times 82$ s centered on that value. To search over the range of orbital period P_{orb} values plausible for each t'_{asc} , we define the “sheared” orbital period

$$\tilde{P} = P_{\text{orb}} - 1.89 \times 10^{-4} (t'_{\text{asc}} - 1379295565) \quad (11)$$

as in K. J. Wagner et al. (2022). The coordinates t'_{asc} and $\tilde{P}$ are approximately uncorrelated both in the parameter space metric of the search and in the astrophysical prior distribution. Note that, rather than defining an elliptical region in t'_{asc} and $\tilde{P}$ as in B. P. Abbott et al. (2022a) and J. T. Whelan et al. (2023), we search over a range of $\tilde{P}$ values $\pm 3.3 \times 0.006$ s centered on 68023.919 s. The choice of 3 and 3.3 times the one-sigma uncertainty in t'_{asc} and $\tilde{P}$, respectively, means the search region contains 99.6% of the prior probability. For reference, in Figure 2 we show this region in the coordinates $(t'_{\text{asc}}, P_{\text{orb}})$, along with the search regions used in J. T. Whelan et al. (2023) and the uncertainty ellipses of the PEGS IV ephemeris (T. L. Killestein et al. 2023), propagated forward in time to the epoch considered in this analysis.

Rather than the A_n^* lattice defined in K. J. Wagner et al. (2022) and K. Wette (2014) and used in B. P. Abbott et al. (2022a) and J. T. Whelan et al. (2023), the present analysis uses a rectangular grid as in B. P. Abbott et al. (2017b) and Y. Zhang et al. (2021). The metric mismatch³³⁹ (J. T. Whelan et al. 2015) between templates was taken to be 0.25, which corresponds, for a four-dimensional grid, to a maximum mismatch between any point in the parameter space and the nearest template that is also no more than 0.25. The resulting spacings are in the ranges $[1.3 \times 10^{-6}, 1.4 \times 10^{-6}]$ Hz in f_0 , $[0.112, 0.115]$ lt-s $\frac{\text{Hz}}{f_0}$ in $a \sin i$, $[1207, 1238]$ s $\frac{\text{Hz}}{f_0} \frac{\text{lt-s}}{a \sin i}$ in t'_{asc} , and $[14, 17]$ s $\frac{\text{Hz}}{f_0} \frac{\text{lt-s}}{a \sin i}$ in $\tilde{P}$, consistent with those used in Y. Zhang et al. (2021) when considering the slightly lower T_{max} value used in that work. Future development is planned to implement the more efficient A_n^* lattice within the resampling CrossCorr pipeline.

³³⁹ This is computed using the included SFT pairs illustrated in the bottom row of Figure 1.

Sco X-1 may undergo stochastic fluctuations in f_0 , known as spin wandering (L. Bildsten et al. 1997; A. Mukherjee et al. 2018). One can set bounds on the loss of S/N within the framework of an idealized model, in which f_0 undergoes a net spin-up or spin-down of magnitude $|\dot{f}|_{\text{drift}}$, fluctuating on a timescale T_{drift} (L. Sammut et al. 2014; C. Messenger et al. 2015; J. T. Whelan et al. 2015; B. P. Abbott et al. 2017b; J. B. Carlin & A. Melatos 2025). For O4a, whose duration from start to end is $T_{\text{run}} = 2.05 \times 10^7$ s, and coherence time $T_{\text{max}} = 86400$ s, the expected loss of S/N is, applying Equation (5.9) of J. T. Whelan et al. (2015),

$$\frac{E[\rho]_{\text{ideal}} - E[\rho]}{E[\rho]_{\text{ideal}}} \approx 0.251 \left(\frac{T_{\text{drift}}}{10^6 \text{ s}} \right) \left(\frac{|\dot{f}|_{\text{drift}}}{10^{-12} \text{ Hz s}^{-1}} \right)^2 \left(\frac{T_{\text{max}}}{86,400 \text{ s}} \right)^2. \quad (12)$$

This gives some indication that spin wandering could be an issue for this longer coherence time. J. B. Carlin & A. Melatos (2025), who assume a somewhat higher level of spin wandering, predict an effect consistent with the scaling in Equation (12). However, as noted in Y. Zhang et al. (2021) and B. P. Abbott et al. (2022a), the predictions of A. Mukherjee et al. (2018) based on the variability of F_X imply considerably less spin wandering than the naïve $|\dot{f}|_{\text{drift}} - T_{\text{drift}}$ model, whose fiducial parameters are taken from C. Messenger et al. (2015), so this search is still likely to be sensitive to a realistic signal.

Finally, the present search assumes a circular orbit for Sco X-1, in keeping with the ephemeris of T. L. Killestein et al. (2023). As computed in Equation (A9) of the Appendix, the fractional loss of S/N due to a small orbital eccentricity e can be estimated as

$$\frac{E[\rho]_{\text{ideal}} - E[\rho]}{E[\rho]_{\text{ideal}}} \approx 0.021 \left(\frac{f_0}{200 \text{ Hz}} \right)^2 \left(\frac{a \sin i}{3.25 \text{ lt-s}} \right)^2 \left(\frac{e}{10^{-4}} \right)^2, \quad (13)$$

from which we conclude it is not an important effect for this search.

