Draft version October 21, 2024
Typeset using LaTeX **twocolumn** style in AASTeX631

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ABSTRACT

We present the results of a search for gravitational-wave transients associated with core-collapse supernova SN 2023ixf, which was observed in the galaxy Messier 101 via optical emission on 2023 May 19th, during the LIGO-Virgo-KAGRA 15th Engineering Run. We define a five-day on-source window during which an accompanying gravitational-wave signal may have occurred. No gravitational waves have been identified in data when at least two gravitational-wave observatories were operating, which covered $\sim 14\,\%$ of this five-day window. We report the search detection efficiency for various possible gravitational-wave emission models. Considering the distance to M101 (6.7 Mpc), we derive constraints on the gravitational-wave emission mechanism of core-collapse supernovae across a broad frequency spectrum, ranging from 50 Hz to 2 kHz where we assume the GW emission occurred when coincident data are available in the on-source window. Considering an ellipsoid model for a rotating proto-neutron star, our search is sensitive to gravitational-wave energy $1\times10^{-5}\,\mathrm{M_\odot c^2}$ and luminosity $4\times10^{-5}\,\mathrm{M_\odot c^2/s}$ for a source emitting at 50 Hz. These constraints are around an order of magnitude more stringent than those obtained so far with gravitational-wave data. The constraint on the ellipticity of the proto-neutron star that is formed is as low as 1.04, at frequencies above 1200 Hz, surpassing results from SN 2019ejj.

Keywords: SN 2023ixf — Gravitational-waves

1. INTRODUCTION

The direct detection of gravitational waves (GWs) from a binary black hole merger (Abbott et al. 2016a) started the field of GW astronomy, and was followed by similar mergers (Abbott et al. 2019, 2021a, 2024, 2023a). Two years later, the merger of two neutron stars was observed both with GWs and across the electromagnetic spectrum (Abbott et al. 2017a,b), leading to the birth of GW multi-messenger astronomy. More recently, the observation of mergers of mixed systems (Abbott et al. 2021b; Abac et al. 2024) is allowing measurement of the merger rates of all types of compact binary systems (Abbott et al. 2023b).

Core-collapse supernovae (CCSNe) are the explosions of massive stars – masses above 8 $\mathrm{M_\odot}$ at the end of their evolution – leading to the production of neutron stars and black holes (Burrows et al. 1995; Kotake et al. 2006; Janka 2012). CCSNe are astrophysical sources with multi-messenger emission, having historically been observed over the electromagnetic spectrum and, for SN 1987A, also with low-energy neutrinos (Hirata et al. 1987; Bionta et al. 1987; Alekseev et al. 1987). However, the GW emission of CCSNe is still undetected. The combination of GW and neutrino observations can provide information about the collapse and the onset of the explosion, since both messengers are emitted from the core very soon after the collapse and have negligible interactions with the surrounding matter (Janka 2012). On the other hand, electromagnetic emission is produced in the outer layers of the star and is delayed.

The GW emission from CCSNe is weaker than the emission from compact binary mergers, making it detectable by the advanced generation of detectors only for nearby supernovae (Gossan et al. 2016; Szczepańczyk et al. 2021; Abbott et al. 2021c). The most likely opportunity for observations are Galactic CCSNe, but the expected rate is of the order of one or two per century (Bergh & Tammann 1991; Cappellaro et al. 1993; Tammann et al. 1994; Diehl et al. 2006; Li et al. 2011; Adams et al. 2013). However, due to the large uncertainties of the progenitors and GW emission models, we carry out searches for GW emission from CCSNe out to distances of 20 Mpc (Abbott et al. 2016b, 2020b; Szczepańczyk et al. 2024).

SN 2023ixf was identified in Messier 101 (M101) during its rise, making it one of the closest type II CCSNe observed. The two LIGO observatories were in observing mode during the fifteenth Engineering Run (ER15) of the LIGO-Virgo-KAGRA network (Aasi et al. 2015;

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[*] Deceased, September 2024.
[†] Deceased, July 2023.
[‡] Deceased, February 2024.

Acernese et al. 2015; Akutsu et al. 2021). In this letter, we report the results of the search for GWs and the new constraints on GW emission obtained with SN 2023ixf.

