

Search for Compact Binary Coalescences with Sub-solar Mass Components in Data from the Second Part of LIGO–Virgo–KAGRA’s Fourth Observing Run

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ABSTRACT

We report on a gravitational wave search for compact binary coalescences with secondary mass between $0.2 M_{\odot}$ and $1 M_{\odot}$ and primary mass between $0.2 M_{\odot}$ and $10 M_{\odot}$, restricting the component mass ratio to lie between 0.1 and 1. The analysis uses data collected by the LIGO and Virgo detectors between 2024 April 10 15:00:00 and 2025 January 28 17:00:00, the second part of the fourth observing run of the LIGO–Virgo–KAGRA Collaboration. Results from two out of three search pipelines show outlier candidates, but not at a sufficient level of significance to provide evidence for detection. We report the combined sensitivity of the current searches over the first and second parts of the observing run to the target sub-solar mass black hole population, as well as to neutron star binaries with one or more sub-solar component. We place upper limits on the merger rate of sub-solar mass black holes, ranging from $50 \text{ Gpc}^{-3} \text{ yr}^{-1}$ to $5000 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (90% confidence) for different component mass combinations. We use the merger rate limits to constrain two illustrative dark matter scenarios that can form sub-solar mass compact objects: primordial black holes, and dark black holes forming in a dissipative dark matter model. Our search limits the fraction of dark matter in primordial black holes, assuming a monochromatic mass distribution, to be $\leq (0.018\text{--}0.032)$ at $1 M_{\odot}$, and $\leq (0.10\text{--}0.18)$ at $0.35 M_{\odot}$ for early-forming binaries; or to be less than 1 at masses above $(0.62\text{--}0.74) M_{\odot}$ for late-forming binaries. For the dissipative model, we constrain the fraction of dark matter for a range of minimum dark black hole masses below $1 M_{\odot}$ to be as low as $(1.0\text{--}1.1) \times 10^{-5}$; we also exclude minimum masses above $(4.2\text{--}4.4) \times 10^{-2} M_{\odot}$, if dark black holes constitute all of the dark matter. For binary neutron stars that include sub-solar mass components, assuming a simple, fixed population model we find a merger rate upper limit of $249 \text{ Gpc}^{-3} \text{ yr}^{-1}$.

1. INTRODUCTION

The LIGO–Virgo–KAGRA Collaboration (LVK; Abbott et al. 2020) has published over 390 probable gravitational wave (GW) candidates from searches for compact binary coalescences (CBCs) in data from the first observing run (O1; Abbott et al. 2019a), second observing run (O2; Abbott et al. 2021, 2024), third observing run (O3; Abbott et al. 2023a), the first part of the fourth observing run (O4a; Abac et al. 2026a,b), and the second part of the fourth observing run (O4b; Abac et al. 2026a,b) of the Laser Interferometer Gravitational-Wave Observatory (LIGO; Capote et al. 2025; Ganapathy et al. 2023; Jia et al. 2024; Soni et al. 2025; Martynov et al. 2016; Harry 2010; Abbott et al. 2016a) and Virgo (Acernese et al. 2015; Virgo Collaboration 2026) detectors in the latest Gravitational-Wave Transient Catalog (GWTC) – GWTC-5.0 (Abac et al. 2026b). These can-

didates are produced by searches targeting the inspiral and merger of binary systems of compact object remnants of massive stars. Namely, binary black holes (BBHs), binary neutron stars (BNSs) and neutron star (NS)–black hole (BH) binaries (NSBHs) with component masses $\geq 1 M_{\odot}$, where the lower bound is motivated observationally by known pulsars (Martinez et al. 2015; Martinez et al. 2017; Lazarus et al. 2016; Stovall et al. 2018), and theoretically by the expectation that NS masses should lie near the Chandrasekhar limit for white dwarfs of $1.4 M_{\odot}$ as determined by the nucleon masses (Chandrasekhar 1931). Some neutron stars observed in X-ray binaries have masses of $\sim 1 M_{\odot}$ (van der Meer et al. 2007; Lattimer & Prakash 2005). Additionally, BHs produced by the gravitational collapse of massive stars are expected to have masses exceeding those of NS.

Although GW detectors are most sensitive to mergers of stellar-mass compact objects, they can also detect signals from less massive binaries of compact objects, if such systems exist in nature (Magee et al. 2018). Targeted searches for sub-solar mass (SSM) compact objects open a window into exotic formation channels that may involve physics be-

yond the standard astrophysical paradigm (Singh 2024). A key motivation for these searches is the possibility that some compact objects could be primordial black holes (PBHs), which are a candidate for dark matter (Hawking 1971; Chappell 1975; Green & Kavanagh 2021). PBHs have been proposed to contribute to the population of GW sources since the first detection of GWs: GW150914 (Abbott et al. 2016b; Bird et al. 2016; Sasaki et al. 2016; Clesse & García-Bellido 2017). They are purported to form in the early universe, and to dominate the merger rate across all redshifts with a peak around $z \gtrsim 30$, compared to the merger rate of stellar BHs, which, if it follows the star formation rate, would peak around $z \sim 1-2$ (Ng et al. 2022, 2023). Although PBHs can populate a wide mass spectrum extending above a solar mass (Carr et al. 2021), we rely on the detection of a SSM candidate to conclusively distinguish them from stellar BHs.

GW observations of BBHs can also constrain theories of dissipative dark matter and its chemistry, where dark halos collapse under gravity to form dark black holes (DBHs) in regions of sufficiently high dark matter density (Shandera et al. 2018; Abbott et al. 2023b; Singh et al. 2021). The merger rate of DBHs in this scenario is inversely proportional to the average DBH mass. Therefore, SSM BHs forming from dissipative halos could have a higher predicted merger rate than BHs forming through regular stellar evolutionary channels, which implies that SSM searches can provide strict limits on dissipative dark matter models (Shandera et al. 2018). Especially if the lowest possible DBH mass is smaller than the white dwarf Chandrasekhar limit, we can start to probe the particle nature of dissipative dark matter using SSM searches.

Additionally, models where accumulation of non-annihilating dark matter transmutes NSs to BHs with masses below the maximum NS mass have been constrained using limits on merger rates from SSM searches. Non-detections of these low-mass BHs provide upper limits on the interaction cross-section of dark matter particles with nucleons for GeV scale dark matter (Dasgupta et al. 2021; Bhattacharya et al. 2023).

Searches for binaries with SSM compact objects have been performed in data from LIGO and Virgo since Initial LIGO’s science runs (Abbott et al. 2005, 2008; Abbott et al. 2018, 2019b, 2022, 2023b; Abac et al. 2026c; Nitz & Wang 2021a,b; Phukon et al. 2021; Nitz & Wang 2022; Kacanja & Nitz 2025; Kacanja et al. 2026). LVK matched-filtering SSM searches have probed masses down to $0.2 M_{\odot}$; this parameter space was initially motivated by gravitational microlensing surveys of the Large Magellanic Cloud which suggested that $\sim 20\%$ of the Galactic halo is composed of compact objects with masses in the range $0.15 M_{\odot}$ to $0.9 M_{\odot}$ (Alcock et al. 2000). Since O2, our SSM searches have allowed for spinning components, initially with dimensionless spin magnitudes ≤ 0.1 (Abbott et al. 2019b). In O3, we allowed the

primary mass to extend up to $10 M_{\odot}$ in order to include systems with more asymmetric masses, while also increasing the maximum dimensionless spin magnitude to 0.9 for compact objects with component masses greater than $0.5 M_{\odot}$ (Abbott et al. 2022, 2023b). We keep these configuration choices unchanged in our search for SSM candidates in O4a and O4b data. Although PBH and DBH formation scenarios can populate the mass spectrum below $0.2 M_{\odot}$, the target parameter space is restricted to alleviate the computational cost of CBC matched-filtering searches, and given that the horizon distance of LIGO and Virgo detectors decreases with decreasing mass (Abbott et al. 2018; Allen et al. 2012; Fairhurst & Brady 2008).

Searches for SSMs have been conducted on publicly available data with parameter spaces that extend outside what is explored by the LVK searches. No detection has been made to date by any of the searches. With O1 and O2 data, Nitz & Wang (2021a) reports a search for SSM mergers with non-negligible orbital eccentricity, for component masses spanning $0.1 - 7 M_{\odot}$ (primary) and $0.1 - 1 M_{\odot}$ (secondary), and Nitz & Wang (2021b) reports a search for mergers of extreme mass-ratio binaries for component mass ranges of $20 - 100 M_{\odot}$ and $0.01 - 1 M_{\odot}$. Phukon et al. (2021) reports a search for mergers of a sub-solar mass component with a component with mass greater than $2 M_{\odot}$ in O2. Nitz & Wang (2022) reports searches on O3 data where the secondary component is sub-solar mass, while the primary mass extends from $0.1 - 100 M_{\odot}$, and orbital eccentricity is allowed for limited mass regions. Using O3 data, Kacanja & Nitz (2025) reports a targeted search for sub-solar mass NS binaries with component masses of $0.1 - 2 M_{\odot}$ and $0.1 - 1 M_{\odot}$, allowing for nonzero tidal deformabilities. Finally, Kacanja et al. (2026) reports the search for SSM mergers in O4a data, where the component masses are $0.1 - 2 M_{\odot}$ and $0.1 - 1 M_{\odot}$ and tidal deformabilities are included for low mass NSs.

Searches for planetary-mass compact object binaries have also been conducted recently over O3 and O4a data, taking advantage of the quasi-monochromatic evolution of the emitted GW in the LVK bandwidth to set limits on the abundance of $[10^{-7}, 10^{-2}] M_{\odot}$ PBHs (Miller et al. 2024; Abac et al. 2025a); in addition, searches for continuous gravitational waves in fourth observing run (O4) data placed limits on PBH formation considering SSM BHs in the asteroid-mass region (Abac et al. 2026d). The absence of detections in previous runs has provided useful constraints on the abundance of PBHs and on dissipative dark matter models (Abbott et al. 2023b; Abac et al. 2026c).

Low-latency SSM searches were operated for the first time in O4a, motivated by the searches’ sensitivity to typical electromagnetically-bright sources. These real-time searches were continued throughout O4 in preparation for enabling prompt follow-up of significant candidates (Alléné et al.

2025; Hanna et al. 2024). However, public alerts from low-latency SSM searches were first issued in third part of the fourth observing run (O4c), thus the corresponding candidates lie out of the scope of the present study.

By contrast, archival (offline) searches can determine the significance of candidates using the noise background collected over an entire observing run, and can undertake large-scale simulation analyses for sensitivity estimation. In this paper, we present results from the archival SSM searches performed by three pipelines: GstLAL, MBTA and PyCBC. We report their detection sensitivities for SSM BBHs and BNSs by repeating the searches on strain data from O4b with simulated signals added. By combining the search sensitivities to SSM signals in O4a and O4b, we derive limits on the merger rate of SSM BBHs, which are used to update the constraints on the fraction of dark matter in PBHs and the fraction of dark matter in DBHs. For the PBH scenario, we present constraints across the component-mass plane in addition to previously used point-mass distributions (Abbott et al. 2018, 2019b, 2022, 2023b; Abac et al. 2026c).