4. Candidates and Follow-up

The detection statistic ρ is normalized to have zero mean and (for low signal amplitudes) unit variance in Gaussian noise. A naïve estimate of the expected background would assume each search template to represent an independent Gaussian random number, and set a threshold based on a desired number of outliers to follow up, as was done in B. P. Abbott et al. (2017b, 2022a) and J. T. Whelan et al. (2023).³⁴⁰ The present search, due to the longer coherence time, uses many more templates for a given frequency range (see Table 3), and therefore requires a higher threshold to maintain a desirable outlier rate. This is compounded by the non-Gaussianity of the tail of the distribution of ρ ; as discussed in Appendix B of J. T. Whelan et al. (2015), this can occur even if the instrumental noise is Gaussian. As shown in Figure 3, we set our follow-up threshold at 7.2 for $25 \text{ Hz} < f_0 < 50 \text{ Hz}$, 7.3 for $50 \text{ Hz} < f_0 < 100 \text{ Hz}$, 7.5 for $100 \text{ Hz} < f_0 < 150 \text{ Hz}$, and 7.6 for $150 \text{ Hz} < f_0 < 200 \text{ Hz}$.

³⁴⁰ A more sophisticated way of estimating this distribution would be the method of R. Tenorio et al. (2022).

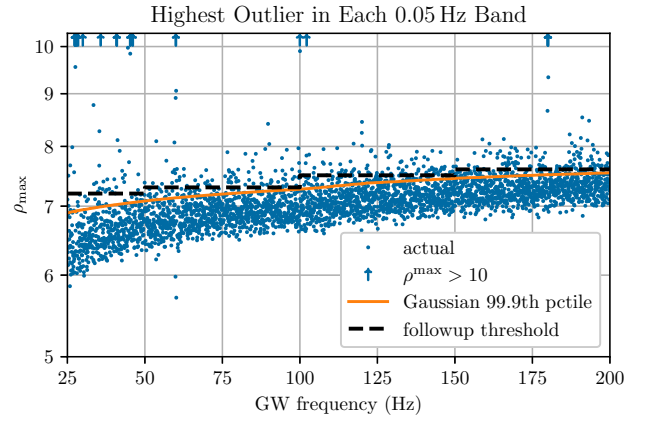


Figure 3. Selection of follow-up threshold as a function of GW frequency. The blue dots represent the highest S/N ρ_{max} in each 0.05 Hz band. If the data contained no signal and only Gaussian noise, each template in the parameter space would have some chance of producing a statistic value exceeding a given threshold. Using the number of templates in each 0.05 Hz band, we can estimate the expected distribution of the highest S/N in the band. The solid orange curve shows the 99.9th percentile of this distribution, i.e., the level at which we would expect 10^{-3} false alarms per 0.05 Hz, or one per 50 Hz. Due to the non-Gaussian nature of the tail of the distribution of ρ , the actual number of outliers is considerably higher. To keep the follow-up volume manageable, we set the thresholds indicated by the black dashed line and shown in Table 3.

Table 3 shows the resulting expected numbers of false alarms in each GW frequency range.

For candidates exceeding the follow-up threshold, we applied a modified version of the hierarchical strategy detailed in B. P. Abbott et al. (2017b, 2022a). In particular, we used the non-resampling “demod” version of the CrossCorr pipeline in the follow-up stages. This version of the pipeline automatically zeros out frequencies associated with known instrumental disturbances (“lines”) (E. Goetz et al. 2025, 2026), reducing the number of outliers reaching the later stages of follow-up. The steps were as follows:

1. Candidates were iteratively “clustered” together in GW frequency, with all templates within 0.01 Hz of the highest S/N being represented by the parameters of this peak, and the process repeated on the remaining templates until no more remained above the threshold. Note that choosing too low a follow-up threshold would result in effectively every 0.02 Hz band containing a candidate.
2. A targeted search using the demod pipeline with $T_{\text{max}} = 24$ hr was performed on every clustered candidate. The primary purpose of this step is to determine the parameter space metric for later stages of follow-up, but it is also used to eliminate candidates arising from known instrumental lines by vetoing any candidate with $\rho < 1.645$. Note that the S/N of a candidate is expected to go down slightly at this stage, because $T_{\text{max}} = 24$ hr corresponds to less correlated data in the demod search than in the original resampling search, as shown in Figure 1. Candidates surviving this veto are known as the “level 0” results.
3. A “refinement” search was performed on each level 0 candidate, with $T_{\text{max}} = 24$ hr and a resolution $\sim 3 \times$ as fine as the 0.25 mismatch grid implied by the level 0 metric. This and later stages of follow-up were run on a rectangular grid in the “sheared” parameters $(f_0, a \sin i, t'_{\text{asc}}, \tilde{P})$. For the refinement stage, the grid contained 13 points in each of the

Table 4
Summary of Loudest Outliers

f_0 (Hz)	ρ_{resamp}^a	$\rho_{\text{lvl 1}}^b$	$\rho_{\text{lvl 2}}^c$	$\rho_{\text{lvl 3}}^c$	$h_{0,\text{resamp}}^{\text{eff}d}$	$h_{0,\text{lvl 1}}^{\text{eff}e}$	$h_{0,\text{lvl 2}}^{\text{eff}e}$	$h_{0,\text{lvl 3}}^{\text{eff}e}$
77.65	7.39	3.81	6.66	8.11	2.31×10^{-26}	1.80×10^{-26}	1.71×10^{-26}	1.34×10^{-26}
84.72	7.74	4.76	7.43	8.48	2.27×10^{-26}	2.09×10^{-26}	1.87×10^{-26}	1.43×10^{-26}
129.20	7.84	5.93	9.58	11.70	1.89×10^{-26}	1.80×10^{-26}	1.64×10^{-26}	1.29×10^{-26}
196.82	7.65	3.91	7.22	6.89	1.63×10^{-26}	1.28×10^{-26}	1.24×10^{-26}	8.65×10^{-27}

Notes. These are the outliers in Figure 4 for which the S/N increased by a factor of more than 1.75 when the coherence time was increased by a factor of 16 from level 1 to level 3. In all but one of the cases, the S/N dropped more than expected in the switch from the original resamp search to the demod follow-up, as reflected in the reduction of the estimated h_0^{eff} associated with the outlier. In those cases, the increase in S/N from level 1 to level 3 still resulted in $\rho_{\text{lvl 3}} < 10$. The one exception was the signal at 129.20 Hz, which, while seeing a reduction in estimated h_0^{eff} at each stage, still ended up with an S/N of $\rho_{\text{lvl 3}} = 11.70$. For comparison, the lowest $\rho_{\text{lvl 3}}$ for injections that survived the veto procedure was 15.96.

