Joint LIGO and TAMA300 Search for Gravitational Waves from Inspiralling Neutron Star Binaries

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We search for coincident gravitational wave signals from inspiralling neutron star binaries using LIGO and TAMA300 data taken during early 2003. Using a simple trigger exchange method, we perform an inter-collaboration coincidence search during times when TAMA300 and only one of the LIGO sites were operational. This data set is complementary to that used in the LIGO S2 search. The observation time of the search is 648 hours. We find no evidence of any gravitational wave signals. We place an observational upper limit on the rate of binary neutron star coalescence with component masses between 1 and $3M_\odot$ of 49 per year per Milky Way equivalent galaxy at a 90% confidence level.

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The first generation of gravitational wave interferometric detectors are rapidly approaching their design sensitivities. These include the LIGO [1] and TAMA300 [2] detectors as well as GEO [3] and Virgo [4]. Inspiralling binaries of neutron stars and/or black holes are one of the most promising sources of gravitational radiation for these detectors. Indeed, several searches for such signals have already been completed [5, 6, 7, 8]. In the long term, the chances of detecting gravitational waves from a binary inspiral are greatly improved by making optimal use of data from all available detectors. The immediate benefit of a multi-detector coincidence search is a significant reduction in the the false alarm rate for a fixed detection efficiency. Additionally, a search involving all available detectors will provide an increase in observation time when, for example, at least two detectors are operating. The different orientations of the detectors make them sensitive to different parts of the sky, thus a combined search can lead

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to improved sky coverage. If an event is detected in multiple instruments it is possible to localize the position of the source and improve parameter estimation. In addition, independent observations in well-separated detectors using different hardware and analysis algorithms would increase confidence in a detection, while reducing the possibility of an error or bias. In this paper, we present the first inter-collaboration search for gravitational waves from the binary inspiral of neutron stars. This represents an important step towards a global network analysis of gravitational wave data.

The joint coincidence search described here uses data from the second LIGO science run (S2) which occurred at the same time as the eighth TAMA300 data taking run (DT8) in 2003. The LIGO S2 data have already been searched for gravitational waves from binary neutron stars [7]. That search used only data in which both of the LIGO sites were operational. In this paper, we report on a coincidence search between LIGO and TAMA300 data on a complementary data set, when only one LIGO site was operating in coincidence with the TAMA300 detector. By performing this joint search between the LIGO and TAMA collaborations, we are able to significantly increase in the length of time searched in coincidence during the S2/DT8 run. The data from each of the detectors are searched independently for event candidates, or "triggers". These triggers are then exchanged between collaboration members and searched for coincidence. The coincidence requirements of the search are determined by adding simulated signals to the data streams of the detectors, and determining the accuracy with which various parameters are recovered [9]. The exchange of single instrument triggers and subsequent coincidence analysis is quite simple and does not involve the exchange of large amounts of interferometer data. It provides a natural first step in an inter-collaboration analysis. If an interesting candidate event were found, it would then be followed up by an optimal, fully coherent analysis of the data around the time of the candidate. In this joint LIGO–TAMA300 search, we find no evidence of any inspiral signals in the data and so we place an observational upper limit on the rate of binary neutron star coalescence in the Milky Way galaxy.