In addition to our constraints on specific dark matter models, following Abac et al. (2026c) we report the sensitivity of the SSM search to binaries comprising one or two low-mass NSs. SSM search templates have non-trivial overlap with BNS signals from an astrophysical population, while extending into the high-spin parameter space typically excluded in template-bank based searches for BNS (Abac et al. 2026a; Abac et al. 2026a). Matter effects involving tidal interactions of the binary components influence the signal phasing starting at an effective fifth post-Newtonian order (Flanagan & Hinderer 2008); for BNSs with super-solar masses, tidal deformations affect waveforms at ≥ 1 kHz, where LIGO and Virgo have reduced sensitivity. However, extremely large tides at low NS masses ($\leq 0.5 M_\odot$) cause dephasing below 1 kHz, which can result in significant mismatches between the BBH template waveforms and BNS signals (Bandopadhyay et al. 2023). Therefore, we extend our sensitivity estimation to include simulated signals from SSM NS mergers (Metzger et al. 2024; Chen & Metzger 2025) to determine the detection efficiency for this population.

NSs are formed in the last phases of stellar evolution, due to gravitational collapse at the endpoint of nuclear burning (Burrows & Vartanyan 2021), or in binary systems where the accretion to a white dwarf induces collapse (Nomoto & Kondo 1990). Simulations of NS formation (Suwa et al. 2018; Ertl et al. 2020; Woosley et al. 2020) predict a resulting minimum NS mass higher than $1 M_\odot$, comparable to the Chandrasekhar limit (Chandrasekhar 1931). However, lower bounds on possible NS masses based on equation of state (EoS) analysis cover a wide range, largely dependent on the type of EoS assumed; bounds for dense hot matter models are $\sim 0.7 M_\odot$ (Burgio & Schulze 2010), closer to the

Chandrasekhar limit, as compared to $\sim 0.1 M_\odot$ for cold matter models (Potekhin et al. 2013). In the case of spinning NSs, the rotation would require a higher gravitational binding force, hence a higher minimum mass is required to keep the NS stable (Colpi et al. 1990). In summary, although the lowest mass NS observed to date is $1.174 \pm 0.004 M_\odot$ (1σ uncertainty) (Martinez et al. 2015), theoretical scenarios for sub-solar NSs remain open.

Various astrophysical mechanisms have been proposed for formation of SSM BNSs: as proposed by Clark & Eardley (1977), if the less massive NS reaches the Roche radius, then tidal disruption can be so extreme as to cause mass stripping. As a consequence of mass transfer to the primary, the less massive NS could therefore fall into the SSM regime. Alternatively, the Chandrasekhar limit, originally derived for the conditions found in stellar cores, might allow lower NS masses if the environment is sufficiently neutron-rich. This situation can be found in unstable disks around a central BH, which result from the gravitational collapse of rapidly rotating stars (Piro & Pfahl 2007). In such disks, gravitational instabilities may lead to the formation of sub-solar NSs from sufficiently neutron-rich regions (Metzger et al. 2024; Chen & Metzger 2025).

The structure and analysis framework of this paper closely follow the search for binaries with at least one SSM compact object in data from O4a (Abac et al. 2026c). Here we update those results analyzing the data collected during O4b; this paper thus presents the most comprehensive results to date of the LVK’s SSM search.

2. SEARCHES

We report results from three independent search pipelines - GstLAL, MBTA, and PyCBC — that analyzed data collected during O4b, from 2024 April 10 15:00:00 to 2025 January 28 17:00:00, and the preceding engineering run, specifically the period with coincident operation of the two LIGO detectors and Virgo detector from 2024 March 20 15:00:00 to 2024 April 10 15:00:00 (Abac et al. 2026). While O4a and the engineering run preceding O4a contained data only from the two LIGO detectors, the data analyzed for this paper and GWTC-5.0 included data from the Virgo detector, which resumed its observations prior to O4b. Details regarding the sensitivity of detectors during O4b can be found in Abac et al. (2026), while details of detector characterization and data quality in O4b are described in LVK (2026) and Abac et al. (2026a), respectively.

All three pipelines employ matched-filtering techniques (Abac et al. 2026a), where the data is correlated with banks of CBC waveform model parameter sets (hereafter referred to as *templates*) that span a common parameter space across all pipelines, yielding the signal-to-noise ratio (SNR) for each candidate. The template banks are de-

signed to search for CBCs with redshifted primary masses $m_1^{\text{det}} = (1+z)m_1$ between $0.2 M_\odot$ and $10.0 M_\odot$, and redshifted secondary masses $m_2^{\text{det}} = (1+z)m_2$ between $0.2 M_\odot$ and $1.0 M_\odot$. Here, $m_{1,2}^{\text{det}}$ is the detector frame mass and $m_{1,2}$ is the source frame mass. The mass ratio, $q = m_2/m_1$ ($m_2 \leq m_1$) is restricted within 0.1–1.0 to maintain a computationally manageable number of templates in the template bank. In the low mass regime considered for SSM search, the inspiral signal is principally determined by a single combination of component masses, the (detector frame) chirp mass:

$$\mathcal{M}^{\text{det}} = (1+z)\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}. \quad (1)$$

Mismatches between signal waveforms with different binary parameters vary much more rapidly with differences in $\mathcal{M}^{\text{det}}$ than with mass ratio or component spins at constant $\mathcal{M}^{\text{det}}$. The sensitivity of search templates to binary signals over a range of component masses and spins may thus be approximately understood in terms of the range of $\mathcal{M}^{\text{det}}$ covered.

We include spin–spin and spin–orbit interaction effects assuming that the spin vectors of the two bodies are either parallel or anti-parallel to the orbital axis. The dimensionless spin magnitudes satisfy $\chi_{1,2} \leq 0.9$ for $m_{1,2}^{\text{det}} \geq 0.5 M_\odot$ and $\chi_{1,2} \leq 0.1$ for $m_{1,2}^{\text{det}} \leq 0.5 M_\odot$. This search covers the same parameter space as the LVK SSM search performed on O3 (Abbott et al. 2022, 2023b) as well as O4a (Abac et al. 2026c) data, making a trade-off between possible astrophysical targets and the computational cost of matched-filter searches in this low-mass region.

GstLAL, MBTA, and PyCBC search pipelines each produced template banks with comparable parameter space coverages. The three pipelines’ template banks were constructed with a target minimal match of 0.965, 0.97 and 0.975, for GstLAL, MBTA, and PyCBC, respectively. The chosen minimal match values are intended to balance the loss of astrophysical signals due to the discreteness of the bank (e.g. a maximum loss of 10% for a minimal match of 0.97 (Owen 1996)) against computational cost considerations. The sensitivity bandwidth of LIGO and Virgo extends down to approximately 15 Hz (Abac et al. 2026). However, higher low-frequency cutoffs have been adopted in order to limit the computational cost of SSM searches: a cutoff of 45 Hz is used by all pipelines when determining template bank placement, thus reducing the number of templates to be processed; in addition, search pipelines impose low-frequency cutoffs higher than 15 Hz when performing matched filtering. This choice reduces computational cost per template, given that GW signals from low-mass CBCs can last for several minutes in the sensitive bandwidth of the detectors. Details of the SSM template bank generation, search optimizations, and individual pipeline configurations are described in the following subsections.

2.1. GstLAL Pipeline

GstLAL (Messick et al. 2017; Sachdev et al. 2019; Cannon et al. 2021; Hanna et al. 2020; Ewing et al. 2024; Tsukada et al. 2023; Sakon et al. 2024; Ray et al. 2023; Joshi et al. 2023, 2025a,b; Adhichary et al. 2026) is a GStreamer-based pipeline that searches for GW signals from CBCs using matched-filtering techniques. A concise overview of the methods developed and adopted for O4 analyses, including the latest archival search workflow employed in this work, is provided in Abac et al. (2026a). Unlike in O3 (Abbott et al. 2022, 2023b), GstLAL uses a bin-dependent gating procedure to mitigate glitches instead of the iDQ algorithm (Huxford et al. 2024). The overview of the methods of GWTC-4.0 and GWTC-5.0 are provided in Abac et al. (2026); Abac et al. (2026a), and Abac et al. (2026c) provides details on specific methods for SSM searches. The methodology, including the template bank (Hanna et al. 2024), used in the analyses for this paper remains nearly identical to that described in Abac et al. (2026c) with differences described below.

For O4 analyses, GstLAL generated the SSM template bank using a geometric placement method, MANIFOLD (Hanna et al. 2023). The template bank used for the SSM search of O4a data (Hanna et al. 2024) is inherited, as the search parameter space of interest remains identical and to avoid additional computational costs to remake a template bank. As in Abac et al. (2026c), the GstLAL template bank consists of over 3.5 million templates, the waveform approximant is IMRPHENOMD (Husa et al. 2016; Khan et al. 2016), the lower frequency cutoff is 45 Hz or higher, the high frequency cutoff is 1024 Hz, and a maximum template duration of ~ 128 s is imposed (Hanna et al. 2024). The limitation on template duration results in higher values of the low-frequency cutoff, given that the waveforms’ GW frequency increases monotonically with time.

In O4 GstLAL searches, including the SSM analysis, a number of enhancements are implemented in the algorithm compared to the O3 SSM analysis (Abbott et al. 2023a). These include an improved ranking statistic (Tsukada et al. 2023), a new singular value decomposition-based grouping method for parallelization (Sakon et al. 2024), and a template weighting derived from the MANIFOLD population model (Ray et al. 2023; Abac et al. 2026). As in the O3 SSM search, we continue to assume a uniform population model in the ranking statistic due to the absence of observational constraints on the underlying source population. Data is match-filtered using the same frequency and waveform duration cutoffs applied in the template bank generation, with waveform models chosen based on the redshifted chirp mass $(1+z)\mathcal{M}$ where the TaylorF2 approximant (Buonanno et al. 2009; Pan et al. 2008; Boyle et al. 2009) is used for $(1+z)\mathcal{M} \leq 1.73 M_\odot$, and the SEOBNRv4ROM approximant (Buonanno et al. 2009; Bohé et al. 2017; Cotesta et al. 2020) for $(1+z)\mathcal{M} > 1.73 M_\odot$.

We adopt different waveform models from that used for template placement in order to reduce computational costs. After matched filtering, GW candidates are ranked using a multi-component likelihood ratio ranking statistic (Tsukada et al. 2023; Cannon et al. 2015). The component for multi-detector signal consistency (Hanna et al. 2020) is evaluated over a frequency range of 45 Hz to 1024 Hz. The ranking statistic is converted to false-alarm rate (FAR), which quantifies the significance of a candidate signal by comparing it to the distribution of noise triggers (Messick et al. 2017).