^a The S/N of the candidate in the initial resampling search with $T_{\text{max}} = 24$ hr.

^b The S/N of the candidate in the “level 1” refinement follow-up. Note that, while this also has $T_{\text{max}} = 24$ hr, it is less sensitive than the initial search because the implications of a T_{max} value are different in the resampling and demod searches, as shown in Figure 1.

^c The S/N of the candidate in the “level 2” and “level 3” follow-up searches with $T_{\text{max}} = 4$ day and 16 day, respectively

^d The estimated h_0^{eff} (4) of the candidate in the original resampling search, estimated from the S/N and the standard sensitivity ϑ defined in e.g., Equation (7) of B. P. Abbott et al. (2017b), recalling that a true signal has expected S/N $E[\rho] = (h_0^{\text{eff}})^2 \vartheta$.

^e The estimated h_0^{eff} of the candidate in the corresponding level of follow-up.

(f_0 , $a \sin i$, t'_{asc}) directions, and between 5 and 13 points as necessary to cover the prior range of $\tilde{P}$. To deal with the effects of unknown narrowband features (“lines”) present in a single detector, we computed a detection statistic using only data from the LLO detector and another using only LHO data. If either of these exceeded the detection statistic constructed from all the data, we vetoed the candidate as a likely instrumental artifact. Candidates from the refinement search that survive this veto are known as the “level 1” results.

- Two successive rounds of follow-up were performed, starting with the level 1 candidates. At each stage, the coherence time T_{max} was quadrupled from the previous stage, and the density of templates in the f_0 direction was increased by a factor of 3. The grid used was $13 \times 5 \times 5 \times 5$ in (f_0 , $a \sin i$, t'_{asc} , $\tilde{P}$), centered on the peak of the previous level’s results. No further refinement was necessary in the orbital parameter directions because the orbital metric saturates for $T_{\text{max}} > P_{\text{orb}} \approx 18.9$ hr. Candidates that increased their S/N from the previous level were known as the “level 2” ($T_{\text{max}} = 4$ days) and “level 3” ($T_{\text{max}} = 16$ days) results.

A total of 51 candidates survive level 3 of follow-up. To determine whether any of them represent convincing detection candidates, we examine the factor by which each increases its S/N when the coherence time is quadrupled from level 1 ($T_{\text{max}} = 24$ hr) to level 2 ($T_{\text{max}} = 4$ days) and again from level 2 to level 3 ($T_{\text{max}} = 16$ days). We plot this in Figure 4 for all of the candidates surviving level 2 (the level 3 follow-up is not run for candidates that fail level 2), and also for the simulated signal injections described in Section 5. We would naïvely expect a real signal to double its S/N between level 1 and level 2, and again between level 2 and level 3. All of the candidates arising from the search fall well short of this. For comparison, we also applied the follow-up procedure to the 289 injected signals (out of 350) that produced ρ values above their respective thresholds. Of these, eight were vetoed at level 1, two at level 2, and two at level 3, all because of the single-detector unknown-line veto. The remaining 277

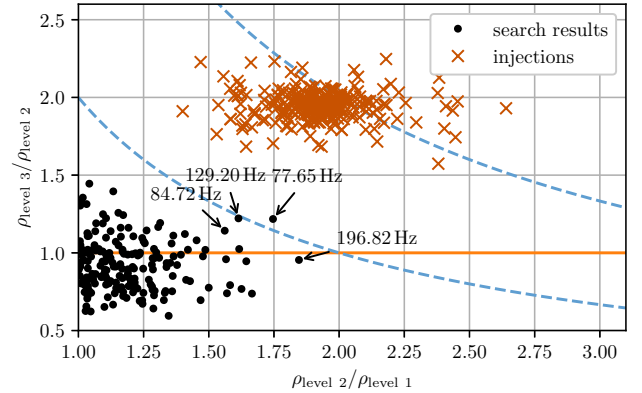


Figure 4. Ratios of follow-up statistics for candidates from the search, and from simulated signals. This plot shows all of the candidates that survived level 2 of follow-up (see Section 4 and Table 3), both from the main search and from the analysis of the simulated signal injections described in Section 5. It shows the ratios of the S/N ρ after follow-up level 1 (a refined demod CrossCorr search with $T_{\text{max}} = 24$ hr), level 2 ($T_{\text{max}} = 4$ days), and level 3 ($T_{\text{max}} = 16$ days). The blue dashed lines are at constant values of $\rho_{\text{level 3}}/\rho_{\text{level 1}}$ equal to 2 and 4, the latter being the theoretically expected value. There are no points with $\rho_{\text{level 2}}/\rho_{\text{level 1}} < 1$, because those candidates do not survive level 2 follow-up and are therefore not subjected to level 3 follow-up. From the construction of the statistic in J. T. Whelan et al. (2015), the naïve expectation is that the S/N will roughly double each time T_{max} is quadrupled. We see that the follow-ups of injections (red crosses) are clustered around this relationship, while the follow-ups of search candidates (black dots) are not. The four candidates which increase their S/N by the largest factor from level 1 to level 3 are indicated, labeled by their frequencies, and considered in Table 4.