The LIGO network of detectors consists of a 4km interferometer "L1" in Livingston, LA and a 4km "H1" and a 2km "H2" interferometer which share a common vacuum system in Hanford, WA. TAMA300 is a 300m interferometer "T1" in Mitaka, Tokyo. Basic information on the position and orientation of these detectors and detailed descriptions of their operation can be found in Refs. [1, 2]. The data analyzed in this search was taken during LIGO S2, TAMA300 DT8 between 16:00 UTC 14 February 2003 and 16:00 UTC 14 April 2003. We only analyze data from the periods when both LIGO and TAMA300 interferometers were operating. Furthermore, we restrict to times when only one of the LIGO sites was operational. Therefore, we have four independent data sets to analyze: the data set during which neither H1 nor H2 were operating — the nH1-nH2-L1-T1 coincident data set (here "n" stands for "not operating") — and three data sets when one or both of the Hanford detectors were operational but L1 was not — the H1-H2-nL1-T1, H1-nH2-nL1-T1, and nH1-H2-nL1-T1 coincident data sets. During the S2 science run, a strong correlation was found in the L1 interferometer between glitches in the auxiliary POB_I channel and inspiral triggers. Therefore, we apply a veto to exclude times of excess noise in POB_I, details of which are given in Ref. [7]. No efficient veto channels were found for the H1, H2 or T1 detectors. After applying the veto to L1, there are 34 hours of nH1-nH2-L1-T1 data. Additionally, there are 334 hours of H1-H2-nL1-T1 data, 212 hours of H1-nH2-nL1-T1 data and 68 hours of nH1-H2-nL1-T1 data, giving a total observation time of 648 hours. The data used in this search are summarized in Figure 1. To avoid any bias from tuning our pipeline using the same data from which we derive our upper limits, the tuning of analysis parameters was done without examining the full coincident trigger sets. Instead, parameter tuning was done on the *playground* data which consists of approximately 10% of the data chosen as a representative sample. In this analysis, the length of playground data is 64 hours. The analysis of the playground data and tuning of the search is described in more detail in Ref. [9]. The playground data *was* searched for candidate gravitational wave events, but was excluded from the data set used to place the upper limit. Subtracting the playground data leaves a total of 584 hours of non-playground data used in placing the upper limit.

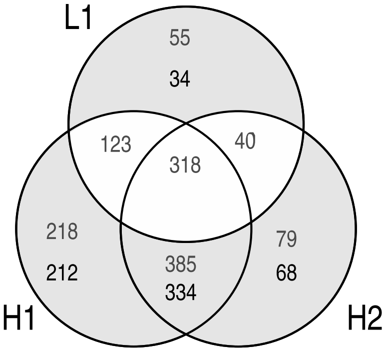

FIG. 1: The number of hours that each combination of detectors was searched during the S2/DT8 run. The upper number gives the amount of time the specific LIGO detectors were coincidentally operational. The lower number gives the total amount of time searched in coincidence with TAMA300. The shaded region corresponds to the data used in this search.

In a search for inspiralling neutron star binaries, we can characterize the sensitivity of the detectors by their maximum observable effective distance, or range. This is defined as the distance at which an inspiral of 1.4–$1.4 M_\odot$ neutron stars, in the optimal direction and orientation with respect to each detector, would produce a signal to noise ratio (SNR) of 8. The effective distance of a signal is always greater than or equal to the actual distance. On average it is 2.3 times as large as the actual distance, with the exact factor dependent upon the source location and orientation relative to the detector. During the S2 science run the ranges of the LIGO detectors, averaged over the course of the run, were 2.0, 0.9 and 0.6 Mpc for L1, H1 and H2 respectively. This made them sensitive to signals from the Milky Way and favorably oriented potential sources in the local group of galaxies. The range of TAMA300 during DT8 was 52 kpc, making it sensitive to the majority of the Milky Way. Since we require a signal to be observed in both the LIGO and TAMA300 detectors, it is natural for this search to restrict our attention to gravitational waves produced by inspiralling neutron star binaries in the Milky Way.

The search methods employed in this paper are similar to those used in the LIGO S2 search [7] and the independent TAMA300 DT8 search [10]. Therefore, in this paper we will not describe the LIGO or TAMA300 analysis pipelines in great detail, but instead emphasize the differences between this search and those described previously.

For the LIGO search, we split the data into analysis blocks of 2048 seconds length, overlapped by 128 seconds. For each chunk, we construct a template bank with a minimal match of 97% and component masses between 1 and $3M_\odot$ [11]. We analyze the data using the FINDCHIRP implementation of matched filtering for inspiral signals in the LIGO Algorithm Library [12, 13]. The most important thresholds used in the LIGO search are given in Table I. Most notably, we use an SNR threshold $\rho^* = 7$ for matched filtering. Additionally, we perform a waveform consistency (χ^2) test [14]. For this, we require the power observed in the signal to be evenly distributed between p frequency bands. The threshold is