The differences in methodology between what was used for O4a SSM analyses and the O4b SSM analyses are the following: the multi-detector signal consistency probability distribution, data calibration, and the detectors used for analyses. The multi-detector signal consistency probability distribution is a data product that assesses the signal probability of the GW candidates based on the observed time difference and phase difference between detectors by downweighting candidates with unphysical time or phase shifts. For the O4a SSM search, GstLAL used a high frequency cutoff of 512 Hz for this data product, which was found to be inconsistent with the bandwidth used to whiten the templates. While the discrepancy was shown to have negligible effects, the high frequency cutoff was corrected to 1024 Hz for O4b SSM analyses. Search pipelines process calibrated detector data. As described in Abac et al. (2026), there are periods of O4b data that required additional calibration correction procedures that were not required for data in O4a. Hence, the GstLAL analysis modified its configurations to use the corrected data, which was publicly released (Abac et al. 2026). Finally, GstLAL analyzed data from the two LIGO detectors and the Virgo detector for O4b analyses, as opposed to only the two LIGO detectors in O4a. The motivation was to increase the search’s sensitivity by including Virgo data, which became available in O4b.

2.2. MBTA Pipeline

The Multi-Band Template Analysis (MBTA; (Abadie et al. 2012; Adams et al. 2016; Aubin et al. 2021; All  n   et al. 2025) pipeline performs a matched-filter search for GWs from CBCs in data from the LIGO and Virgo detectors, using a pre-computed template bank. To reduce computational cost, the MBTA pipeline splits the matched-filtering process in the frequency domain into two bands, performing the filtering in each band before recombining the results (Abac et al. 2026).

Notable changes have been made since O4a. The Virgo data has been added to the analysis. The template bank has been generated using the same parameters as for O4a, but with a more recent power spectral density (PSD). It comprises over 2.3 million templates covering the parameter space described above, and was generated using a geometric

placement algorithm (Brown et al. 2013). The low-frequency and high-frequency template banks have also been regenerated to allow filtering starting at 35 Hz. While the placement of the template bank is defined over the range 45 Hz–1024 Hz, the filtering is performed over 35 Hz to 512 Hz. The reduction of the filtering low-frequency cutoff yields an improvement in sensitivity, while halving the filtering high-frequency limit preserves such an improvement while ensuring a minimal impact on total computational cost. The waveforms used in constructing the template bank are computed using the TaylorF2 approximant (Buonanno et al. 2009; Pan et al. 2008; Boyle et al. 2009); however for matched filtering, different waveform models are used depending on the total mass of the template. SpinTaylorT4 (Isoyama et al. 2020) is used when the total mass $M (= m_1 + m_2) < 4.0 M_\odot$, whereas IMRPhenomTP (Estell  s et al. 2021) is used otherwise.

2.3. PyCBC Pipeline

The PyCBC pipeline (Allen et al. 2012; Dal Canton et al. 2014; Usman et al. 2016; Nitz et al. 2017; Davies et al. 2020; Nitz et al. 2020) performs a matched filtering analysis to detect GW signals from CBCs. The PyCBC SSM search employs the latest version of the pipeline, described in detail in Abac et al. (2026). We made specific choices to tailor the analysis to the O4b search for SSM compact objects and to improve its sensitivity, as summarized below.

The ranking statistic is the same as in the O4a SSM search (Abac et al. 2026c). The major improvement in O4b is that we analyze Virgo data in addition to LIGO Hanford Observatory (LHO) and LIGO Livingston Observatory (LLO). As in O4a, we incorporate single-detector triggers in the search following (Cabourn Davies & Harry 2022); the threshold for fitting the Virgo single trigger background is tuned with a representative chunk of data during O4b.

For the template bank generation, the TaylorF2 (Buonanno et al. 2009; Pan et al. 2008; Boyle et al. 2009) post-Newtonian approximant and a lower frequency cutoff of 45 Hz were adopted to compute the matches between templates. We use the same geometric placement algorithm (Brown et al. 2013) as O4a, though now considering a representative PSD for LHO and LLO during O4b. This results in a bank with 2.6 million templates.

The pipeline starts filtering the data at 30 Hz with an imposed maximum allowed template duration of 1008 s which can lead to truncated templates. The SEOBNRv4ROM approximant (Buonanno et al. 2009; Boh   et al. 2017; Cotesta et al. 2020) is used for matched filtering in templates with $M > 4.0 M_\odot$, while the TaylorF2 approximant is used for $M \leq 4.0 M_\odot$.

2.4. Search Results

2.4.1. Summary

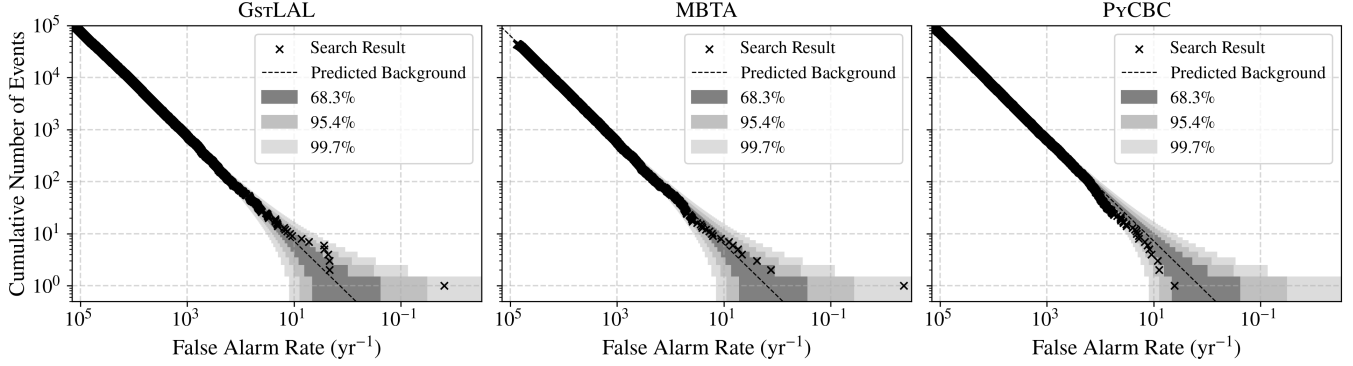


Figure 1. Cumulative number of SSM candidates as a function of the FAR for the GStLAL (left panel), MBTA (middle panel), and PyCBC (right panel) analyses. The black dashed line shows the predicted background, with the shaded regions indicating the 68%, 95%, and 99% confidence intervals for the background count at any FAR threshold, derived from a Poisson distribution given the total analyzed time of O4b and the preceding engineering run. Black crosses indicate the observed cumulative count from each pipeline. The low FAR candidates seen in the GStLAL and MBTA distributions correspond to S240422ed and S241229bq, respectively.

We report no significant GW candidates from SSM searches using the GStLAL, MBTA, and PyCBC pipelines conducted on O4b data. Figure 1 shows the number of candidates with estimated FAR exceeding a given threshold, as a function of the threshold value. The observed candidates are fully consistent with the Poisson statistical expectation, except for two outliers identified by the GStLAL pipeline on 2024 April 22 21:35:13.42 UTC and by the MBTA pipeline on 2024 December 29 13:52:36.83 UTC, discussed in detail below.

Table 1 lists candidates identified by the search pipelines with a FAR below 2 yr^{-1} . The third most significant candidate, despite having a higher SNR than the two outliers, is ranked lower due to the reduced sensitivity of the contributing detectors (LHO and Virgo rather than LHO and LLO). As its FAR is consistent with noise origin given the observing time of O4b, we do not investigate this candidate further.

Candidate significance and trials factors—Considering the duration of O4b data, the FARs reported for the most significant GStLAL and MBTA candidates correspond to a false alarm probability (FAP) (or p-value) of 0.011 and 0.0027, respectively. Thus, neither of these candidates surpasses a 3σ threshold, and we do not consider them as providing evidence for detection. We present follow-up studies on the two outlier candidates below.

The significance reported for individual offline SSM search pipelines over O4b does not incorporate trials factors, which account for the fact that multiple distinct search results have been reported using Advanced LIGO (aLIGO) and Advanced Virgo (aVirgo) data, and every search has a finite probability of producing a false positive. To attempt to quantify this effect, we consider the LVK’s SSM searches conducted from O1 through O4b. The numbers of pipelines participating for each observing run are as follows:

- O1: 1 (GStLAL)
- O2: 1 (GStLAL)
- first half of the third observing run (O3a): 3 (GStLAL, MBTA, PyCBC)
- second half of the third observing run (O3b): 3 (GStLAL, MBTA, PyCBC)
- O4a: 3 (GStLAL, MBTA, PyCBC)
- O4b: 3 (GStLAL, MBTA, PyCBC)

resulting in 14 separate search results. While the effect of these multiple searches on the significance threshold required to claim evidence for observation of an astrophysical signal is difficult to quantify exactly, if we consider events due to detector noise in different pipelines to be independent to a good approximation, the FAP of a candidate will increase by around an order of magnitude when considering trials factors.

2.4.2. GStLAL SSM Outlier Candidate

The outlier candidate identified by the GStLAL pipeline corresponds to S240422ed (LIGO Scientific Collaboration et al. 2024a) in the LVK GRACEDB (Moe et al. 2014). All three detectors were operating at the time of the candidate but triggers were produced above the pipeline’s SNR threshold only in LLO and LHO.

This candidate was initially identified by the low-latency stellar-mass (broad CBC parameter space) search in the GStLAL and PyCBC pipelines, with FARs of 10^{-5} yr^{-1} and 10.3 yr^{-1} , respectively. Both pipelines identified the candidate in templates with masses consistent with a NSBH source binary, with a (redshifted) chirp mass of $\sim 1.7 M_{\odot}$ and a effective inspiral spin $\chi_{\text{eff}} \equiv (m_1\chi_{1z} + m_2\chi_{2z})/(m_1 + m_2)$ of $\gtrsim 0.75$. The MBTA pipeline’s low-latency stellar-mass search did not detect this candidate.

Table 1. Candidates recovered with a FAR below 2 yr^{-1} .

FAR (yr^{-1})	Pipeline	Coalescence time	m_1^{det} ($M_\odot$)	m_2^{det} ($M_\odot$)	χ_{1z}	χ_{2z}	Inst. operating	Inst. contributing	Network SNR
0.0043	MBTA	2024 December 29 13:52:36.83 UTC	1.04	0.49	-0.33	0.040	HLV	HL	10.2
0.015	GstLAL	2024 April 22 21:35:13.42 UTC	5.28	0.85	0.79	0.79	HLV	HL	9.74
1.3	MBTA	2025 January 2 09:44:02.30 UTC	0.32	0.23	0.02	-0.02	HLV	LV	10.6

NOTE—For each candidate we report the redshifted primary (1) and secondary (2) masses $m_{1,2}^{\text{det}}$ and the dimensionless spin components projected along the orbital axis $\chi_{1,2z}$, for the highest ranked template. The detectors operating at the time of the candidate are listed under “Inst. operating”, while detectors where the SNR is high enough to contribute to the estimated significance are listed under “Inst. contributing”, where H (L, V) denotes LIGO Hanford Observatory (LIGO Livingston Observatory, Virgo). The minimum SNR thresholds for a detector to contribute to candidate significance for GstLAL and MBTA are 4.0 and 4.4, respectively. The network SNR is the quadrature sum of SNRs for all detectors operating at the time of the candidate for MBTA, or only for detectors with SNR above 4.0 for GstLAL.

