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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 19, 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 gravitational-wave 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 $1 \times 10^{-4}\,M_\odot c^2$ and luminosity $2.6 \times 10^{-4}\,M_\odot c^2\,\mathrm{s}^{-1}$ for a source emitting at 82 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 1.08, at frequencies above 1200 Hz, surpassing past results.

Unified Astronomy Thesaurus concepts: Gravitational waves (678)

1. Introduction

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

Core-collapse supernovae (CCSNe) are the explosions of massive stars—masses above 8 $M_\odot$ at the end of their evolution—leading to the production of neutron stars and black holes (A. Burrows et al. 1995; K. Kotake et al. 2006; H.-T. Janka 2012). CCSNe are astrophysical sources with multimessenger emission, having historically been observed over the electromagnetic spectrum and, for SN 1987A, also with low-energy neutrinos (R. M. Bionta et al. 1987; K. Hirata et al. 1987; E. N. 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

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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 (H.-T. 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 (S. E. Gossan et al. 2016; R. Abbott et al. 2021c; M. J. Szczepańczyk et al. 2021). The most likely opportunity for observations are Galactic CCSNe, but the expected rate is of the order of one or two per century (S. V. Bergh & G. A. Tammann 1991; E. Cappellaro et al. 1993; G. A. Tammann et al. 1994; R. Diehl et al. 2006; W. Li et al. 2011; S. M. 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 (B. P. Abbott et al. 2016b, 2020; M. J. 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 (J. Aasi et al. 2015; F. Acernese et al. 2015; T. Akutsu et al. 2021). In this article, 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 Multimessenger Observations

SN 2023ixf (R.A. = 14:03:38.562, decl. = +54:18:41.94, J2000) was discovered on 2023 May 19 by K. 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 Section 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 prediscovery observations. SN 2023ixf was quickly classified as a type II supernova a few hours after the discovery (D. A. Perley et al. 2023). Due to its prompt discovery and short 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 (D. Hiramatsu et al. 2023; G. Hosseinzadeh et al. 2023; L. A. Sgro et al. 2023; R. S. Teja et al. 2023; M. Yamanaka et al. 2023; G. Li et al. 2024). The early spectroscopic observations show flash ionization features of hydrogen, helium, nitrogen, and carbon, and an increase in temperature not explained by pure shock cooling, suggesting a delayed shock breakout in a dense circumstellar medium (E. Berger et al. 2023; K. A. Bostroem et al. 2023; B. W. Grefenstette et al. 2023; D. Guetta et al. 2023; D. Hiramatsu et al. 2023; G. Hosseinzadeh et al. 2023; W. V. Jacobson-Galan et al. 2023; C. D. Kilpatrick et al. 2023; M. Koenig 2023; Z. Niu et al. 2023; J. L. Pledger & M. M. Shara 2023; N. Smith et al. 2023; R. S. Teja et al. 2023; S. S. Vasylyev et al. 2023; M. Yamanaka et al. 2023; M. C. Bersten et al. 2024; P. Chandra et al. 2024; G. Li et al. 2024; L. Martinez et al. 2024; K. Murase 2024; Y.-J. Qin et al. 2024; S. D. Van Dyk et al. 2024; D. Xiang et al. 2024; E. A. Zimmerman et al. 2024). The earliest detections of X-ray and radio emission occurred four days (B. W. Grefenstette et al. 2023) and one month (D. Matthews et al. 2023) after the discovery, respectively. The hard X-ray (B. W. Grefenstette et al. 2023) and soft X-ray (P. Chandra et al. 2024; S. Panjkov 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 (G. Marti-Devesa 2023) or in neutrinos (R. Abbasi et al. 2023; M. Nakahata & Super-Kamiokande Collaboration 2023; J. Thwaites et al. 2023).