$$\chi^2 \leq (p + \delta\,\rho^2)\xi^*\,. \tag{1}$$

Those familiar with the LIGO S2 analysis will note that we use a higher threshold on SNR (7 rather than 6) and also a tighter χ^2 threshold (5 rather than 12.5 in the Hanford detectors). This is due to the fact that we limit our attention to signals from the Milky Way which tend to be have a large SNR in the LIGO S2 data stream. The tighter thresholds vastly reduce the false alarm rate while giving a negligible loss of detection efficiency. For times during which both the H1 and H2 detectors were operational, we perform a triggered analysis of H2, as described in detail in Ref. [7]. We produce a template bank and matched filter the H1 data. Only for those times and masses that we obtain a trigger in H1 do we filter the H2 data. This significantly reduces our analysis time while having no effect on the detection efficiency. We then search for triggers coincident in time and mass between the H1 and H2 detectors. The use of a triggered search allows us to require the mass parameters of coincident triggers to be identical. Studies performed by injecting simulated signals show we can determine the end time of an inspiral to within $1\mathrm{ms}$ and consequently we use this as our time coincidence window. Finally, we implement an amplitude consistency test between triggers in H1 and H2 [7]; this includes keeping any triggers from H1 whose recovered effective distance renders them unobservable in the less sensitive H2 detector.

For the TAMA300 search, we split the data into analysis blocks of 52.4288 seconds length. The adjacent blocks of data are overlapped by 4.0 seconds in order not to lose signals which lie on the border of two adjacent blocks. We construct a template bank with a minimal-match of 97% [15] for each locked segment, in which the detector was continuously operated without any interruptions. The most significant thresholds in the TAMA300 search are listed in Table II. We use a SNR threshold $\rho^* = 7$ for matched filtering. In the TAMA300 only search, we introduce a threshold on the value of $\rho/\sqrt{\chi^2}$ to reduce the number of false alarms [10, 16]. However, in the LIGO–TAMA300 analysis, we introduce a χ^2 threshold as in Eq. (1). By cutting on χ^2, the number of triggers is significantly reduced. In addition, some of the coincidence analysis becomes much simpler since LIGO and TAMA300 use a similar criterion for χ^2. More details of the TAMA300 analysis pipeline are available in Ref. [10, 16].

Parameter	Description	value
MM	Templatebank Minimal Match	97%
ρ^*	Matched Filter Threshold	7.0
p	Number of χ^2 bins	15
δ	χ^2 threshold parameter	0.023
ξ^*	χ^2 threshold parameter	5.0
δt_{HH}	H1/H2 Timing Coincidence	1.0 ms
δm_{HH}	H1/H2 Mass Coincidence	0

TABLE I: A list of the most significant parameters used for the search of the LIGO data.

Parameter	Description	value
MM	Templatebank Minimal Match	97%
ρ^*	Matched Filter Threshold	7.0
p	Number of χ^2 bins	16
δ	χ^2 threshold parameter	0.046
ξ^*	χ^2 threshold paramater	2.3

TABLE II: A list of the most significant parameters used for the search of the TAMA300 data.

The requirements for coincidence between triggers in the LIGO and TAMA300 detectors are determined by adding simulated inspiral events to the data streams of the detectors. Thresholds are chosen so that injected signals seen separately in both the LIGO and TAMA300 detectors survive the coincidence step with near 100% efficiency, while minimizing the rate of accidental coincidences. Since both the LIGO and TAMA300 pipelines can accurately determine the coalescence time and mass of an injected signal, it is natural to require consistency of these values in our coincidence test. We measure the accuracy with which these parameters are recovered in each detector and set the coincidence window to be the sum of these accuracies. The values of time and mass coincidence parameters are given in Table III. Both pipelines recover the end time with an accuracy of 1 ms, to which we must add the light travel time between sites to obtain the values given in the table. The mass parameter most accurately recovered by the pipelines is the chirp mass of a signal. The chirp mass is defined as $\mathcal{M} = M\eta^{3/5}$, where $M = m_1 + m_2$ is the total mass of the system and $\eta = m_1 m_2/M^2$ is the dimensionless mass ratio. To pass coincidence, we require the chirp masses of two triggers to agree within $0.05M_\odot$. Further details of how these parameters were chosen are available in Ref. [9].