At the time of the candidate, the GstLAL and MBTA pipelines were operating low-latency SSM searches (Hanna et al. 2024; All  n   et al. 2025). However, these searches did not identify candidates for S240422ed. The GstLAL low-latency SSM template bank’s spins are limited to $|\chi_{1,2}| \leq 0.3$ (Hanna et al. 2024), hence, this bank did not cover the preferred template parameters for S240422ed.

Further analyses of this candidate in the GstLAL stellar-mass search including information from subsequent data in the background model reduced its significance; the FAR in the GstLAL stellar-mass search is now estimated to be ~ 1 per 35 days, comparable with the PyCBC pipeline’s stellar-mass search (LIGO Scientific Collaboration et al. 2024b). While S240422ed is included in GWTC-5.0 (Abac et al. 2026b), it is no longer a significant candidate.

However, the GstLAL SSM offline search of O4b data reported here identifies a candidate corresponding to S240422ed with a FAR of 0.015 yr^{-1} . Neither the MBTA nor the PyCBC offline SSM searches identify a corresponding candidate for S240422ed at a FAR inconsistent with noise.

Data quality checks performed for S240422ed in low latency indicated that data from both LLO and LHO were affected by non-stationary noise, but not at a level sufficient to justify retracting the alert. Additionally, the trigger identified in LHO data is well within the distribution of SNR and chi-squared values for noise triggers. Follow-up Bayesian inference analyses, under the hypothesis of an astrophysical signal in Gaussian noise, infer a chirp mass consistent with the search pipeline value from coherent analysis of data from all three detectors. However, both LHO data and Virgo data, when analyzed on their own, are consistent with a vanishing signal amplitude for this range of chirp mass. While such behaviour is not impossible for an astrophysical signal, overall these followup analyses do not change our assessment that the GstLAL candidate is consistent with a noise origin.

2.4.3. MBTA SSM Outlier Candidate

The outlier candidate identified by the MBTA pipeline corresponds to S241229bq. As with S240422ed, all three detectors were operating at the time of the candidate but triggers were produced above the pipeline’s SNR threshold only in LLO and LHO.

This candidate was initially identified as S241229bq by the low-latency SSM search in the MBTA and GstLAL pipelines, with a FAR of 570 yr^{-1} and 100 yr^{-1} , respectively. The PyCBC pipeline’s low-latency stellar-mass search did not detect this candidate; note that the PyCBC pipeline does not operate a low-latency SSM search. Since S241229bq was identified as a low-significance candidate, a public alert was not issued, and neither manual checks for data quality nor low-latency parameter estimation (PE) were performed.

As shown in Table 1, the MBTA SSM offline search of O4b data identifies a candidate corresponding to S241229bq with a FAR of 0.0043 yr^{-1} , equivalent to a significance of 2.8 standard deviations. (As mentioned previously, this value does not account for trials factors.) The GstLAL and PyCBC offline SSM searches both identify a candidate corresponding to S241229bq, but with FARs consistent with noise: 34 yr^{-1} and 7.7 yr^{-1} for GstLAL and PyCBC, respectively. The probability for the FAR of an astrophysical signal to be higher than 1 yr^{-1} for GstLAL and PyCBC, but lower than 0.005 yr^{-1} for MBTA, was estimated via analysis of simulated signals (*injections*, see Section 3 below) to be of the order of 10^{-3} .

Further investigations confirmed that the MBTA noise model used to estimate the FAR for this candidate was stable across the observing period, and that the candidate was not affected by data quality issues. The SNR evolution of the trigger when lowering the matched filter low frequency cut-off was also investigated, finding a decrease of the SNR, and consequently of the significance, between 35 Hz and 25 Hz cutoffs. A decrease of the SNR is also observed when performing the matched filtering over a single frequency band that covers the range of the usual two frequency bands in

MBTA. Further checks on injections indicate that this behavior, while possible for a low-amplitude astrophysical signal, was approximately twice as likely to be caused by a noise fluctuation.

3. SEARCH SENSITIVITY

In this section we quantify the sensitivity of our searches over O4a and O4b data to GW signals from SSM CBCs. This enables us to set upper limits on SSM merger rates, as described in Section 4. Due to the changing sensitivity across the observing run and the complex nature of the detection process, we determine this sensitivity empirically via the injection procedure laid out in Abac et al. (2026); Essick et al. (2025). We simulate the GW strain for large numbers of signals and add them to detector strain data, and pipelines perform the search described in Section 2 on this augmented data. Our sensitivity to a possible population of SSM sources depends on their distribution over masses and spins. Therefore, we provide estimates of sensitivity to SSM sources as a function of an assumed population. Re-weighting a single set of results from our injection recovery analysis via importance sampling (Tiwari 2018) enables us to determine the sensitivity to multiple population models.

3.1. Estimation methods

Search sensitivity for a given assumed population distribution Λ , with a merger rate which we assume constant over comoving volume and time, is described by the sensitive hypervolume, $\langle VT \rangle$. This is an effective spacetime volume over which the search would detect mergers with a significance above some chosen detection threshold. It may be expressed as

$$\langle VT \rangle(\Lambda) = \xi(\Lambda) VT_{\text{total}}, \quad (2)$$

where $\xi(\Lambda)$ is the fraction of detectable mergers, and VT_{total} denotes the total volume–time accessible to the analysis, given by the comoving volume–time enclosed out to the most distant source included in the population, over the duration T_{obs} of the data searched. For injections generated up to a maximum redshift z_{max} , we have

$$VT_{\text{total}} = T_{\text{obs}} \int_0^{z_{\text{max}}} \frac{1}{1+z} \frac{dV_c}{dz} dz, \quad (3)$$

where the $1/(1+z)$ factor accounts for time dilation between the source frame and the detector frame, and dV_c/dz is the differential element of comoving volume over redshift. The detectable fraction $\xi(\Lambda)$ is defined as

$$\xi(\Lambda) = \int p_{\text{det}}(d) p(d|\theta) p(\theta|\Lambda) dd d\theta, \quad (4)$$

where $p(d|\theta)$ denotes the probability of obtaining data d in the presence of a GW signal characterized by source parameters θ , and $p(\theta|\Lambda)$ denotes the probability distribution of these

parameters conditioned on the population hyperparameters Λ . Finally, $p_{\text{det}}(d)$ is the probability that our search identifies a candidate above the given detection threshold, when given data d as input; as our search pipelines process data deterministically, this takes values of either 0 or 1.

We estimate $\xi(\Lambda)$ for a given population model Λ via importance sampling (Tiwari 2018; Essick & Farr 2022). We perform a Monte Carlo sum over the subset of recovered injections $\{\theta\}_{\text{found}}$, applying appropriate importance sampling weights for the desired population distribution:

$$\xi(\Lambda) \simeq \frac{1}{N_{\text{inj}}} \sum_{\theta \in \{\theta\}_{\text{found}}} \frac{p(\theta|\Lambda)}{p(\theta|\Lambda_0)}, \quad (5)$$

where N_{inj} is the total number of injections initially generated, $p(\theta|\Lambda_0)$ is the distribution of source parameters under the fiducial population model Λ_0 used to generate injections, and $p(\theta|\Lambda)$ is the corresponding parameter distribution for the desired population model Λ for which we want to estimate sensitivity. The uncertainty in the estimated $\langle VT \rangle$ propagates directly from the variance in this Monte Carlo sum (Farr 2019) via Equation (2).

3.2. Injections

To determine the sensitivity to populations of CBCs which include at least one SSM BH or NS component in O4b, we define two fiducial populations from which we draw simulated source parameters when constructing the injection sets used by the searches. The injections were produced using PSDs derived from LHO, LLO and Virgo data throughout O4b, and were added to the O4b strain data for searches. These populations are summarized in Table 2, and are similar to those considered in the O4a analysis of Abac et al. (2026c), differing only in the aspects highlighted below.

The maximum primary mass for the BNS population is set to $2.5 M_{\odot}$ (as compared to $3.0 M_{\odot}$ adopted in O4a), to narrowly include the maximum NS mass of approximately $\sim 2.4 M_{\odot}$, which is allowed by the EoS used to produce the injections in both O4a and O4b. We adopt the GPPVA_DD2 EoS, which is closely related to DD2 and represents one of the stiffest EoS still consistent with GW170817 multimessenger constraints (Radice et al. 2018), making $2.5 M_{\odot}$ a physically reasonable upper limit. Other EoS considered in Abbott et al. (2018) are either too soft or excluded by multimessenger observations of GW170817; meanwhile, studies including NICER pulsar X-ray observations do not require a higher maximum mass (Raaijmakers et al. 2021).

The simulated population, for both BBH and BNS, has isotropically distributed spin orientations and is distributed uniformly in comoving volume out to a given maximum redshift z_{max} . For BNS we set $z_{\text{max}} = 0.2$, which corresponds to a total hypervolume of $VT_{\text{total}} = 1.83 \text{ Gpc}^3 \text{ yr}$ while for BBH we use $z_{\text{max}} = 0.25$, corresponding to $VT_{\text{total}} = 3.34 \text{ Gpc}^3 \text{ yr}$.

Table 2. Fiducial populations of simulated BBH and BNS sources used for estimating search sensitivities.

	BBH	BNS
	$m_{1,2}^\alpha, \alpha = -1$	$m_{1,2}^\alpha, \alpha = -1$
MASS MODEL	$m_1 \in [0.19 M_\odot, 11.1 M_\odot]$ $m_2 \in [0.19 M_\odot, 1.1 M_\odot]$	$m_1 \in [0.5 M_\odot, 2.5 M_\odot]$ $m_2 \in [0.5 M_\odot, 1.1 M_\odot]$
	$w\mathcal{N}(\mu, \sigma) + (1 - w)\text{Beta}(\alpha, \beta)$	
SPIN MAGNITUDE MODEL	$\mu = 0, \sigma = 0.1, \alpha = 1, \beta = 4, w = 0.5$ $\chi_{1,2} \in [0, 1]$	
WAVEFORM MODEL	IMRPHENOMXPHM	IMRPHENOMXP_NRTIDALV3 (Abac et al. 2024)
EQUATION OF STATE	Not used	GPPVA_DD2

NOTE—Source parameters are drawn from the given distributions for (source-frame) component masses $m_{1,2}$, and dimensionless spin magnitudes $\chi_{1,2}$, to generate simulated signals for searching augmented O4b data. We assume isotropic spin directions, i.e. uniform in the cosines of the angles between the orbital angular momentum vector and the component spin vectors. The sources are distributed uniformly in comoving volume and time up to a maximum redshift $z_{\text{max}} = 0.25$ (0.2) for BBH (BNS). These fiducial populations are denoted by Λ_0 in Equation (5).