2.2. Nature and Mass of Progenitor

A large set of M101 prediscovery imaging observations from ground-based telescopes, the Hubble Space Telescope, and the 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 $M_{\odot}$ (Y. Dong et al. 2023; N. Flinner et al. 2023; D. Hiramatsu et al. 2023; J. E. Jencson et al. 2023; J. M. M. Neustadt et al. 2023; Z. Niu et al. 2023; J. L. Pledger & M. M. Shara 2023; M. D. Soraisam et al. 2023; L. Ferrari et al. 2024; T. J. Moriya & A. Singh 2024; C. L. Ransome et al. 2024; S. D. Van Dyk et al. 2024; D. Xiang et al. 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 (Y. Dong et al. 2023; N. Flinner et al. 2023; J. E. Jencson et al. 2023; J. M. M. Neustadt et al. 2023; M. D. Soraisam et al. 2023; C. L. Ransome et al. 2024), while detecting amplitude pulsations (C. D. Kilpatrick et al. 2023; M. D. Soraisam et al. 2023).

2.3. M101 Distance

The distance of the supernova host galaxy is relevant to constrain the GW energy emitted. 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 Extragalactic Database (G. Helou et al. 1991), a total of 115 measurements using 12 different methods: Cepheids, planetary nebulae luminosity function, supernova Ia, tip of the 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 of 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 nondetections before the rise to peak brightness as shown in Figure 1. The first detection is at MJD = 60082.82611, at a CV magnitude of 18.76 ± 0.25 (V. Chufarin et al. 2023), following the last prediscovery observation at MJD = 60082.66041667, clear magnitude > 20.4 (Y. 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, which occurs at

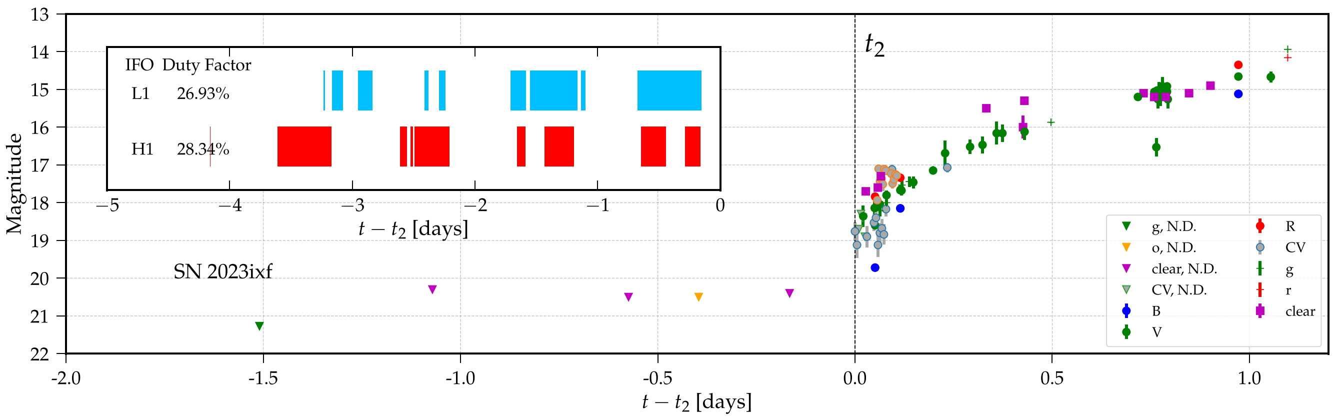

Figure 1. Early evolution of SN 2023ixf covering different photometric bands (B, V, R, g, o) and unfiltered observations (CV, clear); N.D. marks nondetections; inset: duty cycle of LIGO Hanford (H1) and Livingston (L1) detectors within the on-source window described in the text. Photometric data sources: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

a time between t_2 and the latest prediscovery observation. The time delay depends on many properties of the progenitor, including its mass. Considering the large spread in mass estimations and the relation between mass and time delay found by B. L. Barker et al. (2022, Figure 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 LIG. 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 collected 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 toward 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 that in previous observing runs (L. 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 day.

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 (R. 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) (D. Davis et al. 2021) and represent 15% of the coincident time within the on-source window. This gives the analysis time of ∼0.68 day.