The coincidence parameters described above were chosen to provide a good efficiency to simulated events. However,

Parameter	Description	value
δt_{HT}	Timing between Hanford and TAMA	27.0 ms
δt_{LT}	Timing between Livingston and TAMA	35.0 ms
$\delta \mathcal{M}$	Chirp mass window	0.05 $M_{\odot}$

TABLE III: The coincidence windows used for the LIGO–TAMA300 search.

there is some chance that noise induced events in the detectors might survive our coincidence tests. In order to estimate the background of such chance coincident triggers we perform a time shift analysis [17]. To do this, we time shift the TAMA300 triggers by multiples of 5 seconds and search for coincidence between the time shifted TAMA300 triggers and LIGO triggers. We perform 100 time shifts, with a value of the time shift ranging from -250 to 250 seconds. These shifts are much longer than the light travel time between the sites, so that any coincidence cannot be from actual gravitational waves. They are also longer than the typical detector noise auto-correlation time, longer than the longest signal template duration (4 seconds) and shorter than typical timescales of detectors' non-stationarity, so that each time shift provides an independent estimate of the accidental coincident rate. The SNRs of the triggers obtained from the time shift analysis are plotted in Figure 2. The plot shows that the distribution of background coincidences does not follow the circular false alarm contours expected for Gaussian noise [18]. Instead, a statistic which more accurately reflects the constant false alarm probability contours is the sum of the SNR in the two detectors,

$$\rho_{\mathrm{C}} = \rho_{\mathrm{LIGO}} + \rho_{\mathrm{TAMA}} \,. \tag{2}$$

We use this statistic in our analysis to distinguish background triggers from detection candidates.

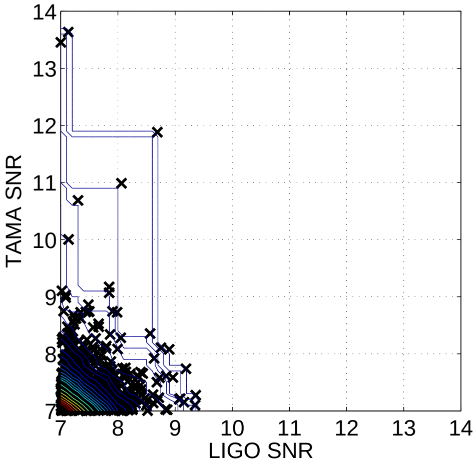

FIG. 2: The signal to noise ratios ρ_{LIGO} vs ρ_{TAMA} of the accidental coincident triggers using 100 time shifts. The contours of constant false alarm probability are also shown.

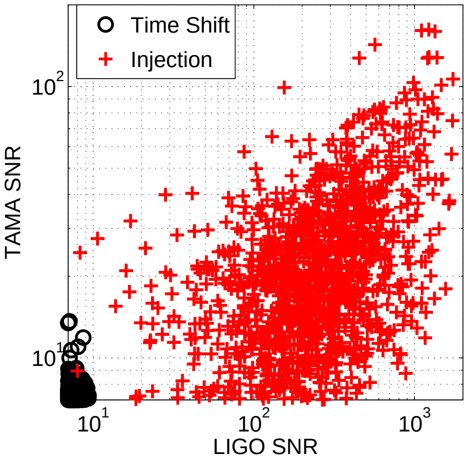

FIG. 3: The signal to noise ratios ρ_{LIGO} vs ρ_{TAMA} of the triggers associated with injections (+) and those from accidental coincidences arising in 100 time shifts (○).

To measure the sensitivity of the search, we perform a set of injections into both sets of data. The simulated waveforms added to the data consist of galactic binary neutron star inspiral signals. The majority of neutron stars in the Milky Way lie in the galactic bulge, which we take to have a radius of 4 kpc and height of 1.5 kpc. The sun is assumed to lie 8.5 kpc from the center of the galaxy. Further details of the galactic model used are available in Ref. [19]. The mass distribution is described in detail in Ref. [20]. Of the injections performed, 76% have an associated coincident trigger in the LIGO and TAMA300 detectors. The majority of the injections not detected have an effective distance at the TAMA300 site greater than TAMA300's range during DT8. However, there were also a few injections which were very poorly oriented for the LIGO detectors, and hence have a large effective distance, making them unobservable to LIGO. Finally, several injections produce triggers in both the LIGO and TAMA300 detectors but these fail our coincidence requirements. The SNRs of these triggers are close to threshold in TAMA300 and the injection parameters, in particular the chirp mass, are recovered poorly. In Figure 3 we plot the coincident triggers associated with injections superimposed on those from the time shift analysis. This shows that triggers from the found injections are well separated from the accidental coincidences found in the time shift analysis.