Compared to O4a where a limit $z_{\text{max}} = 0.2$ was applied to all injections, here we extend the range for BBH, motivated by the improvement in LIGO sensitivity and the higher network SNR with Virgo joining the observing run (Abac et al. 2026). We injected a total of 3.7×10^7 simulated signals; BBH signals are injected every 32 s, and BNS signals are injected on the same cadence, but offset by 16 s relative to the BBH injections. These spacings are intended to avoid significant bias of the strain data PSD caused by the presence of a high total signal rate.

3.3. Combined O4a and O4b sensitivity estimates

In this study we introduce an estimation of search sensitivity to SSM binaries over the combined runs O4a and O4b. This combined estimate uses an increased total observing time T_{obs} , while consistently accounting for different search efficiencies $\xi(\Lambda)$ between runs. We follow Essick (2021) to construct a mixture model for both runs, using the O4a injections detailed in Abac et al. (2026c) and O4b injections described above. The mixture unifies the two injection sets, assigning individual injection weights based on the rate of Monte Carlo sample generation in any given piece of data. This weighting ensures uniformity over detector-frame time throughout the observing period, even in disjoint runs; the resulting weights are incorporated in the term $p(\theta|\Lambda_0)$ for Equation (5) (Essick 2021; Essick et al. 2025). The procedure described in Section 3.1 is then applied to the mixture model set to obtain sensitivity estimates for the combined runs. For runs that are disjoint in time, this combined estimate of $\langle VT \rangle$ for a given population is equal to a sum of estimated sensitivities over separate runs. However, the mixture model method has the advantage of being more generally applicable and valid even in cases of overlapping injection distributions (including overlapping in time). Hereafter,

combined sensitivity estimates for both runs will be labelled as O4a+b.

The results and analyses presented in the remainder of this study adopt different detection thresholds for sensitivity estimation corresponding to distinct inference methods. Table 3 summarizes these detection thresholds, and the corresponding figures, for later reference.

3.4. Sub-solar mass BBH systems

We report sensitivity estimates, $\langle VT \rangle$, for BBH systems with at least one SSM component recovered by the GstLAL, MBTA and PyCBC pipelines. We expect search sensitivity to be primarily a function of the binary chirp mass (Blanchet 2014) as the GW frequency evolution and emitted flux during binary inspiral are determined, to first approximation, only by the value of $\mathcal{M}$ (Cutler & Flanagan 1994). Considering both the masses covered by the search template banks in the detector frame, and the maximum redshift of 0.25 reached by our injection campaign, we consider a chirp mass space covering the range $0.16 M_\odot \leq \mathcal{M} \leq 2.72 M_\odot$; we then divide this space into equally-spaced bins, treating each bin as a separate population. Additionally, we reject binaries with $q < 0.05$ for consistency with previous estimates in Abbott et al. (2022, 2023b); Abac et al. (2026c). Note that since search pipelines can have sensitivities to injections that lie outside the parameter spaces covered by their template banks, we assess the sensitivities using a cutoff at $q = 0.05$ while the template banks are limited to q within 0.1–1.0.

In this study we estimate sensitivity for low-spin binaries, as previously in Abac et al. (2026c), and also for high-spin SSM binaries. Low-spin SSM binaries correspond to the simplest scenario of PBHs formed by gravitational collapse of overdensities that enter the horizon in the radiation era, which are expected to have zero or negligible spin at formation (García-Bellido 2017; Chiba & Yokoyama 2017;

Table 3. Significance thresholds used for search sensitivity estimates in downstream analyses, and the corresponding figures.

Analysis	Detection threshold	Figures
Low-spin SSM BBH $\langle VT \rangle$ estimates	$\text{FAR} = 1 \text{ yr}^{-1}$	2, 3, 4, 5
High-spin SSM BBH $\langle VT \rangle$ estimates	$\text{FAR} = 1 \text{ yr}^{-1}$	5
SSM BNS $\langle VT \rangle$ estimates	$\text{FAR} = 1 \text{ yr}^{-1}$	6
Low-spin SSM BBH frequentist merger rate limits	Per-pipeline loudest event over O4a and O4b	7, 8
SSM BNS frequentist merger rate limits	Per-pipeline loudest event over O4a and O4b	9
PBH constraints derived from low-spin SSM BBH rate limits	Per-pipeline loudest event over O4a and O4b	10, 11
Bayesian constraints on DBH model	$\text{FAR} = 0.01 \text{ yr}^{-1}$	12

Mirbabayi et al. 2020; De Luca et al. 2019). However, several mechanisms could increase the spin of one or both components of the coalescing binaries. In close hyperbolic encounters, PBHs can acquire a relatively mild spin of order $\chi \sim 0.2$ (Jaraba & García-Bellido 2021). In sufficiently dense clusters of PBHs, the spin can reach 0.7 due to this mechanism only if significantly unequal mass BHs participate in multiple close hyperbolic encounters. Alternatively, if the PBHs inhabit a sufficiently gas-rich environment for accretion disks to be formed, the transfer of angular momentum due to gas accretion can increase substantially the spin magnitude (De Luca et al. 2020), although this mechanism needs to be confirmed with simulations of SSM PBHs.

For the low-spin case, we choose a uniform distribution in spin magnitudes limited to $\chi_{1,2} \leq 0.1$, consistent with previous reported results (Abbott et al. 2022, 2023b; Abac et al. 2026c). Then, for the high-spin case we choose a spin magnitude distribution uniform in $0.1 \leq \chi_{1,2} \leq 0.7$: the upper limit here is motivated by upper bounds in the literature (De Luca et al. 2020; Jaraba & García-Bellido 2021), and in order to avoid an excess of variance in the estimate of $\langle VT \rangle$ (Farr 2019) caused by low support of the injected $\chi_{1,2}$ distribution beyond 0.7. Spin orientations are considered as isotropically distributed for both low- and high-spin cases.

In addition to reporting sensitivity estimates in bins of chirp mass, we also report sensitivity as a function of component masses $m_{1,2}$. Similarly to the chirp mass case, we split the space of component masses into equally spaced bins covering the range $0.19 M_{\odot} \leq m_1 \leq 11.1 M_{\odot}$ and $0.19 M_{\odot} \leq m_2 \leq 1.1 M_{\odot}$, with the mass ratio constraint $q \geq 0.05$, and treat each grid bin as a separate population, described by a log-uniform distribution limited by the bin bounds. For component mass sensitivity estimates, we only consider the low-spin case with a uniform magnitude distribution $\chi_{1,2} \leq 0.1$ and isotropically distributed spin orientations.

We present sensitivity estimates for SSM BBH at a reference significance threshold of $\text{FAR} 1 \text{ yr}^{-1}$ (in contrast to Abac et al. (2026c), where a loudest event threshold was used). This uniform choice follows Abac et al. (2026b) and facilitates one-to-one comparisons between pipelines and/or between observing periods. Figure 2 shows the combined estimates for low-spin BBHs, with similar performance between different search pipelines. Larger differences in sensitivity between PyCBC and the other two pipelines seen at low chirp mass are due to a lower starting frequency for filtering (see Section 2.3), which affects the power recovered from long duration signals characteristic of low-mass binaries.

We also show a comparison of sensitive $\langle VT \rangle$ in Figure 3 for low-spin BBHs during O4a, O4b and the combination of both runs. Increased sensitivity in O4b is due to a combination of increased observing time from 0.76 yr (O4a) to 0.84 yr (O4b) translated in a $\approx 11\%$ gain; improved LIGO detector sensitivity, and the resumption of Virgo observations after O4a; and improvements in search pipeline methods which enhance detection efficiency by up to 50%. In particular, the MBTA sensitivity increases for O4b as compared to O4a reaching a 73% improvement in higher chirp mass bins, which we can attribute to search improvements described in Section 2.2. On the other side, GstLAL and PyCBC increase at most 33%. For the combined O4a+b runs, T_{obs} increases by a factor 2.1 with respect to O4a. Together with improvements to the detectors' sensitivities and the addition of the Virgo detector, the sensitivity gain is nearly a factor of 3.

Uncertainties in $\langle VT \rangle$ are propagated from the Monte Carlo sum standard deviation, as discussed in Section 3. The great majority of injected signals in the last chirp mass bin, $2.44\text{--}2.72 M_{\odot}$, have a chirp mass above the range covered by the pipelines' template banks, leading to a much reduced sensitivity. As the estimated sensitivity in this bin is subject to large statistical uncertainties, as follows from Farr (2019),

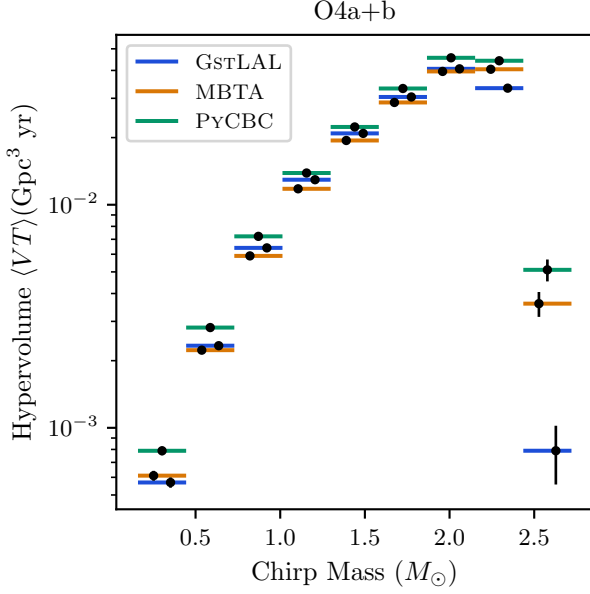


Figure 2. Low spin BBH population sensitive hypervolume estimates at a FAR 1 yr^{-1} threshold for each pipeline over the combined O4a+b runs, computed in chirp mass bins. Vertical bars show Monte Carlo sampling standard deviations.

we display the estimate here for completeness but we do not proceed to derive astrophysical limits for the last bin.

The O4a estimates (Abac et al. 2026c) in Figure 3 used loudest-event FAR thresholds of 1.2 yr^{-1} , 0.87 yr^{-1} and 1.3 yr^{-1} for GstLAL, MBTA and PyCBC respectively, while here we report $\langle VT \rangle$ at a 1 yr^{-1} FAR threshold. This caveats a direct comparison, since varying the significance threshold will change the Monte Carlo sums in Equation (5). However, these differences in FAR threshold have a very small effect on $\langle VT \rangle$: GstLAL and PyCBC would miss less than 1.1% of the recovered injections if changing their O4a threshold to 1 yr^{-1} , while MBTA would gain less than 0.7%. We consider these differences to be negligible when comparing O4a sensitivity estimates to our current results.

We also compute the sensitivity as a function of component masses $m_{1,2}$ for low spins, shown in Figure 4. As expected, search sensitivity appears mainly determined by the binary chirp mass; the highest sensitivity is obtained for the more massive bins, except for the top right (highest total mass) bin which lies beyond the space covered by the search template banks. Sensitivities are broadly similar between different pipelines. While the fractional uncertainty in $\langle VT \rangle$, shown in the bottom panel, is generally small, excess uncertainty in one bin ($m_1, m_2 = (6.74-8.92, 0.19-0.37) M_\odot$) is caused by our population model constraint on mass ratio $q \geq 0.05$: this bin then lies at the edge of the population, receiving very few Monte Carlo samples. (The blank bin at lower right lies

completely outside our population model and hence cannot be constrained.)