2. SN 2023IXF AND ER15 DATA

2.1. *Summary of SN 2023ixf multi-messenger observations*

SN 2023ixf (RA = 14:03:38.562, DEC = +54:18:41.94, J2000) was discovered on 2023 May 19 by Itagaki (2023) with a clear (unfiltered) magnitude of 14.9 in the host galaxy M101 (NGC 5457, Pinwheel Galaxy). M101 is at a distance of about 6.7 Mpc (see Sec. 2.3), making SN 2023ixf one of the nearest CCSNe observed in recent years. In addition, this galaxy is a well-observed object with an extensive set of pre-discovery observations. SN 2023ixf was quickly classified as a type II supernova a few hours after the discovery (Perley et al. 2023). Due to the prompt discovery and the close distance, SN 2023ixf was the target of extensive electromagnetic coverage. The optical light curve shows a rise to a maximum at about five days, followed by a plateau lasting for about one month, and a slow decline later (Hiramatsu et al. 2023; Hosseinzadeh et al. 2023; Li et al. 2024; Sgro et al. 2023; Teja et al. 2023; Yamanaka et al. 2023). The early spectroscopic observations show flash ionization features of hydrogen, helium, nitrogen, carbon and a temperature increase not explained by pure shock cooling, suggesting a delayed shock breakout in a dense circumstellar medium (Berger et al. 2023; Bersten, M. C. et al. 2024; Bostroem et al. 2023; Grefenstette et al. 2023; Chandra et al. 2024; Guetta et al. 2023; Hiramatsu et al. 2023; Hosseinzadeh et al. 2023; Koenig 2023; Jacobson-Galan et al. 2023; Kilpatrick et al. 2023; Li et al. 2024; Martinez, L. et al. 2024; Murase 2024; Niu et al. 2023; Pledger & Shara 2023; Qin et al. 2024; Smith et al. 2023; Teja et al. 2023; Van Dyk et al. 2023; Vasylyev et al. 2023; Xiang et al. 2024; Yamanaka et al. 2023; Zimmerman et al. 2024). The earliest detections of X-ray and radio emission occurred four days (Grefenstette et al. 2023) and one month (Matthews et al. 2023) after the discovery, respectively. The hard X-ray (Grefenstette et al. 2023) and soft X-ray (Chandra et al. 2024) observations suggest a high and decreasing neutral hydrogen column density close to SN 2023ixf. SN 2023ixf was not detected in gamma-rays (Marti-Devesa 2023) or in neutrinos (Thwaites et al. 2023; Nakahata & Super-Kamiokande Collaboration 2023; Abbasi et al. 2023).

2.2. *Nature and mass of progenitor*

A large set of M101 pre-discovery imaging observations from ground-based telescopes, Hubble Space Telescope and Spitzer Space Telescope suggest the nature of the SN 2023ixf progenitor to be a dusty and variable red supergiant, with an estimated mass ranging from 8 to 20 $M_\odot$ (Dong et al. 2023; Flinner et al. 2023; Hiramatsu et al. 2023; Jencson et al. 2023; Neustadt et al. 2023; Niu et al. 2023; Pledger & Shara 2023; Ransome et al. 2024; Soraisam et al. 2023; Van Dyk et al. 2023; Xiang et al. 2024; Ferrari, Lucía et al. 2024; Moriya & Singh 2024).

The circumstellar medium could have been produced by an enhancement in the mass loss before the SN explosion, but several archival investigations did not find any pre-explosion outburst in the years before the discovery (Dong et al. 2023; Flinner et al. 2023; Jencson et al. 2023; Neustadt et al. 2023; Ransome et al. 2024; Soraisam et al. 2023), while detecting amplitude pulsations (Kilpatrick et al. 2023; Soraisam et al. 2023).