survived all the levels of follow-up, and approximately doubled their S/N at each stage, as shown in Figure 4

We give details of some of the most interesting outliers in Table 4. The most intriguing outlier from the search is at a frequency of 129.20 Hz. As shown in Table 4, it has an initial ρ of 7.84 in the original resampling search. The targeted level 0 and refined level 1 follow-ups (both with $T_{\text{max}} = 24$ hr) produced $\rho_{\text{level 0}} = 5.91$ and $\rho_{\text{level 1}} = 5.93$. This reduction in S/N is expected because of the smaller number of SFT pairs in the demod search at a given T_{max} , and indeed the estimated

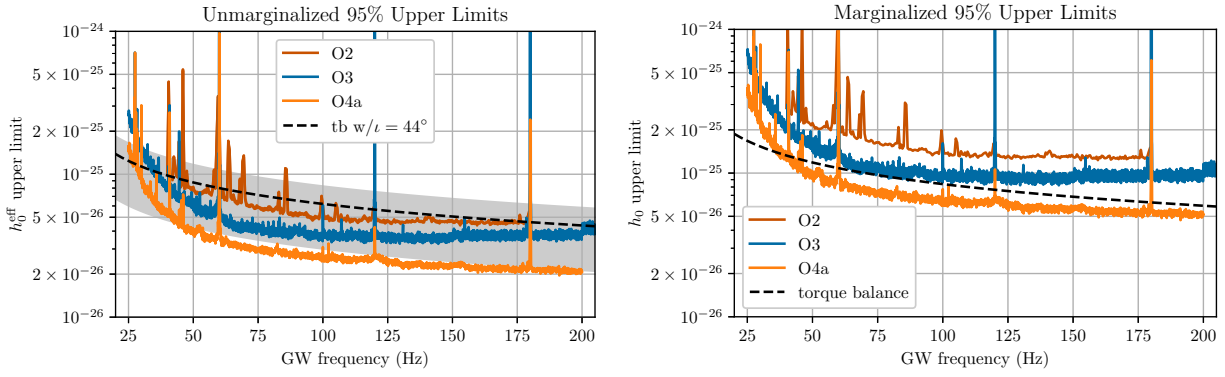


Figure 5. Upper limits from cross-correlation searches for Sco X-1 in Advanced LIGO data. Left: the upper limit shown is on h_0^{eff} , defined in Equation (4). This is equivalent to the upper limit on h_0 assuming circular polarization. The “O4a” curve shows the results of the present resampling CrossCorr search. “O3” is the CrossCorr search (B. P. Abbott et al. 2022a), and “O2” is the resampling CrossCorr search of Y. Zhang et al. (2021). For comparisons among O3 searches with different methods, see B. P. Abbott et al. (2022a). The gray shaded region corresponds to the range of amplitudes corresponding to the nominal expected level assuming torque-balance [Equation (7)], which depends on the unknown inclination angle. The dashed line (labeled as “tb w/ $i = 44^\circ$ ”) corresponds to the assumption that the NS spin is aligned to the most likely orbital angular momentum, and $i \approx i \approx 44^\circ$. (See Table 1.) Right: marginalized upper limits on h_0 , assuming an isotropic prior on the neutron star spin inclination i , with the dashed line indicating the level predicted by torque balance. (Note that this marginalized upper limit is dominated by linear polarization, and so is a factor of almost $\sqrt{8}$ higher than the unmarginalized upper limit.) The present search has, for the first time, set an upper limit below the torque-balance prediction at *any* inclination angle for $50 \text{ Hz} < f_0 < 200 \text{ Hz}$.

h_0^{eff} decreases negligibly between the original search and the level 1 follow-up. At level 2 ($T_{\text{max}} = 4$ days), the signal increased its S/N by a factor of 1.61 to 9.58, and at level 3 ($T_{\text{max}} = 16$ days), it increased by a further factor of 1.22 to 11.70, the highest follow-up S/N of any of our candidates. This is of particular interest because a signal with spin wandering might be expected to have a lower S/N than predicted in searches with longer coherence times of $T_{\text{max}} \gtrsim 10$ days.

To check whether the 129.20 Hz could be due to a signal whose frequency was stochastically “wandering,” an analysis was performed with the Viterbi/HMM pipeline (S. Suvorova et al. 2016, 2017) over a narrow range of frequency and orbital parameters centered on those of the outlier. This search also found a feature at the parameters of this candidate, which survived its known lines (P. B. Covas et al. 2018; E. Goetz et al. 2026), single interferometer (B. P. Abbott et al. 2022b), and Doppler modulation-off (D. Jones et al. 2022) vetoes. However, the most likely path for the wandering signal frequency oscillated between two frequencies separated by less than 2×10^{-7} Hz. At the resolution of the final CrossCorr follow-up step, a frequency offset of $\pm 10^{-7}$ Hz would result in a loss of S/N of less than 13%, so the difference in behavior between the candidate and simulated signals does not seem to be explained by spin wandering.