Moving to the high-spin case, $0.1 \leq \chi_{1,2} \leq 0.7$, we find minor changes in the sensitive hypervolume compared to low spins, summarized in Figure 5. The sensitivity for O4b is reduced by $\sim 25\%$, while the combined O4a+b estimates drop by $\sim 20\%$. A weak trend towards lower relative sensitivity for high-spin BBHs at higher chirp mass is visible, except in the lowest mass bin; note that search template banks cover a reduced range of effective inspiral spin χ_{eff} at the lowest binary masses ($\chi_{1,2} \leq 0.1$ for $m_{1,2}^{\text{det}} \leq 0.5 M_\odot$). The high-spin population model implies larger statistical uncertainties: reweighting to a uniform distribution in spin magnitudes from the injected distribution (see Section 3.2) reduces the number of effective samples, increasing the variance of the Monte Carlo sums by up to a factor of 6 which translates to a greater uncertainty in $\langle VT \rangle$.

3.5. Sub-solar mass BNS systems

Following Abac et al. (2026c), we also report sensitivity estimates for BNS coalescences with at least one SSM component, using injection waveforms that include tidal effects: this aims to quantify how recovery of such signals is affected by the absence of tidal effects in the search template waveforms. We consider BNS injections recovered by MBTA and PyCBC; in contrast to the BBH injection analyses, the GstLAL pipeline did not analyze simulated BNS signals, in order to limit its total computational cost.

As in Abac et al. (2026c), we extend the sensitivity estimates for NSs with masses down to $0.5 M_\odot$, in contrast to estimates for GWTC releases such as Abac et al. (2026a) where the minimum mass considered is $1 M_\odot$. We present the sensitivity for BNS systems at several combinations of component masses, considered as representing two different astrophysical scenarios.

- **Double SSM systems:** these have both component masses below $1 M_\odot$. We show selected points at $m_{1,2} = \{0.6, 0.8, 1.0\} M_\odot$.
- **Single SSM systems:** for these the secondary is the only SSM component, with the primary above $1 M_\odot$. We show estimates at m_1 equal to $\{1.4, 1.8, 2.2\} M_\odot$, while m_2 equal to $\{0.6, 0.8, 1.0\} M_\odot$.

To evaluate search sensitivity for each of these combinations, we consider a population of BNS systems following a log-normal distribution in each component mass, centered at each $m_{1,2}$ point, with a standard deviation of $0.1 M_\odot$.

NS spin magnitudes, in contrast to those of BHs, are not limited to a maximum of 1; instead, they are constrained to the mass-shedding limit, balancing gravitational force with rotational acceleration. The most rapidly spinning NS observed within a BNS system, PSR J1946+2052, rotates with

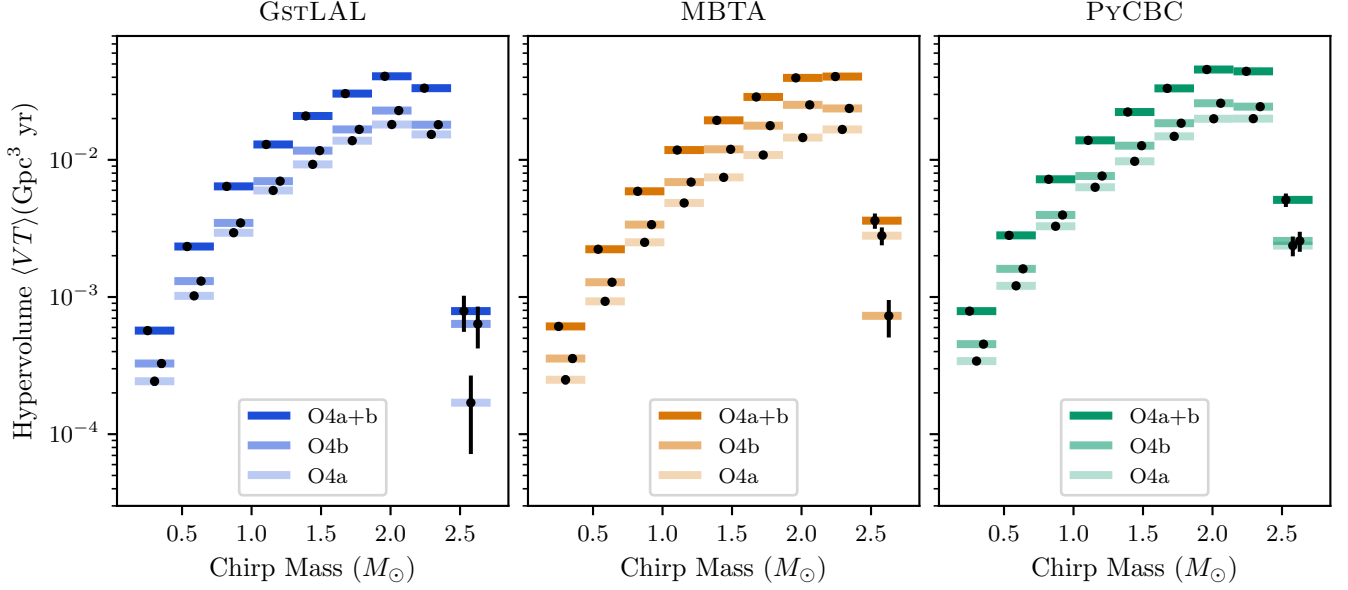


Figure 3. Low spin BBH population sensitive hypervolume estimates at a FAR 1 yr^{-1} threshold for O4a, O4b and combined runs O4a+b, displayed for each pipeline in chirp mass bins. Dimmer solid lines represent O4a while subsequent runs are shown as darker lines. Vertical bars show Monte Carlo sampling standard deviations.

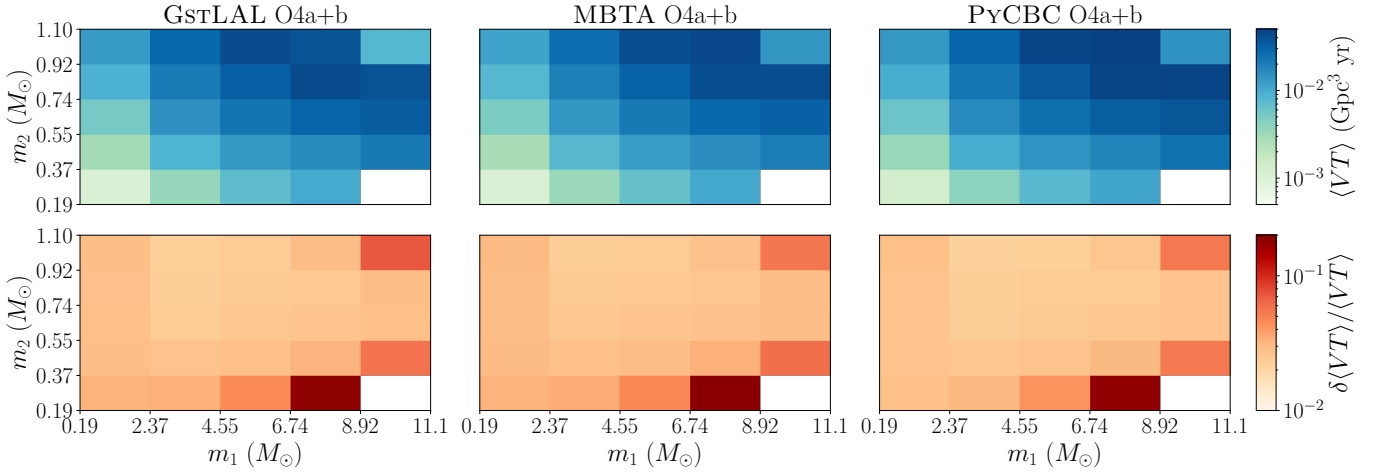


Figure 4. Low spin BBH population sensitive hypervolume estimates at a FAR 1 yr^{-1} threshold for each pipeline over the combined O4a+b runs (top panel), and their corresponding Monte Carlo sampling standard deviations (bottom panel). Blank bins correspond to zero efficiency, i.e. no injections found by the pipelines with significance above detection threshold.

a period of 16.96 ms (Stovall et al. 2018). Following the dimensionless spin magnitude definition

$$\chi = \frac{c J}{G M^2} \quad , \quad (6)$$

and assuming a $1.4 M_\odot$ object and the GPPVA_DD2 EoS,¹ we find a spin magnitude $\chi \approx 0.042$. However, if we instead

¹ In contrast to other authors such as Brown et al. (2012), we opt for a moment of inertia corresponding to a solid sphere $I = 2/5 M R^2$ dependent on the EoS, instead of a constant $I = J/\Omega = 1.5 \times 10^{45} \text{ g cm}^2$.

consider this object a sub-solar NS of $0.5 M_\odot$ then its spin would correspond to $\chi \approx 0.12$, based on keeping the period fixed while decreasing the mass. Going further, higher rotational frequencies have been found for NSs in binary systems with other types of object (e.g., Hessels et al. 2006); thus, given the high uncertainties affecting possible SSM BNS we allow for rapidly-spinning components, comparable to millisecond pulsars (Bildsten et al. 1997). Imposing an upper limit on the NS spin magnitude of 0.4, consistent with Abac et al. (2026); Abac et al. (2026c), our sensitivity

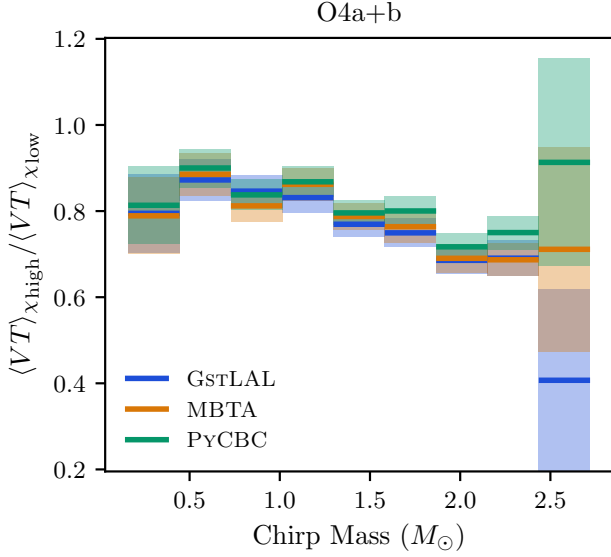


Figure 5. Ratio of sensitivities between high- and low-spin populations of BBH in chirp mass bins, for the combined O4a+b runs. Uncertainties are propagated from the $\langle VT \rangle$ uncertainty for each population.

estimates consider a uniform distribution in spin magnitude constrained to $\chi_{1,2} \leq 0.4$, and isotropic spin orientations.