2.3. *M101 distance*

The distance of the supernova host galaxy is relevant to constrain the GW energy emission. Since astronomical distances are estimated using a broad range of methods, we have considered the available published values to estimate the distance to M101. More precisely, we have considered the distance estimations reported in the NASA Extragalacic Database (Helou et al. 1991), a total number of 115 measurements using 12 different methods: Cepheids, Planetary Nebulae Luminosity Function, Supernova Ia, Tip of Red Giant Branch, SN II optical, Brightest Stars, Tully-Fisher relation, M Stars, RSV Stars, S Dor stars, H II region diameter and SN II radio. We adopt the median to the remaining 115 data points, 6.7 Mpc, with a standard deviation of 0.9 Mpc, as the estimated distance of SN 2023ixf.

2.4. *On-source window*

The on-source window is the time interval containing the core bounce and the following GW emission. We denote the start and end times of this interval as t_1 and t_2, respectively. Due to the availability of well-sampled public photometric data of SN 2023ixf, the on-source window could be estimated using the early photometric observations that include the non-detections before the rise to peak brightness as shown in Fig. 1. The first detection is MJD = 60082.82611, at a CV magnitude of 18.76 ± 0.25 (Chufarin et al. 2023), following the last pre-discovery observation at MJD = 60082.66041667, clear magnitude > 20.4 (Mao et al. 2023). For SN 2023ixf, t_2 is well approximated by the first detection, while t_1 involves the delay between collapse and shock breakout, whose time falls between t_2 and the latest pre-discovery observation. The time delay depends on many properties of the progenitor, including its mass. Considering

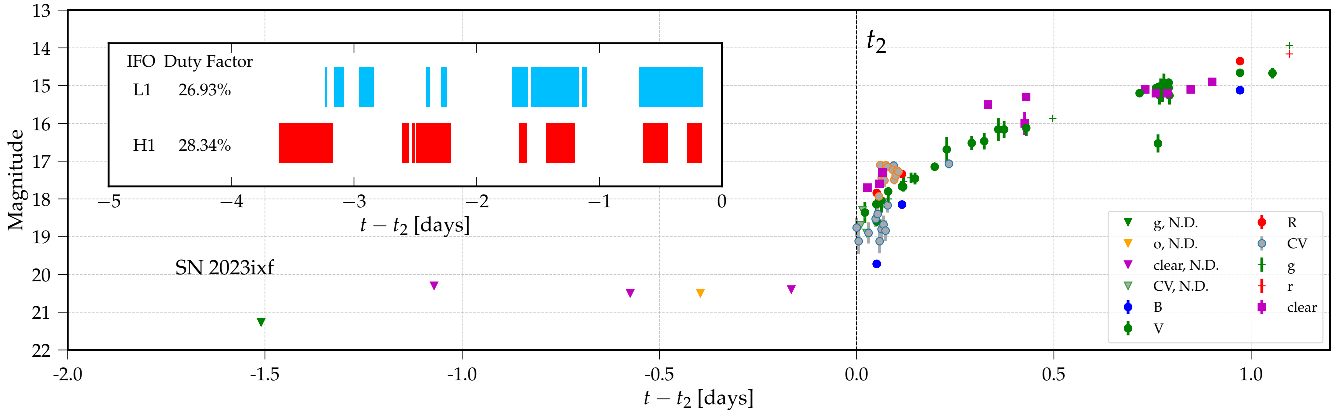

Figure 1. Early evolution of SN 2023ixf covering different photometric bands (B, V, R, g, o) and unfiltered observations (CV, clear); N.D. marks non detections; inset: LIGO Hanford (H1) and Livingston (L1) detectors duty cycle within the OSW described in the text. Photometric data sources: Transient Name Server Astronotes, Astronomical Telegrams, AAVSO, Sgro et al. (2023); Li et al. (2024).

the large spread in mass estimations and the relation between mass and time delay found by Barker et al. (2022) (Fig. 6), we have adopted a conservative maximal on-source window duration of five days, from 2023-05-13T19:49:35 to 2023-05-18T19:49:35 UTC.

2.5. *ER15 data*

ER15 took place at the LIGO Livingston and Hanford Observatories from 2023 April 7 to 2023 May 24 following a period of upgrades and commissioning that improved the detectors' sensitivity from the previous observing run. During ER15, the observatories collect data as if it were a normal observing run with the exception that calibration, commissioning, and noise investigations are performed. These studies are concentrated near the beginning of ER15 and taper to an as-needed basis towards the last week. The collapse of SN 2023ixf likely happened during this end period of ER15 as did the time period spanned by this search.