As an independent check of the 129.20 Hz candidate, we applied the resampling CrossCorr search with $T_{\text{max}} = 24$ hr to the corresponding region of parameter space in data from the second part of the fourth observing run (O4b), which began on 2024 April 10 15:00:00 UTC (GPS 1396796418) and ended on 2025 January 28 17:00:00 UTC (GPS 1422118818), but no signal was seen with $\rho > 6.13$. A true persistent signal at these parameters should have been seen with $\rho \gtrsim 8.30$, given the greater duration and sensitivity of the O4b dataset compared to O4a. We conclude that this feature in the O4a data, while suggestive, does not appear to be associated with a gravitational wave signal.

5. Upper Limits and Implications

In the absence of convincing detection candidates, we set upper limits on the strength of GWs from Sco X-1 as a function of GW frequency, using the method described in detail in B. P. Abbott et al. (2017b). The starting point is a naïve Bayesian upper limit within each 0.05 Hz band, set using the 95th percentile of the posterior on h_0^2 or $(h_0^{\text{eff}})^2$ deduced from the highest S/N seen in each band. These were adjusted by a factor determined through Bayesian logistic regression on injected simulated signals.

The upper limits are plotted in Figure 5, and for the first time set constraints below the standard torque-balance limit for all values of the neutron star spin inclination angle, across a range of frequencies from 50 to 200 Hz. The most sensitive upper limits are at the upper end of the frequency band, and approach a GW amplitude of 5×10^{-26} marginalized over inclination angle and 2×10^{-26} , assuming the most favorable inclination. In Figure 6, we show the marginalized upper limits in terms of the sensitivity depth $D = \sqrt{S(f)}/h_0^{\text{ul}}$ defined in B. Behnke et al. (2015) and C. Dreissigacker et al. (2018), which separates the inherent sensitivity of the search from the effects of the reduction of noise level between observing runs. The present search achieves a sensitivity depth of $D \sim 70\text{--}75 \text{ Hz}^{-1/2}$, improving upon previous searches, which had a depth of around $50\text{--}60 \text{ Hz}^{-1/2}$.

In Figure 7, we convert the upper limits into limits on the physical process associated with the GW generation. In the case of triaxiality, we compute an upper limit on ellipticity $\epsilon = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$, assuming a gravitational wave amplitude of (K. Riles 2023; K. Wette 2023)

$$h_0 = \frac{4\pi^2 G}{c^4 d} (I_{zz}) \epsilon f_0^2, \quad (14)$$

where we assume the most likely distance $d = 2.8 \text{ kpc}$ from Table 1 and a moment of inertia of $I_{zz} = 10^{38} \text{ kg m}^2$. For f_0 between 75 and 200 Hz, the upper limits (marginalized isotropically over inclination angle) are between 3×10^{-5} and

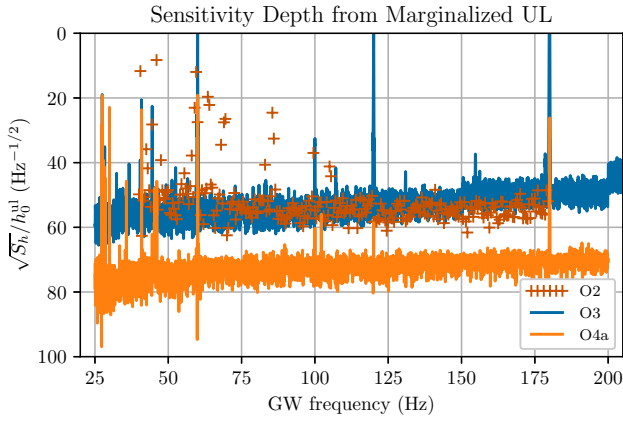


Figure 6. The marginalized upper limits from Figure 5, expressed in terms of the quantity known as sensitivity depth (B. Behnke et al. 2015; C. Dreissigacker et al. 2018) $D = \sqrt{S(f)}/h_0^{ul}$, which scales out the effect of detector sensitivity by using the averaged noise power spectral density $S(f)$ for the observing run in question. Note that the (resampling) O2 search of Y. Zhang et al. (2021) and the (demod) O3 search of B. P. Abbott et al. (2022a) have similar sensitivity depths of around 50–60 $\text{Hz}^{-1/2}$, with the longer coherence time of the resampling analysis being offset by the longer duration of O3. The variable choice of T_{max} in the O3 analysis, designed to trade off computing cost versus scientific return, results in a deeper search at low frequencies and shallower at high frequencies. The present O4a resampling analysis achieves a sensitivity depth of around 70–75 $\text{Hz}^{-1/2}$.

3×10^{-6} , probing ellipticities that are potentially supportable by ordinary matter (N. K. Johnson-McDaniel & B. J. Owen 2013; F. Gittins 2024). For the case of GWs driven by r -modes, we use Equation (24) of B. J. Owen (2010):

$$\alpha = 0.028 \left(\frac{h_0}{10^{-24}} \right) \left(\frac{d}{1 \text{ kpc}} \right) \left(\frac{100 \text{ Hz}}{f_0} \right). \quad (15)$$

Our strongest constraints are at the upper end of the frequency range, $f_0 \approx 200 \text{ Hz}$ [corresponding to a spin frequency of 120–150 Hz (B. J. Owen & B. Rajbhandari 2025)], and amount to (subject to all the assumptions that go into (15)) $\alpha \lesssim 5 \times 10^{-4}$. This is just within the plausible range of saturation amplitudes for a newborn NS (R. Bondarescu et al. 2009), but still slightly above what is expected for an accreting NS such as Sco X-1 (R. Bondarescu et al. 2007).