As in the previous section, we choose a reference FAR threshold of 1 yr^{-1} to present sensitivity estimates for each pipeline. Figure 6 shows the sensitive hypervolume computed at the proposed points in the $m_{1,2}$ space. We observe an increase between a factor of 2.2 and 3 when comparing the combined estimate to previous O4a results (Abac et al. 2026c). Uncertainties propagated from the Monte Carlo sum variance range between 1.2% and 5.2% for the most and least massive $m_{1,2}$ points, respectively.

Comparing SSM BBH and BNS with the same population mass and spin distributions, we find that sensitivity to BNSs can be slightly lower, ranging over $\sim (0.8\text{--}1)$ times the BBH sensitivity. Loss in sensitivity for BNS is primarily caused by the mismatch between the templates (see Section 2) and injected waveforms including tidal effects. In the case of super-solar NSs such mismatch is expected to be subdominant (Williams et al. 2022) and restricted to a small portion of the parameter space, which would appear with a fitting factor below the designed minimal match of the bank (Piccari & Pannarale 2025). However, given we employ the stiffest EoS and consider masses in the sub-solar regime, this effect is magnified and can lead to significant sensitivity loss due to template bank mismatch (Bandopadhyay et al. 2023). Additionally, waveforms including tidal effects are not calibrated in this low mass range: thus, tidal deformations in SSM NSs are extrapolated into the sub-solar regime, which may intro-

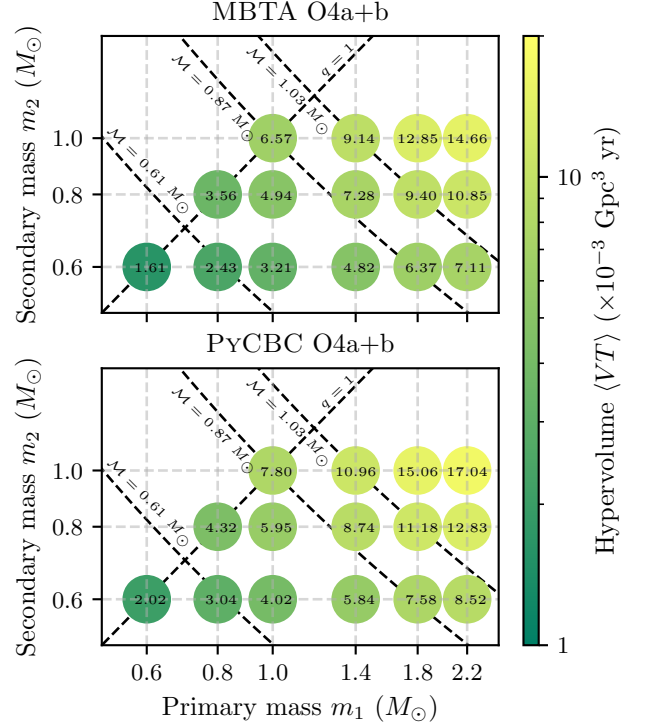


Figure 6. Sensitive hypervolume estimates for a SSM BNS population at a FAR 1 yr^{-1} threshold. We report the sensitivities of the MBTA and PyCBC pipelines over the combined O4a+b runs evaluated at points in the component mass space.

duce systematic uncertainty in our sensitivity estimates due to waveform errors.

4. MERGER RATES

The $\langle VT \rangle$ sensitivity estimates obtained in the previous section, coupled with the non-detection search results of Section 2.4, can be used to derive upper limits on the merger rate of possible populations of low-spin SSM BBHs or BNSs. Hereafter, the rates and constraint results quoted for SSM BBHs are for the low-spin population. Assuming the physical independence of different mergers, we treat them as an inhomogeneous Poisson process, with an intensity varying over binary component masses and spins and over redshift. We make the further assumption, reasonable given the maximum redshift $z_{\text{max}} \sim 0.25$ probed by our searches, that the merger rate is constant over comoving volume and source-frame time, notating the total rate density of BBHs over the SSM parameter space as $\mathcal{R}$.²

A model of the SSM BBH population Λ is then described by a normalized distribution of mergers over intrinsic parameters (component masses and spins), $p(\theta|\Lambda)$. If identified by

² A SSM BNS population is described similarly, but has its own independent rate parameter.

a search pipeline, a merger signal is assigned a ranking parameter x such that louder signals correspond to higher x values; here, we may identify x with the inverse false-alarm rate. The expected number of mergers identified by a search above some threshold value of x is then given by

$$\mu(x, \Lambda) = \mathcal{R}VT(x, \Lambda), \quad (7)$$

where we explicitly indicate the dependence of VT on the threshold and on the model Λ , cf. Equation (2). Search candidates due to astrophysical mergers, which are assigned a ranking above a threshold x , can then be treated as a Poisson process with parameter $\mu(x, \Lambda)$.

We then obtain upper limits on $\mathcal{R}$ by the (frequentist) loudest event statistic method (Brady et al. 2004): the value of μ is bounded above by the fact that there were no candidates identified with higher ranking than the loudest event recorded by a search, $\hat{x}$. Imposing the ranking threshold $\hat{x}$, we have for a $p\%$ confidence upper limit $\mathcal{R}_p$,

$$1 - \frac{p}{100} = \exp(-\mu_p(\hat{x}, \Lambda)) \implies \mathcal{R}_p = -\frac{\ln(1 - p/100)}{VT(\hat{x}, \Lambda)}, \quad (8)$$

yielding a standard 90% confidence upper limit $\mathcal{R}_{90} \simeq 2.3\langle VT(\hat{x}, \Lambda) \rangle^{-1}$. We replace the sensitivity VT by its estimated value $\langle VT \rangle$ assuming its statistical uncertainty is negligible.

Adopting the loudest event formalism as above, we obtain upper limits on the merger rate for each pipeline considering the combined O4a+b runs. We estimate the sensitive hypervolume (Section 3) at the FAR threshold determined by the loudest event recorded by each pipeline over both the O4a and O4b runs, and follow Equation (8) to derive 90% confidence upper limits. PyCBC found a louder event during O4a (Abac et al. 2026c) compared to the most significant event in O4b (see Section 2.4) while GstLAL and MBTA found the loudest events in O4b. Therefore, we use the following FAR thresholds: 0.015 yr^{-1} for GstLAL, 0.0043 yr^{-1} for MBTA, and 1.3 yr^{-1} for PyCBC. This is in contrast to Sections 3.4 and 3.5, where sensitivity estimates adopted a constant 1 yr^{-1} FAR threshold.

Figure 7 shows the upper limit on the SSM BBH merger rate at the 90% confidence level for GstLAL, MBTA, and PyCBC as a function of the chirp mass, $\mathcal{M}$, and the relative improvement between the different observing periods. Since a high-spin population of SSM BBH shows only minor variation in $\langle VT \rangle$ with respect to a low-spin population (see Section 3.4), we show upper limits only for the low-spin case, following previous studies (Abac et al. 2026c). As expected from Equation (8), our rate limits are more constraining by a factor comparable to the increases in $\langle VT \rangle$ from O4a to O4a+b. The lowest upper limits $\mathcal{R}_{90}$ are $66.8 \text{ Gpc}^{-3} \text{ yr}^{-1}$, $72.0 \text{ Gpc}^{-3} \text{ yr}^{-1}$, and $50.0 \text{ Gpc}^{-3} \text{ yr}^{-1}$ for GstLAL, MBTA, and PyCBC respectively.

We also report upper limits on the merger rate as a function of $m_{1,2}$, following the binning described in Section 3.4, as shown in Figure 8. We find the most constraining limit $\mathcal{R}_{90}$ to be $65.6 \text{ Gpc}^{-3} \text{ yr}^{-1}$, $68.0 \text{ Gpc}^{-3} \text{ yr}^{-1}$, and $47.8 \text{ Gpc}^{-3} \text{ yr}^{-1}$ for GstLAL, MBTA, and PyCBC respectively. Blank bins correspond to two cases: the $(m_1, m_2) = (6.74\text{--}8.92, 0.19\text{--}0.37) M_\odot$ bin, which is found to have an excessive variance (see Figure 4), and the $(m_1, m_2) = (8.92\text{--}11.10, 0.19\text{--}0.37) M_\odot$ bin, which corresponds to zero efficiency.

Additionally, we report the upper limit on the SSM BNS merger rate at the 90% confidence level based on the MBTA and PyCBC results, assuming a simple fixed population model as in Abac et al. (2026) (SIMPLE UNIFORM BNS). This consists of a uniform mass distribution between $0.5 M_\odot$ and $2.5 M_\odot$ for m_1 , and a uniform mass distribution between $0.5 M_\odot$ and $1.0 M_\odot$ for m_2 with $m_2 \leq m_1$, isotropically distributed spins with uniform spin magnitudes below 0.4, and a merger rate uniform in comoving volume up to $z_{\text{max}} = 0.2$. Following the same loudest event formalism we find the upper limit at the 90% confidence level to be $249 \text{ Gpc}^{-3} \text{ yr}^{-1}$. In Figure 9 we show the relative improvement from O4a and combined runs in the estimation of the upper limit. Our inferred SSM BNS merger rate limit lies at the upper limit of the rate interval estimated in (Abac et al. 2026) ($8.8\text{--}250 \text{ Gpc}^{-3} \text{ yr}^{-1}$) for BNS with masses above $1 M_\odot$, assuming the SIMPLE UNIFORM BNS distribution. While these rates are not strictly comparable due to the different NS mass ranges considered, we cannot rule out that the rate of SSM BNS is close to that of super-solar mass BNS.

5. DARK MATTER CONSTRAINTS

The upper limits on merger rates obtained in Section 4 are the main results derived from our SSM search through O4a and O4b, being the most restrictive to date. These limits can be used to constrain any model that predicts a non-negligible rate of binary mergers within the parameter space analysed by the search. In particular, we use the rates and sensitivities of low-spin SSM BBHs for the constraints presented in the following sections. Following Abac et al. (2026c), in the next subsections we update the constraints on two possible sources of BBH mergers: primordial black holes in Section 5.1 and dissipative dark matter black holes in Section 5.2.