The uncertainty in the strain calibration has been found to be similar to previous observing runs (Sun et al. 2021). Its effect on the search is marginal and thus ignored. Within the on-source window, the two LIGO observatories were operating jointly for ∼ 0.8 days.

Transient data artifacts, referred to as glitches, contaminate the data and can affect the confidence estimation of candidate events. The search has been carried out with strain channels `L1:GDS-CALIB_STRAIN_CLEAN_AR` and `H1:GDS-CALIB_STRAIN_CLEAN_AR` where `CLEAN` means some of the well identified noise sources have been removed (Abbott et al. 2023c). Data quality studies reveal auxiliary channels that are insensitive to GWs and have a strong correlation to the glitches in the output of the detector. These times of poor data quality are then removed (vetoed) (Davis et al. 2021), representing 15 % of the coincident time within the on-source window. This gives the analysis time of ∼ 0.68 days.

3. SEARCH

3.1. *Coherent WaveBurst*

We use coherent WaveBurst (cWB), a model-agnostic search algorithm, for the detection and reconstruction of transient GW signals (Klimenko et al. 2016). The algorithm identifies GW transients by searching for excess power in spectrograms and reconstructs coherent signals in multiple detectors. In previous CCSN searches (Szczepańczyk et al. 2023), spectrograms were obtained with the Wilson-Daubechies-Meyer wavelet transform (Necula et al. 2012). The SN 2023ixf analysis uses the high-resolution wavescan transform (Klimenko 2022) that utilizes both the excess-power and cross-power statistics for the identification of GW signals and enables more accurate reconstruction of the signal waveforms. The signal detection statistic η_0 is defined as $\eta_0 = \sqrt{E_c}$ where E_c is the total coherent energy across the detector network (Klimenko et al. 2016). To further separate GW signals from the noise, the triggers are then re-ranked with a reduced statistic $\eta_r = \eta_0 \cdot W_{XGB}$, where W_{XGB} is the XGBoost classification penalty factor which ranges between 0 (noise-like) and 1 (signal-like) (Szczepańczyk et al. 2023; Mishra et al. 2021). For this search, the XGBoost algorithm uses the SN 2023ixf sky location to improve detection sensitivity.

3.2. *CCSN models*

To test the sensitivity of the search, we use a range of different waveforms from numerical simulations, that span the expected progenitor parameter space. For non-rotating sources we use the $15\,M_\odot$ SFHx s15 model