In Figure 4, we plot the sensitivity of the search to injected Milky Way signals. This is done by plotting the number of galaxies N_G (or equivalently the fraction of the Milky Way) the search is sensitive to as a function of the threshold on the combined statistic given in Eq. (2).

We analyze the S2/DT8 data using the pipeline described. The cumulative distribution of ρ_{C} of the coincident triggers is shown in Figure 5. On this plot, the expected number of triggers obtained from the time shift analysis is shown, as well as the standard deviation of the number of triggers obtained in the time shifts. The results of the analysis of the full data

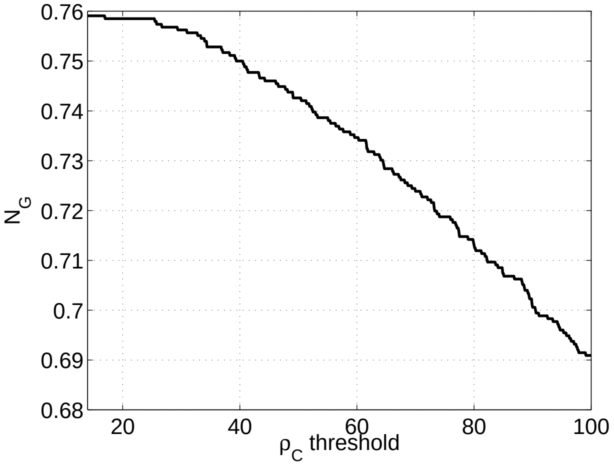

FIG. 4: The efficiency of the LIGO–TAMA300 joint analysis to simulated galactic inspiral events. The number of galaxies (N_G) to which the search is sensitive is plotted as a function of the threshold on the combined statistic ρ_{C} $(= \rho_{\mathrm{LIGO}} + \rho_{\mathrm{TAMA}})$.

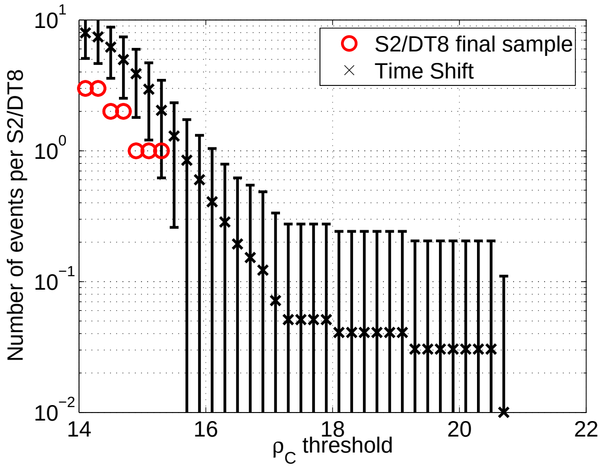

FIG. 5: The triggers from the analysis of the full LIGO–TAMA300 data set. The × represent the expected background number of triggers at or above a given combined SNR ρ_{C} based on the 100 time shifts performed. The bars indicate the standard deviation of the number of events, calculated from the time shift results. The triggers from the final S2/DT8 data set are shown as $\circ$.

are overlayed on top of this. It is clear from the figure that the distribution of coincident triggers is consistent with the background estimated from time shifts. There are no triggers with combined SNR greater than $\rho_{\max} = 15.3$. Therefore, we conclude that there is no evidence for gravitational wave signals in the LIGO–TAMA S2/DT8 data set.

Given the set of triggers displayed in Figure 5 we can obtain an upper limit on the rate of binary neutron star coalescences per year per Milky Way Equivalent Galaxy (MWEG). (Although this search is only sensitive to galactic inspiral events, we maintain the standard "MWEG" [7] for describing the upper limit). We use the loudest event statistic [21], which makes use of the detection efficiency at the combined SNR of the loudest event in order to construct the upper limit. The 90% confidence frequentist upper limit is given by

$$\mathcal{R}_{90\%} = \frac{2.303 + \ln P_b}{T N_G(\rho_{\max})} \,. \qquad (3)$$

In the above, T is the observation time of 584 hours, P_b is the probability that all background triggers have a SNR less than $\rho_{\max}$, and N_G is the number of MWEGs the search is sensitive to at the combined SNR of the loudest event $\rho_{\max}$. N_G is determined from Figure 4 to be $0.76\,\mathrm{MWEG}$ for $\rho_{\max} = 15.3$. Although the time shift analysis provides us with an estimate of $P_b = 0.2$, we note that it is difficult to establish a systematic error associated with this estimate, and therefore take the conservative choice of setting $P_b = 1$. From these numbers, we obtain an upper limit of $\mathcal{R}_{90\%} = 45\,\mathrm{y}^{-1}\,\mathrm{MWEG}^{-1}$.