3. Search

3.1. Coherent WaveBurst

We use coherent WaveBurst, a model-agnostic search algorithm, for the detection and reconstruction of transient GW signals (S. 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 (M. J. Szczepańczyk et al. 2023), spectrograms were obtained with the Wilson–Daubechies–Meyer wavelet transform (V. Necula et al. 2012). The SN 2023ixf analysis uses the high-resolution wavescan transform (S. 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 T. Mishra et al. (2025). 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 (S. Klimenko et al. 2016). To further separate GW signals from the noise, the triggers are then reranked with a reduced statistic $\eta_r = \eta_0 \times W_{XGB}$, where W_{XGB} is the XGBoost classification penalty factor, which ranges between 0 (noiselike) and 1 (signal-like) (T. Mishra et al. 2021; M. J. Szczepańczyk et al. 2023). For this search, the XGBoost algorithm uses the sky location of SN 2023ixf 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, which span the expected progenitor parameter space. For nonrotating sources we use the 15 $M_\odot$ SFHx s15 model from T. Kuroda et al. (2016; Kur+16 s15), the 15 $M_\odot$ D15 model from A. Mezzacappa et al. (2023; Mez+23 D15), the 20 $M_\odot$ mesa20_pert model from E. P. O'Connor & S. M. Couch (2018; Oco+18 m20p), the 18 $M_\odot$ s18 model from J. Powell & B. Müller (2019; Pow+19 s18), the 40 $M_\odot$ nonrotating (NR) model from K.-C. Pan et al. (2021; Pan+21 NR), and the 25 $M_\odot$ s25 model from D. Radice et al. (2019; Rad+19 s25). For examples of progenitors at the lower mass end, we include model he3.5 from J. Powell & B. Müller (2019; Pow+19 he3.5), which is an ultrastripped progenitor with a 3.5 $M_\odot$ helium core, and the 13 $M_\odot$ s13 model from D. Radice et al. (2019; Rad+19 s13).

We also include waveforms from more energetic types of explosions. We include the 50 $M_\odot$ s50 model from T. 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 $M_\odot$ model SR from K.-C. Pan et al. (2021; Pan+21 SR), the 15 $M_\odot$ s15fr model from H. Andresen et al. (2019; And+19 s15fr), and the 39 $M_\odot$ helium star model m39 from J. Powell &

B. Müller (2020; Pow+20 m39). We also include two models that include both rapid rotation and magnetic fields, as this can result in powerful magnetorotational explosions. They are the 39 $M_\odot$ m39_B12 model from J. Powell et al. (2023; Pow+23 B12) and model 3d_signal_O from M. Obergaulinger & M. A. 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; C. D. Ott 2010; S. E. Gossan et al. 2016). Assuming the PNS is well modeled as a triaxial ellipsoid rotating around the z-axis, one can approximate the GW emission with sine-Gaussian waveforms

$$h_+(t) = \frac{1}{2}h_0[1 + \cos^2\iota]e^{-t^2/\tau^2}\cos(2\pi f_0 t),$$
$$h_\times(t) = h_0 \cos\iota\, e^{-t^2/\tau^2}\sin(2\pi f_0 t), \quad (1)$$

where

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

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 $I_{zz} = 10^{45}$ g cm^2 (V. Paschalidis & N. Stergioulas 2017) and keep ϵ as a free parameter.

4. Results

4.1. Search Result and Background Estimation

The detector data contain 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 event candidate with the lowest FAR 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 ($T_{\rm obs} = 0.68$ day). This suggests that this trigger is likely due to noise.