From an astrophysical point of view, the upper limits from the current search allow us to essentially exclude the GW-dominated torque-balance scenario in the range between roughly 50 and 200 Hz. One can ask whether altering the assumptions in Equation (7) would allow for torque balance at a lower GW amplitude. By taking the lever arm at the NS surface ($r = R_*$) and assuming a very compact neutron star, with mass $M = 1.4 M_\odot$ and radius $R = 10 \text{ km}$, we are already using a low torque-balance amplitude. Microphysically motivated equations of state (EoSs) generally predict less compact stars; even for softer EoS, such as for example the GR15 EoS (F. Gulminelli & A. R. Raduta 2015) considered by B. P. Abbott et al. (2022a), one cannot construct a model that would allow for torque balance below the upper limits reported in this Letter.

Although it is important to keep in mind that significant uncertainties are present in torque modeling, and that GW torques may be active only part of the time (B. Haskell et al. 2015), our results essentially exclude the possibility that Sco X-1 includes an NS in equilibrium between accretion torques and GW torques with a GW frequency between

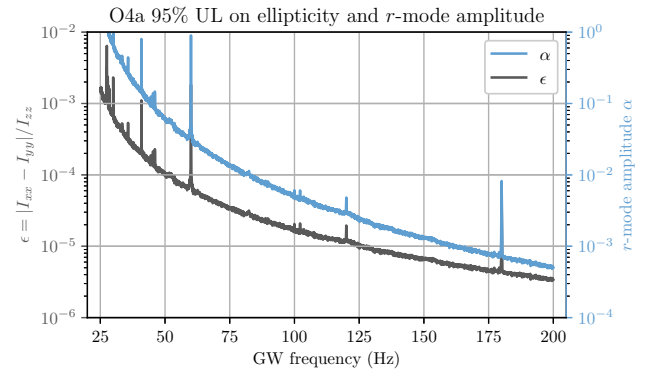


Figure 7. The marginalized upper limits from Figure 5, converted to limits on the ellipticity $\epsilon = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$ (K. Riles 2023; K. Wette 2023) of the NS in Sco X-1 (left axis scale), or alternatively, the r -mode amplitude α (right axis scale). The ellipticity assumes a moment of inertia of 10^{38} kg m^2 and a distance of 2.8 kpc. For GW frequencies between 75 and 200 Hz, the constraints are between 3×10^{-5} and 3×10^{-6} . At the highest frequencies, these are entering the range of possible ellipticities for ordinary NS matter. The r -mode amplitudes use equation (24) of B. J. Owen (2010); the best limits of $\sim 5 \times 10^{-4}$ are probably still slightly above what one might expect in Sco X-1 (B. J. Owen & B. Rajbhandari (2025) and references therein).

approximately 50 and 200 Hz. (This corresponds to a spin frequency ν_s between 25 and 100 Hz if triaxiality is the dominant GW emission mechanism, or between ~ 15 –20 and ~ 120 –150 Hz if the GWs are driven by r -modes.)

The torque-balance scenario remains hypothetically possible for a very compact quark star, an object that has been conjectured to exist in LMXBs (D. Gondek-Rosińska et al. 2003). In this case, if for example we consider a quark star described by the MIT bag model, with a bag constant $B = 60 \text{ MeV fm}^{-3}$, then stars with masses $M \lesssim 0.5 M_\odot$ (and corresponding radii $R \lesssim 8 \text{ km}$) would still be consistent with the torque-balance scenario and the reported upper limits.

6. Conclusions and Outlook

We have presented the results of the most sensitive search to date for GWs from Sco X-1, using LIGO detector data from the first eight months of the fourth observing run of Advanced LIGO, Advanced Virgo, and KAGRA. Using the resampling CrossCorr pipeline to search with a coherence time of $T_{\text{max}} = 24 \text{ hr}$, we have set upper limits for GW signal frequencies $25 \text{ Hz} < f_0 < 200 \text{ Hz}$, corresponding to NS spin frequencies of $12.5 \text{ Hz} < \nu_s < 100 \text{ Hz}$ (or 15 – $20 \text{ Hz} \lesssim \nu_s \lesssim 120$ – 150 Hz for r -modes). The sensitivity of the search now surpasses, for the first time, the naïve torque-balance prediction for plausible signal strengths regardless of assumptions about the NS inclination angle, for $50 \text{ Hz} < f_0 < 200 \text{ Hz}$.

It is, of course, quite possible that the spin frequency of Sco X-1 is above 100 Hz, with a GW frequency above 200 Hz. In particular, the distribution of spin frequencies of the observed accreting millisecond X-ray pulsars (AMXPs) appears to be bimodal (A. Patruno et al. 2017), with a “fast” population of pulsars, narrowly distributed around $\nu_s \approx 550 \text{ Hz}$, which can be explained theoretically by the presence of GW torques (F. Gittins & N. Andersson 2019), and would lead to gravitational emission at frequencies as high as 1100 Hz. Forthcoming analysis of additional data from the fourth observing run will apply a variety of search methods that balance sensitivity and robustness to signal model assumptions across a wider range of signal frequencies.