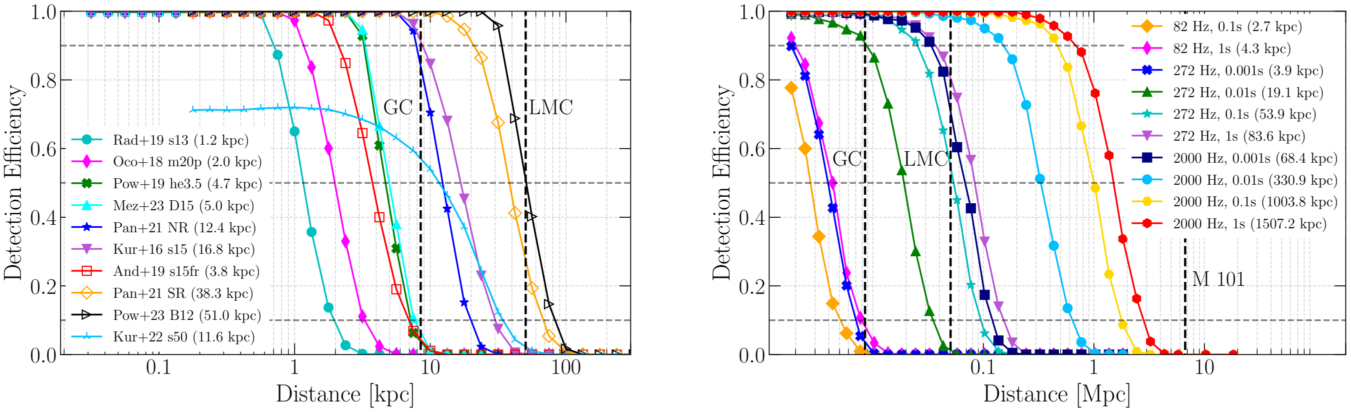

Figure 2. The detection efficiency as a function of distance for SN 2023ixf for different CCSN waveform models. The numbers in the parentheses are distances at 50% detection efficiencies. Horizontal dashed lines show 10%, 50%, and 90% detection efficiencies. The left panel shows the efficiencies for 10 CCSN models derived from multidimensional CCSN simulations. The rotating models are marked with open markers. The right panel provides the detection efficiencies for the long-lasting bar-mode model for various peak frequencies and durations, assuming $I_{zz}\epsilon = 0.1 \times 10^{45}\,\mathrm{g\,cm^2}$. The Galactic Center (GC), Large Magellanic Cloud (LMC) and M101 distances are shown as references.

from Kuroda et al. (2016) [Kur+16 s15], the 15 $\mathrm{M_\odot}$ D15 model from Mezzacappa et al. (2023) [Mez+23 D15], the 20 $\mathrm{M_\odot}$ mesa20_pert model from O'Connor & Couch (2018) [Oco+18 m20p], the 18 $\mathrm{M_\odot}$ s18 model from Powell & Müller (2019) [Pow+19 s18], the 40 $\mathrm{M_\odot}$ NR model from Pan et al. (2021) [Pan+21 NR], and the 25 $\mathrm{M_\odot}$ s25 model from Radice et al. (2019) [Rad+19 s25]. For examples of progenitors at the lower mass end, we include model he3.5 from Powell & Müller (2019) [Pow+19 he3.5], which is an ultra-stripped progenitor with a 3.5 $\mathrm{M_\odot}$ helium core, and the 13 $\mathrm{M_\odot}$ s13 model from Radice et al. (2019) [Rad+19 s13].

We also include waveforms from more energetic types of explosions. We include the 50 $\mathrm{M_\odot}$ s50 model from Kuroda et al. (2022) [Kur+22 s50], as an example of a CCSN explosion powered by a first-order quantum-chromodynamics phase transition. We include several rotating models, as the rotation can significantly increase the GW amplitude. They are the 40 $\mathrm{M_\odot}$ model SR from Pan et al. (2021) [Pan+21 SR], the 15 $\mathrm{M_\odot}$ s15fr model from Andresen et al. (2019) [And+19 s15fr], and the 39 $\mathrm{M_\odot}$ helium star model m39 from Powell & Müller (2020) [Pow+20 m39]. We also include a few models that include both rapid rotation and magnetic fields, as this can result in powerful magnetorotational explosions. They are the 39 $\mathrm{M_\odot}$ m39_B12 model from Powell et al. (2023) [Pow+23 B12], and model 3d_signal_O from Obergaulinger & Aloy (2020) [Obe+20 signal_O].

We also consider a phenomenological emission model related to the development of long-lasting bar-mode instabilities inside the proto-neutron star (PNS) (Ott 2010; Gossan et al. 2016). Assuming the PNS is well modelled as a triaxial ellipsoid rotating around the z axis, one can approximate the GW emission with sine-Gaussian waveforms

$$\begin{aligned} h_+(t) &= \frac{1}{2}\ h_0\ (1+\cos^2\iota)\ \mathrm{e}^{\frac{-t^2}{\tau^2}}\ \cos(2\pi f_0 t)\ , \\ h_\times(t) &= h_0\ \cos\iota\ \mathrm{e}^{\frac{-t^2}{\tau^2}}\ \sin(2\pi f_0 t)\ , \end{aligned} \tag{1}$$

where

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

I_{zz} and ϵ are the moment of inertia and ellipticity of the ellipsoid, f_0 is twice the rotation frequency, D is the source distance and ι is the inclination angle of the z axis with respect to the line of sight. $I_{zz}\epsilon$ is a free parameter. Throughout the paper, we consider the canonical value for neutron stars $I_{zz} = 10^{45}\,\mathrm{g\,cm^2}$ (Paschalidis & Stergioulas 2017) and we fix ϵ to 0.1 to estimate the sensitivity of the search. This order-of-magnitude estimate of ϵ has been derived from simulations in which bar-mode instabilities at low rotational kinetic energy over gravitational potential energy ratio (T/|W|) are present (Shibagaki et al. 2020; Bugli et al. 2020).