4.2. Detection Efficiency

To evaluate the search sensitivity, we take the signal models described in Section 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 1 event in 10 years. This FAR corresponds to a false-alarm probability of 1.9×10^{-4}. At the distance of SN 2023ixf none of the 14 models from numerical simulations are detected. In Table 1 we report the distance at which we recover 90% of the added signals for all 14 CCSN models. The distances reach up to 6.9 kpc for the nonrotating explosions, which means that signals from nonrotating or slowly rotating progenitor CCSNe could be missed within the Galaxy for sources further than the Galactic center. The distances for the more extreme models are around a factor of 4 larger than for the nonrotating explosions, exceeding the Galaxy boundaries—29.9 kpc for model Pow+23 B12—but without reaching the distance of the Large Magellanic Cloud. Finally, for the explosion driven by a first-order quantum-chromodynamics phase transition, a detection of 90% is never achieved because only one polarization is extracted from the 2D numerical simulations.

Table 1
Distance of the 90% Detection Efficiency Reached with CCSN Waveform Models for a FAR of 1 Event in 10 Years

Waveform Models		Distance (kpc)
Nonrotating models	Kur+16 s15	**6.9**
	Mez+23 D15	2.9
	Oco+18 m20p	1.0
	Pow+19 s18	5.5
	Pow+19 he3.5	2.8
	Rad+19 s13	0.6
	Rad+19 s25	5.8
	Pan+21 NR	6.6
Rotating models	And+19 s15fr	1.8
	Obe+20 Signal_O	13.4
	Pan+21 SR	18.2
	Pow+20 m39	19.6
	Pow+23 B12	**29.9**
Phase transition model	Kur+22 s50	8.9*

Note. Values in bold represent the farthest distance reached for each family of models. For the model 2D Kur+22 s50, detection efficiency remains lower than 90% whatever the distance because there is only one polarization. We report the 50% detection efficiency instead, which is marked with *.

Figure 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 right plot is as a function of $I_{zz}\epsilon$ for a source at the location of SN 2023ixf. The left plot is as a function of distance for $I_{zz}\epsilon \sim 0.1 \times 10^{45}$ g cm^2. The sensitivity increases with the signal's peak frequency and duration. For instance, we could detect at 90% confidence level a signal lasting 1 s at 2 kHz for $I_{zz}\epsilon \sim 10^{45}$ g cm^2. For lower frequencies, if we assume the canonical value $I_{zz} \sim 10^{45}$ g cm^2, the source would need to be highly deformed ($\epsilon \gg 1$).

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 model. These bar-mode instabilities are sometimes present in simulations at a low ratio of rotational kinetic energy to gravitational potential energy ($T/|W|$).

5.1. Constraints on GW Energy and Luminosity

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

$$E_{\rm GW} = \frac{2}{5}\frac{\pi^2 c^3}{G}D^2 f_0^2\int_{-\infty}^{\infty}[h_+^2(t) + h_\times^2(t)]\quad dt$$
$$= \frac{2}{5}\frac{\pi^2 c^3}{G}\sqrt{\frac{\pi}{2}}\,\tau D^2 f_0^2\, h_0^2 \quad (3)$$