The possible systematics which arise in a search for binary neutron stars are described in some detail in Ref. [7], and we will follow the analysis presented there to calculate the systematic errors for the above result. The most significant effects are due to the possible calibration inaccuracies of the detectors, the finite number of Monte Carlo injections performed, and the mismatch between our search templates and the actual waveform. We must also evaluate the systematic errors associated with the chosen astrophysical model of potential sources within the galaxy. All systematic effects in the analysis pipeline (such as less than perfect coverage of the template bank) are taken into account in the Monte Carlo estimation of the detection efficiency.

This search was sensitive to most, but not all, signals from the Milky Way. Thus, the specific model of the source distribution within the galaxy will affect the upper limit. The majority of the mass in the galaxy, and hence the potential sources, is concentrated near the galactic center. Therefore, our efficiency will be most affected by changing the distance from the sun to the center of the galaxy in the model. In this search, the sun's galactocentric distance is assumed to be $8.5\,\mathrm{kpc}$. Varying this distance between 7 and $10\,\mathrm{kpc}$ leads to a change in efficiency of $0.04\,\mathrm{MWEG}$. Different models for NS-NS formation can lead to variations in the NS mass distribution. Based on simulations with a 50% reduction in the number of binary systems with masses in the range $1.5M_\odot < m_1, m_2 < 3.0M_\odot$, we can estimate the variation in N_G to be $0.01\,\mathrm{MWEG}$

Any calibration inaccuracy in TAMA300 could have a significant effect upon our efficiency. This is clear from Figure 3 which shows a significant number of injections found in TAMA300 close to threshold. Two effects contribute to this calibration error: an overall normalization error (associated with the magnetic actuation strength uncertainty and its effect on calibration), and uncertainty in the frequency-dependent response. The error in the normalization is of order 5%, but the long-term drift is unknown, so we conservatively use 10% in this paper. The frequency-dependent error was estimated and shown to be $\ll 10\%$, so it is subsumed into the overall 10% error on the SNR of the triggers. This calibration uncertainty leads to a $0.02\,\mathrm{MWEG}$ effect on our efficiency. The majority of injections are observed well above threshold in the LIGO detectors, and consequently the calibration uncertainty of 8.5% in L1 and 4.5% in H1/H2 results in a smaller uncertainty in the efficiency of $< 0.01\,\mathrm{MWEG}$. The error in the efficiency measurement due to the finite number of injections performed is $0.01\,\mathrm{MWEG}$. Differences between the theoretical waveforms used in matched filtering the data and the real waveforms would decrease the efficiency of our search. Allowing for a 10% loss in SNR due to inaccuracies in the model waveform [22, 23, 24] leads to a $+0/-0.02\,\mathrm{MWEG}$ effect on the efficiency. Combining these effects, we obtain an efficiency of $N_G = 0.76^{+0.05}_{-0.06}$. Taking the downward excursion on N_G, we obtain a conservative upper limit of

$$\mathcal{R}_{90\%} = 49\,\mathrm{y}^{-1}\,\mathrm{MWEG}^{-1}\,. \tag{4}$$

This rate is comparable with the rate limit of $47\,\mathrm{y}^{-1}\,\mathrm{MWEG}^{-1}$ obtained from the LIGO-only S2 search [7]. The decreased sensitivity and range of the LIGO detectors in the current search is balanced by the greater analysis time.

In this paper, we have presented the results and upper limit from the joint LIGO–TAMA300 inspiral analysis of the S2/DT8 data. We see no evidence of any gravitational wave inspiral signals in the data. We conclude that the rate of binary neutron star coalescences is less than $49\,\mathrm{y}^{-1}\,\mathrm{MWEG}^{-1}$ with a 90% confidence. In addition, this is the first multi-collaboration search for gravitational waves from inspiralling binary systems. This joint analysis allows an additional 648 hours of data to be searched in coincidence. The simple trigger exchange and coincidence methods developed during this search will be further developed in future joint network searches for gravitational waves from coalescing binary systems.

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