4. RESULTS

4.1. *Search result and background estimation*

The detector data contains a variety of transient noise sources that contribute to the search background. To assess the significance of each trigger, we compute the false-alarm rate (FAR), which estimates the frequency of noise triggers mistakenly identified as potential GW events. Within the on-source window, the trigger with the lowest FAR is considered a GW event candidate. In this search, the lowest FAR event candidate has a FAR of 2.11 per day, giving a false-alarm probability of

$1 - e^{-T_{\rm obs}\times{\rm FAR}} = 0.75$; i.e., a probability of 0.75 that noise alone would produce a trigger of this FAR or lower ($T_{\rm obs} = 0.68$ days). This suggests that this trigger is likely due to noise.

4.2. *Detection efficiency vs distance*

To evaluate the search sensitivity, we take the signal models described in Sec. 3.2 and randomize the source orientation such that it is uniformly distributed over a sphere. Then we add waveforms to the detector coincident data within the on-source window for the sky location of SN 2023ixf. We compute the search detection efficiency, defined as the fraction of detected signals with FAR lower than that of the lowest-FAR trigger found in the on-source window. Fig. 2 shows the detection efficiencies as a function of distance to a source in the direction of SN 2023ixf. We also plot the distances to the Galactic Center (∼ 8.5 kpc), the Large Magellanic Cloud (∼ 49.6 kpc) that hosted SN 1987A and the distance to M101. Table 1 shows the distances corresponding to a 50% detection efficiency for all 14 CCSN models. The distances reach up to 16.8 kpc for the non-rotating explosions. Detection capabilities for the Kur+16 s15, Pow+18 s18, Rad+19 s25, and Pan+21 NR models exceed the Galactic Center. The distances for the more extreme models are around an order of magnitude larger than for the non-rotating explosions. The Pow+23 B12 model reaches the distance of the Large Magellanic Cloud with 51.0 kpc. On the other hand, an explosion driven by a first-order quantum-chromodynamics phase transition (Kur+22 s50) an explosion driven by a first-order quantum-chromodynamics phase transition (Kur+22 s50)could be observed up to around 11.6 kpc.

The right panel in Fig. 2 shows the detection efficiency for long-lasting bar-mode waveforms with frequencies between 82 Hz and 2 kHz and signal durations between 1 ms and 1 s. The sensitivity distance, defined as the distance for which an efficiency of 50% is reached, increases with the signals' peak frequency and duration, up to a few Mpc. For example, a source emitting at 2 kHz for 1 s could have been detected in this search above the threshold with an efficiency of 50% up to 1.5 Mpc. This distance reach, lower than the distance to SN 2023ixf, depends linearly on $I_{zz}\epsilon$ which is fixed to 0.1×10^{45} g cm^2 but could be actually larger.

5. CONSTRAINTS

Assuming the GW emission occurred when coincident data are available in the on-source window, we establish constraints on several quantities characterizing a core collapse, including emitted GW energy, luminosity, and PNS ellipticity, considering the long-lasting bar-mode models.

Table 1. Distance of the 50% detection efficiency reached with CCSN waveform models. Values in bold represent the farthest distance reached for each family of models.

Waveform Models		Distance [kpc]
Non-rotating models	Kur+16 s15	**16.8**
	Mez+23 D15	5.0
	Oco+18 m20p	2.0
	Pow+19 s18	9.3
	Pow+19 he3.5	4.7
	Rad+19 s13	1.2
	Rad+19 s25	10.5
	Pan+21 NR	12.4
Rotating models	And+19 s15fr	3.8
	Obe+20 Signal_O	28.4
	Pan+21 SR	38.3
	Pow+20 m39	46.7
	Pow+23 B12	**51.0**
Phase transition model	Kur+22 s50	**11.6**