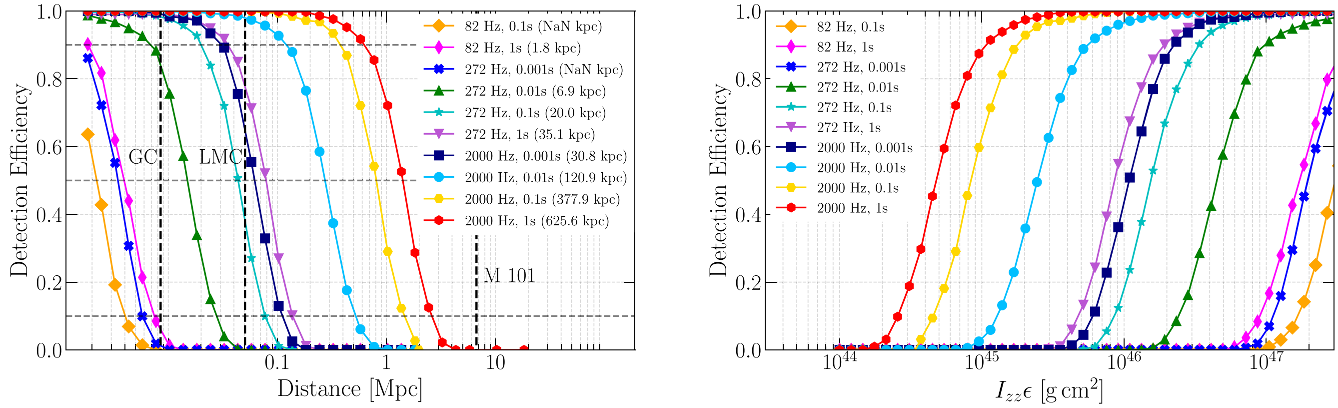

Figure 2. Detection efficiency of a GW source in the direction of M101, and within the on-source window of SN 2023ixf, for a FAR of less than 1 event in 10 years. The long-lasting bar-mode GW emission model is considered for various peak frequencies and durations. In the left panel $I_{zz}\epsilon$ is fixed to 0.1×10^{45} g cm^2 and the detection efficiency is shown as function of the distance to the source. Horizontal dashed lines show 10%, 50%, and 90% detection efficiencies, and the distances of the Galactic center (GC), Large Magellanic Cloud (LMC), and and M101 are shown as references. On the right panel, the distance is fixed to M101 and the detection efficiency is shown as function of $I_{zz}\epsilon$.

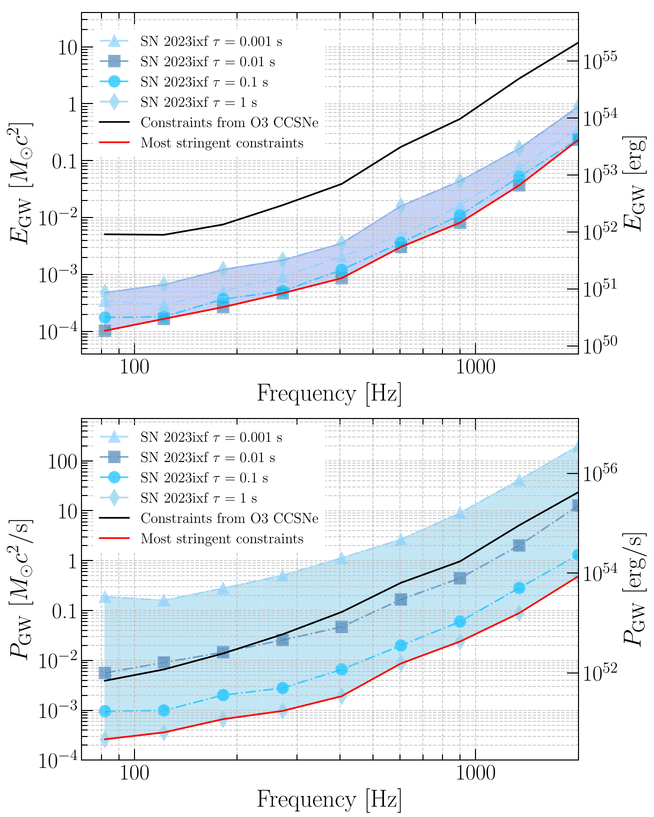

Figure 3. GW energy ($E_{\rm GW}$) and luminosity ($P_{\rm GW}$) as a function of the frequency for bar-mode signals with a detection efficiency of 90% and a FAR of 1 event in 10 years. The shaded region contains combined results from all analyzed models for SN 2023ixf.

where the GW strain squared integral is computed 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 average luminosity is given by