Acknowledgments

This material is based upon work supported by NSF’s LIGO Laboratory, which is a major facility fully funded by the National Science Foundation. The authors also gratefully acknowledge the support of the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO 600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS), and the Netherlands Organization for Scientific Research (NWO) for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación (AEI), the Spanish Ministerio de Ciencia, Innovación y Universidades, the European Union NextGenerationEU/PRTR (PRTR-C17.I1), the ICSC—Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by the European Union NextGenerationEU, the Comunitat Autònoma de les Illes Balears through the Conselleria d’Educació i Universitats, the Conselleria d’Innovació, Universitats, Ciència i Societat Digital de la Generalitat Valenciana and the CERCA Programme Generalitat de Catalunya, Spain, the Polish National Agency for Academic Exchange, the National Science Centre of Poland and the European Union - European Regional Development Fund; the Foundation for Polish Science (FNP), the Polish Ministry of Science and Higher Education, the Swiss National Science Foundation (SNSF), the Russian Science Foundation, the European Commission, the European Social Funds (ESF), the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the French Lyon Institute of Origins (LIO), the Belgian Fonds de la Recherche Scientifique (FRS-FNRS), Actions de Recherche Concertées (ARC) and Fonds Wetenschappelijk Onderzoek - Vlaanderen (FWO), Belgium, the Paris Île-de-France Region, the National Research, Development and Innovation Office of Hungary (NKFIH), the National Research Foundation of Korea, the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Foundation for Innovation (CFI), the Brazilian Ministry of Science, Technology, and Innovations, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Israel Science Foundation (ISF), the US–Israel Binational Science Fund (BSF), the Leverhulme Trust, the Research Corporation, the National Science and Technology Council (NSTC), Taiwan, the United States Department of Energy, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, INFN, and CNRS for provision of computational resources.

This work was supported by MEXT, the JSPS Leading-edge Research Infrastructure Program, JSPS Grant-in-Aid for Specially Promoted Research 26000005, JSPS Grant-in-Aid for Scientific Research on Innovative Areas 2402: 24103006, 24103005, and 2905: JP17H06358, JP17H06361, and JP17H06364, JSPS Core-to-Core Program A. Advanced Research Networks, JSPS Grants-in-Aid for Scientific Research (S) 17H06133, 20H05639, and 20H05639, JSPS Grant-in-Aid for Transformative Research Areas (A) 26A204: JP26H00407, the joint research program of the Institute for Cosmic Ray Research, University of Tokyo, the National Research Foundation (NRF), the Computing Infrastructure Project of the Global Science experimental Data hub Center (GSDC) at KISTI, the Korea Astronomy and Space Science Institute (KASI), the Ministry of Science and ICT (MSIT) in Korea, Academia Sinica (AS), the AS Grid Center (ASGC), and the National Science and Technology Council (NSTC) in Taiwan, under grants including the Science Vanguard Research Program, the Advanced Technology Center (ATC) of NAOJ, the Mechanical Engineering Center of KEK, and Vietnam National Foundation for Science and Technology Development (NAFOSTED) 103.01-2025.147.

Additional acknowledgments for support of individual authors may be found in the following document: <https://dcc.ligo.org/LIGO-M2300033/public>. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version arising. We request that citations to this Letter use “A. G. Abac et al. (LIGO-Virgo-KAGRA Collaboration), ...” or similar phrasing, depending on journal convention.

Software: LALSuite (LIGO Scientific Collaboration et al. 2018), SWIGLAL (K. Wette 2020) numpy (C. R. Harris et al. 2020), matplotlib (J. D. Hunter 2007), scipy (P. Virtanen et al. 2020).

The data and script used to make the figures and tables in this Letter are available at doi:[10.5281/zenodo.21997204](https://doi.org/10.5281/zenodo.21997204)

We would like to thank Maria Alessandra Papa, as well as the anonymous journal referee, for useful feedback.

This Letter has been assigned LIGO Document No. LIGO-P2500260-v14.

Appendix

Effects of Elliptical Binary Orbit

The orbit of Sco X-1 is believed on the basis of modeling of the binary evolution to be nearly circular ($e \lesssim 10^{-4}$) (D. Steeghs & J. Casares 2002; L. Wang et al. 2018; T. L. Killestein et al. 2023). Direct observational constraints on orbital eccentricity are complicated by systematic effects, and are at the level of $e \leq 0.0132$ (T. L. Killestein et al. 2023). Here, we consider the possible loss of S/N in the cross-correlation search, due to nonzero orbital eccentricity.

The fractional loss of S/N, due to searching at parameter values $\{\lambda_i\}$ for a signal whose true parameter values are $\{\lambda_i^s\}$, is given in the metric approximation by

$$\frac{E[\rho]^{\text{ideal}} - E[\rho]}{E[\rho]^{\text{ideal}}} \approx \sum_i \sum_j g_{ij} (\lambda_i - \lambda_i^s) (\lambda_j - \lambda_j^s). \quad (\text{A1})$$

The metric elements for the cross-correlation search are given by (J. T. Whelan et al. 2015)

$$g_{ij} = \frac{1}{2} \left\langle \frac{\partial \Delta \Phi_{KL}}{\partial \lambda_i} \frac{\partial \Delta \Phi_{KL}}{\partial \lambda_j} \right\rangle_{KL}, \quad (\text{A2})$$

where $\Delta\Phi_{KL} = \Phi_K - \Phi_L$ is the GW phase difference for SFT pair KL , and $\langle \cdot \rangle_{KL}$ is an average over SFT pairs weighted by antenna patterns and detector noise.