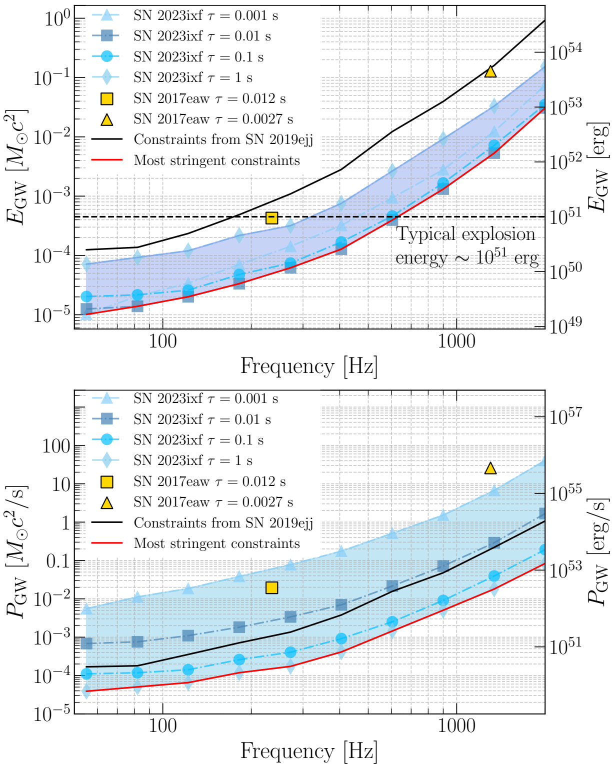

Figure 3. GW energy ($E_{\rm GW}$) and luminosity ($P_{\rm GW}$) as a function of the frequency for bar-mode signals with a detection efficiency of 50% and a FAR of 2.04 per day. The shaded region contains combined results from all analyzed models for SN 2023ixf.

5.1. *Constraints on GW energy and luminosity*

Assuming a rotating core, the emitted GW energy is (Sutton 2013)

$$E_{\rm GW} = \frac{2}{5}\frac{\pi^2 c^3}{G} D^2 f_0^2 h_{\rm rss}^2\,, \tag{3}$$

where $h_{\rm rss}$ is the source root-sum-squared GW strain for an optimally oriented source.

The GW luminosity is the ratio between the emitted GW energy and the duration of the emission. We define the duration as the time interval τ_{90} that contains 90% of the energy such that the GW power is given by

$$P_{\rm GW} = \frac{0.9\ E_{\rm GW}}{\tau_{90}}\,. \tag{4}$$

For the sine-Gaussians of Eq. (1) $\tau_{90} = 1.65\ \tau$. Considering 50% detection efficiency we derive constraints on $E_{\rm GW}$ and $P_{\rm GW}$ shown in Fig. 3. The shaded region contains results from all long-lasting bar-mode models that are compared to the typical CCSN explosion energy of around 10^{51} erg, which can be as high as 5×10^{52} erg for hypernovae (Nomoto et al. 2010; Tanaka et al. 2009; Utrobin & Chugai 2011). At 50 Hz the more stringent energy constraints are $\sim 1 \times 10^{-5}\,{\rm M_\odot c^2}$. Fig. 3 also shows the constraints derived from SN 2019ejj, located at 15.7 Mpc (Szczepańczyk et al. 2024) and from SN 2017eaw located at 6.7 Mpc (Abbott et al. 2020a). The constraints with SN 2023ixf are ~ 21 times more stringent than for SN 2019ejj over the whole frequency range. For the emitted GW luminosity shown in the bottom panel, the constraints are $4 \times 10^{-5}\,{\rm M_\odot c^2/s}$ for signals at 50 Hz and 1 s long. They are a factor of ~ 8 more stringent compared to the SN 2019ejj over the whole frequency range.

5.2. *Constraints on PNS ellipticity*

As shown in Sec. 3.2, the amplitude of the GW signal emitted by a rotating PNS can be parametrized by its ellipticity and its moment of inertia given by the relation

$$I_{zz}\epsilon = \frac{Dc^4}{G(2\pi f_0)^2}\left(\frac{2}{\pi\tau^2}\right)^{1/4} h_{\rm rss}. \tag{5}$$

Fig. 4 reports the ellipticity for a range of bar-mode GW signal frequencies and durations for a detection efficiency of 50%. The most stringent constraints on ellipticity are obtained for the signals with $\tau = 1$ s, ranging from 1×10^3 at the lowest search frequency to 1.04 at 2 kHz. The ϵ constraints get stricker with shorter signals. Over the whole frequency range, the constraints given by SN 2023ixf on the ellipticity are ~ 2.6 more stringent than for SN 2019ejj.