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

For the sine-Gaussians of Equation (1) $\tau_{90} = 1.65\tau$. Considering the h_0 value corresponding to 90% detection efficiency, we derive constraints on $E_{\rm GW}$ and $P_{\rm GW}$ shown in Figure 3. The shaded region contains results from all long-lasting bar-mode models. At 82 Hz the more stringent energy constraints are $\sim 1 \times 10^{-4} M_\odot c^2$. Figure 3 also shows the constraints derived from GW searches targeting CCSNe during the third observing run (O3) of the LIGO–Virgo–KAGRA network. The constraints with SN 2023ixf are ∼49 times more stringent than for O3 CCSNe over the whole frequency range. For the average emitted GW luminosity shown in the bottom panel, the constraints are $2.6 \times 10^{-4} M_\odot c^2\,{\rm s}^{-1}$ for signals at 82 Hz and 1 s long. They are a factor of ∼36 more stringent than for the O3 CCSNe over the whole frequency range. This upper limit is between two and five orders of magnitude larger than the average GW luminosity predicted by numerical simulations for the different explosion mechanisms (M. J. Szczepańczyk et al. 2021), showing that we could soon exclude some of the most optimistically luminous models with a closer CCSN. It is also ∼7 orders of magnitude larger than the bolometric luminosity reported by E. A. Zimmerman et al. (2024).

5.2. Constraints on PNS Ellipticity

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

$$I_{zz}\,\epsilon = \frac{Dc^4}{G(2\pi f_0)^2} h_0. \tag{5}$$

Figure 4 reports the ellipticity for a range of bar-mode GW signal frequencies and durations for a detection efficiency of 90%. The most stringent constraints on ellipticity are obtained for the signals with $\tau = 1$ s, ranging from 3.6×10^2 at the lowest search frequency to 1.08 at 2 kHz. The ϵ constraints get stricter with longer signals. Over the whole frequency range, the constraints given by SN 2023ixf on the ellipticity are $\sim 6.8\times$ more stringent than for O3 CCSNe.

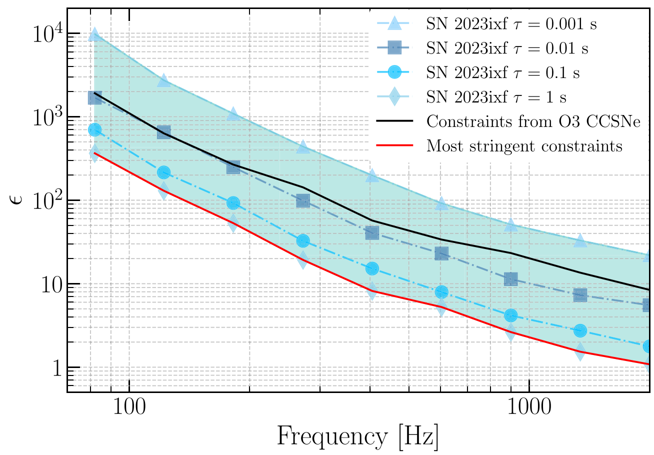

Figure 4. PNS ellipticity as a function of the frequency for bar-mode signals with a detection efficiency of 90% and a FAR of 1 per 10 years. The moment of inertia I_{zz} is fixed to 10^{45} g cm^2. The shaded region contains combined results from all analyzed bar-mode models for SN 2023ixf.

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 ∼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 90% of the simulated GW signals are detected. The reported distances are up to 6.9 kpc for nonrotating explosions, and up to 29.9 kpc for rapidly rotating models. These distance sensitivities have been obtained using the FAR of 1 event in 10 years. We derive constraints on the GW energy, luminosity, and PNS ellipticity, which are the most stringent than GW detector data have achieved to date. Assuming the PNS is well modeled as a rotating triaxial ellipsoid whose moment of inertia along the rotation axis is fixed to $I_{zz} = 10^{45}$ g cm^2, we find that the ellipticity should be lower than 1.08. This value, obtained for a hypothetical 1 s long signal at 2 kHz, is one order of magnitude larger than plausible estimates (∼0.1) derived from simulations where bar-mode instabilities are present (M. Obergaulinger & M. A. Aloy 2021; S. Shibagaki et al. 2021; M. Bugli et al. 2023).

Despite the large distance of SN 2023ixf, this event probes regions of the parameter space for bar-mode instabilities that are physically interesting. On the other hand, in the case of a neutrino-driven, magnetorotational or more exotic explosion model such as a first-order quantum-chromodynamics phase transition, we show that for detecting GWs from CCSNe, events within the Local Group are still the best prospect.

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