For an LMXB in a noncircular orbit, the usual parameters $\{\lambda_i\} \equiv \{f_0, a \sin i, t_{\text{asc}}, P_{\text{orb}}\}$ are supplemented by two additional orbital parameters: the eccentricity e and the argument of periape ω (measured from the ascending node). For small values of e , it is convenient to work in terms of the Laplace–Lagrange parameters $\kappa = e \cos(\omega)$ and $\eta = e \sin(\omega)$ (C. Lange et al. 2001). To lowest order in e , the GW phase in SFT K (Equation (4.15) of J. T. Whelan et al. 2015) becomes (C. Messenger 2011; P. Leaci & R. Prix 2015)

$$\begin{aligned} \Phi_K &= \Phi_0 + 2\pi f_0 \\ &\times \left\{ t_K - d_K - a \sin i \right. \\ &\times \left[\sin \Psi_K + \frac{\kappa}{2} \sin 2\Psi_K - \frac{\eta}{2} \cos 2\Psi_K \right] \Big\} \\ &+ O(e^2), \end{aligned} \quad (\text{A3})$$

where $\Psi_K = \frac{2\pi(t_K - t_{\text{asc}})}{P_{\text{orb}}}$ is the mean orbital phase, and κ and η are both $O(e)$. The GW phase difference $\Delta\Phi_{KL}$ is thus

$$\begin{aligned} \Delta\Phi_{KL} &= 2\pi f_0 \left\{ \Delta t_{KL} - \Delta d_{KL} - a \sin i \right. \\ &\times \left[\sin \Psi_K - \sin \Psi_L + \frac{\kappa}{2} (\sin 2\Psi_K - \sin 2\Psi_L) - \frac{\eta}{2} \right. \\ &\times (\cos 2\Psi_K - \cos 2\Psi_L) \Big] \Big\} + O(e^2), \end{aligned} \quad (\text{A4})$$

where $\Delta t_{KL} = t_K - t_L$ is the time difference between SFTs K and L . Here, $\Delta d_{KL} = d_K - d_L$ is the projection onto the line of sight of the separation vector between the detector positions corresponding to the two SFTs, and like $a \sin i$, it is measured in light-seconds.

Using the identities $\sin u - \sin v = 2 \cos \frac{u+v}{2} \sin \frac{u-v}{2}$ and $\cos u - \cos v = -2 \sin \frac{u+v}{2} \sin \frac{u-v}{2}$, we can rewrite Equation (A4) as

$$\begin{aligned} \Delta\Phi_{KL} &= 2\pi f_0 \left\{ \Delta t_{KL} - \Delta d_{KL} - a \sin i \left[2 \cos \bar{\Psi}_{KL} \sin \frac{\Delta\Psi_{KL}}{2} \right. \right. \\ &\quad \left. \left. + (\kappa \cos 2\bar{\Psi}_{KL} + \eta \sin 2\bar{\Psi}_{KL}) \sin \Delta\Psi_{KL} \right] \right\} + O(e^2) \end{aligned} \quad (\text{A5})$$

where $\bar{\Psi}_{KL} = \frac{2\pi}{P_{\text{orb}}} \left(\frac{t_K + t_L}{2} - t_{\text{asc}} \right)$ and $\Delta\Psi_{KL} = \frac{2\pi \Delta t_{KL}}{P_{\text{orb}}}$.

The derivatives with respect to f_0 , $a \sin i$, t_{asc} , and P_{orb} agree to lowest order in e with those given in J. T. Whelan et al. (2015). The derivatives with respect to the Laplace–Lagrange parameters are, to lowest order,

$$\begin{aligned} \frac{\partial \Delta\Phi_{KL}}{\partial \kappa} &= -2\pi f_0 a \sin i \cos 2\bar{\Psi}_{KL} \\ &\times \sin \left(\frac{2\pi}{P_{\text{orb}}} \Delta t_{KL} \right) + O(e); \end{aligned} \quad (\text{A6a})$$

$$\begin{aligned} \frac{\partial \Delta\Phi_{KL}}{\partial \eta} &= -2\pi f_0 a \sin i \sin 2\bar{\Psi}_{KL} \\ &\times \sin \left(\frac{2\pi}{P_{\text{orb}}} \Delta t_{KL} \right) + O(e). \end{aligned} \quad (\text{A6b})$$

Arguing, as in J. T. Whelan et al. (2015), that the mean orbital phase $\bar{\Psi}_{KL}$ is evenly sampled over the duration of the run, we can show that the off-diagonal metric elements (A2) involving κ and/or η vanish, and the new diagonal elements are, to lowest order in e ,

$$\begin{aligned} g_{\kappa\kappa} &\approx g_{\eta\eta} \approx \pi^2 f_0^2 (a \sin i)^2 \\ &\times \left\langle \sin^2 \left(\frac{2\pi}{P_{\text{orb}}} \Delta t_{KL} \right) \right\rangle_{KL}. \end{aligned} \quad (\text{A7})$$

In general, the form of $\left\langle \sin^2 \left(\frac{2\pi}{P_{\text{orb}}} \Delta t_{KL} \right) \right\rangle_{KL}$ depends on the value of T_{max} , scaling as T_{max}^2 when $T_{\text{max}} \ll P_{\text{orb}}$. However, in the present search, T_{max} exceeds P_{orb} , the average approaches $\frac{1}{2}$, and the metric elements in Equation (A7) (like the other orbital metric elements) saturate, giving us

$$g_{\kappa\kappa} \approx g_{\eta\eta} \approx \frac{\pi^2 f_0^2 (a \sin i)^2}{2}. \quad (\text{A8})$$

Note that this agrees with the “long-segment regime” metric of P. Leaci & R. Prix (2015) for coherent and semi-coherent F -statistic based searches.

If we search for a signal with true parameters κ and η using a template that has $\kappa = 0 = \eta$, the mismatch is thus

$$\begin{aligned} \frac{E[\rho]^{\text{ideal}} - E[\rho]}{E[\rho]^{\text{ideal}}} &= \frac{\pi^2 f_0^2 (a \sin i)^2}{2} (\kappa^2 + \eta^2) \\ &= \frac{\pi^2 f_0^2 (a \sin i)^2 e^2}{2}. \end{aligned} \quad (\text{A9})$$

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