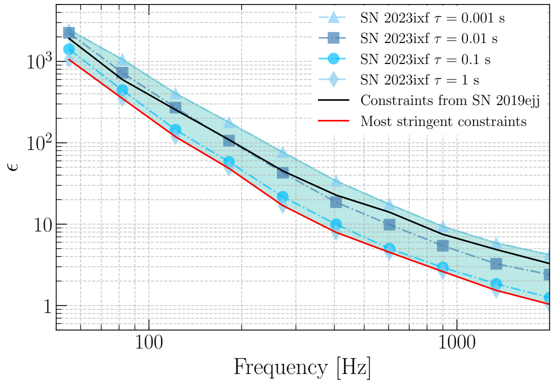

Figure 4. PNS ellipticity as a function of the frequency for bar-mode signals with a detection efficiency of 50% and a FAR of 2.04 per day. The moment of inertia I_{zz} is fixed to $10^{45}\,{\rm g\,cm^2}$. The shaded region contains combined results from all analyzed bar-mode models for SN 2023ixf.

6. SUMMARY AND DISCUSSION

We present the results of a search for GW signals coincident with SN 2023ixf, which was observed during the LIGO-Virgo-KAGRA Engineering Run 15, 2023 April 24 to 2023 May 24. No significant GW candidates were identified within the $\sim 14\,\%$ of the on-source window where coincident good quality GW data are available. With different CCSN waveform models, we quantify the search sensitivity by estimating the distances at which 50% of the GW simulated signals are detected. The reported distances are up to 16.8 kpc for non-rotating explosions, and up to 51.0 kpc for rapidly rotating models. These distance sensitivities have been obtained using the FAR of 2.04 per day from the most significant event found by the search. We derive constraints on the GW energy, luminosity, and PNS ellipticity, which are the most stringent that GW detector data have achieved to date. Assuming the PNS is well modelled as a rotating triaxial ellipsoid whose moment of inertia along the rotation axis is fixed to I_{zz}=$10^{45}\,{\rm g\,cm^2}$, we find that the ellipticity should be lower than 1.04. This value, obtained for an hypothetical 1 s-long signal at 2 kHz, is within the order of magnitude of plausible estimates derived from simulations where bar-mode instabilities are present (Obergaulinger & Aloy 2021; Bugli et al. 2023).

Despite the large distance of SN2023ixf, this event probes regions of the bar-mode instabilities parameter space that are physically interesting. On the other hand, in the case of a neutrino-driven, magnetorotational or more exotic explosion model such as first-order quantum-chromodynamics phase transition, we show that for detecting GWs from CCSNe, events within the Local group are still the best prospect.

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 - CentroNazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by the European Union NextGenerationEU, the Comunitat Autonòma de les Illes Balears through the Direcció General de Recerca, Innovació i Transformació Digital with funds from the Tourist Stay Tax Law ITS 2017-006, the Conselleria d'Economia, Hisenda i Innovació, the FEDER Operational Program 2021-2027 of the Balearic Islands, 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 Hungary (NKFIH), the National Research Foundation of Korea, the Natural Science and Engineering Research Council Canada, 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 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 2905: JP17H06358, JP17H06361 and JP17H06364, JSPS Core-to-Core Program A, Advanced Research Networks, JSPS Grants-in-Aid for Scientific Research (S) 17H06133 and 20H05639, JSPS Grant-in-Aid for Transformative Research Areas (A) 20A203: JP20H05854, the joint research program of the Institute for Cosmic Ray Research, the University of Tokyo, the National Research Foundation (NRF), the Computing Infrastructure Project of 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 Rising Star Program and Science Vanguard Research Program, the Advanced Technology Center (ATC) of NAOJ, and the Mechanical Engineering Center of KEK.

We would like to thank all of the essential workers who put their health at risk during the COVID-19 pandemic, without whom we would not have been able to complete this work.

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