5.1. Primordial Black Holes

PBHs are natural dark matter candidates that could give rise to BBH mergers in the SSM range. Many models have been proposed (Carr et al. 2024; Bagui et al. 2025) for which the PBH abundance is characterized by the fraction of the dark matter cosmological density in the form of PBHs, $f_{\text{PBH}} = \rho_{\text{PBH}}/\rho_{\text{DM}}$, where ρ_{PBH} and ρ_{DM} are the present-day

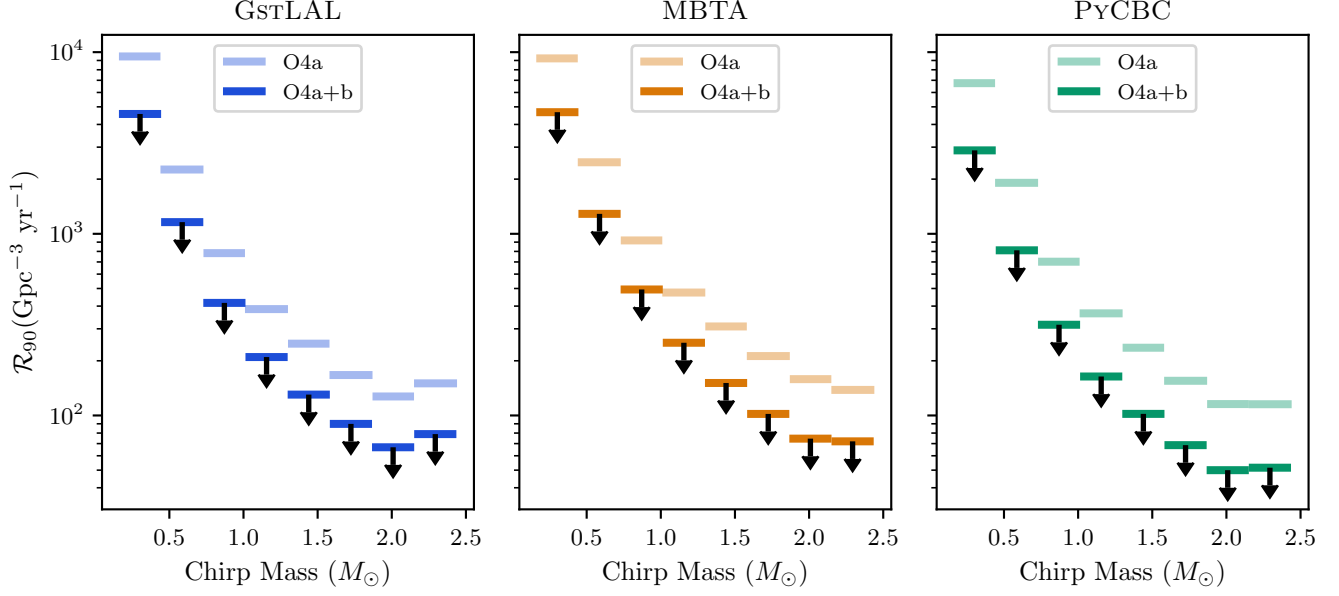


Figure 7. 90% confidence upper limit $\mathcal{R}_{90}$ on the merger rate for a BBH population, inferred for O4a and the combined O4a+b runs, displayed for each pipeline as a function of chirp mass. Arrows point in the direction of the possible merger rate not constrained by the O4a+b search.

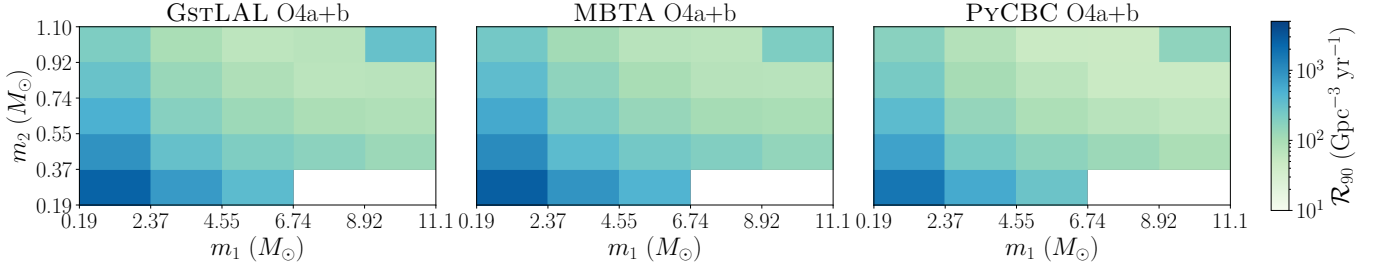


Figure 8. 90% confidence upper limit $\mathcal{R}_{90}$ on the merger rate as a function of $m_{1,2}$ for the combined O4a+b runs, displayed for each pipeline.

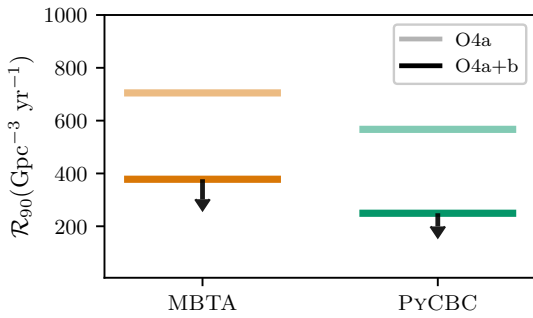


Figure 9. 90% confidence level upper limit on a broad population of SSM BNSs reported by PyCBC and MBTA during O4a and combined O4a+b runs. Arrows point in the direction of the possible merger rate not constrained by the O4a+b search.

mass densities of PBHs and dark matter, respectively. Models also differ in the shape of the PBH mass distribution, which depends in detail on specific formation mechanisms.

Furthermore, PBH models producing GW signals today involve environments in which binaries can form and merge.

Possible constraints on f_{PBH} , based on our BBH merger rate upper limits, are thus particularly dependent on model assumptions. First of all, merger rates depend strongly on the initial (extended) mass distributions, which determine the relative abundance of mass combinations in the binaries and the properties of the PBH clusters. Secondly, the merger rate predictions are strongly influenced by complex phenomena of the formation environment, such as many-body interactions and non-linear gravitational effects, which are difficult to model accurately. Finally, specifically for SSM BHs, the merger times may be so much longer than the age of the universe that the probability of detecting a single merger in a given LVK observation run is negligible. PBH binaries are commonly assumed to form in two different scenarios, that we refer as early binaries and late binaries. Early binaries (EB) bind shortly after PBH formation as pairs of PBHs decouple from the Universe's expansion

and form eccentric binaries through tidal interactions with nearby PBHs (Nakamura et al. 1997). Consequently, merger rates of EB are strongly influenced by the initial PBH clustering and mass distribution (Carr et al. 2026). In contrast, late binaries (LB) form in dense halos through dynamical interactions, with merger rates shaped by local density and halo properties (Siles & García-Bellido 2025).

To illustrate how the upper limit of merger rates can be mapped to constraints on an underlying astrophysical population of PBHs, we model the merger rate of EB as in Abbott et al. (2023b), using the analytical approximations developed in Hütsi et al. (2021); Vaskonen & Veermäe (2020); Chen & Huang (2018); Ali-Haïmoud et al. (2017) and parametrized with N -body simulations via Raidal et al. (2019)

$$\frac{d^2 \mathcal{R}_{\text{EB}}^{\text{PBH}}}{d \ln m_A d \ln m_B} = 1.6 \times 10^6 \text{ Gpc}^{-3} \text{ yr}^{-1} \times f_{\text{sup}} f_{\text{PBH}}^{53/37} \times f(\ln m_A) f(\ln m_B) \left(\frac{m_A + m_B}{M_\odot} \right)^{-32/37} \left[\frac{m_A m_B}{(m_A + m_B)^2} \right]^{-34/37}, \quad (9)$$

where m_A and m_B denote the component masses of the PBH binary, without imposing any ordering between them, in contrast to the convention $m_1 \geq m_2$ used elsewhere. The normalized PBH mass function $f(\ln m) = 1/\rho_{\text{DM}} \cdot d\rho_{\text{PBH}}/d \ln m$ is defined as the differential PBH energy density with respect to $\ln m$, normalised to the total energy density in DM. The suppression factor f_{sup} accounts for binary disruption due to gravitational interactions with other PBHs or surrounding matter. The merger-rate expression of Equation (9), while widely used in the literature, has only been validated by N -body simulations in the case of monochromatic and narrow peaked mass distributions. The simulations of Raidal et al. (2019) consider $\sim O(10^2)$ equal-mass $\sim 30 M_\odot$ PBHs with $f_{\text{PBH}} \lesssim 0.1$, which differs significantly from the lower masses and larger PBH abundances explored here. Further developments in EB formation may substantially change the suppression factor in the case of extended mass functions; in this study we adopt $f_{\text{sup}} = 2.3 \times 10^{-3} f_{\text{PBH}}^{-0.65}$ to remain consistent with Abbott et al. (2023b), which represents a high-suppression scenario (Hütsi et al. 2021), and thus yields conservative constraints, in the monochromatic mass case.

Predicting the merger rate of LB involves the modeling of complex dynamical interactions. Following Clesse & García-Bellido (2022); Phukon et al. (2021), we assume

$$\frac{d^2 \mathcal{R}_{\text{LB}}^{\text{PBH}}}{d \ln m_A d \ln m_B} = R_{\text{clust}} f_{\text{PBH}} f(\ln m_A) f(\ln m_B) \frac{(m_A + m_B)^{10/7}}{(m_A m_B)^{5/7}}, \quad (10)$$

where R_{clust} is a scaling factor that depends on the PBH clustering properties, including their velocity distribution. While there is general agreement on the mass dependence of the LB

merger rate (e.g., Clesse & García-Bellido 2017), the overall amplitude remains highly uncertain due to its strong sensitivity to the underlying clustering scenario. As in Clesse & García-Bellido (2022); Phukon et al. (2021), and to remain consistent with Abbott et al. (2023b), we assume $R_{\text{clust}} = 420 \text{ Gpc}^{-3} \text{ yr}^{-1}$; this overall factor can be easily rescaled for different assumptions or clustering models.

We use the theoretical merger rate models of Equations (9, 10) to set upper limits on f_{PBH} , assuming a monochromatic PBH mass distribution, i.e., $f(\ln m) = \delta(\ln m - \ln m_{\text{PBH}})$. The limits are obtained by identifying the value of f_{PBH} for which the theoretical rates match the 90% confidence upper bounds on merger rates derived using Equation (8). Figure 10 shows the resulting upper limits for both EB and LB for the GstLAL, MBTA, and PyCBC pipelines searching the combined O4a+b run, as well as the O4a results for comparison. The upper limits obtained in the combined O4a+b run are approximately half of the O4a ones, reflecting the comparable duration of the O4a and O4b observing periods. The combined O4a+b runs provide the strongest LVK limits to date on the PBH fraction, $f_{\text{PBH}} \leq (0.018-0.032)$ at $1 M_\odot$ and $f_{\text{PBH}} \leq (0.10-0.18)$ at $0.35 M_\odot$. These direct search constraints are complementary to the bounds derived from the non-observation of a stochastic GW background from inspiralling SSM PBH binaries at high redshift (Boyd et al. 2025; Abac et al. 2025b).

While the constraints presented above assume a monochromatic PBH mass function, this is not realistic in most early formation scenarios (Carr et al. 2024). PBHs are generally expected to form with an extended and non-trivial mass distribution (Bagui et al. 2025). To remain agnostic about the specific shape of the mass function, we instead constrain the quantity

$$F_{\text{PBH}} = \frac{f_{\text{sup}}}{2.3 \times 10^{-3}} f_{\text{PBH}}^{53/37} f(\ln m_A) f(\ln m_B) = f_{\text{PBH}}^{0.78} f(\ln m_A) f(\ln m_B), \quad (11)$$

which encapsulates the dependence of the merger rate of EB on both the PBH abundance f_{PBH} , and the underlying mass distribution $f(\ln m)$. The definition of F_{PBH} explicitly incorporates the assumption $f_{\text{sup}} = 2.3 \times 10^{-3} f_{\text{PBH}}^{-0.65}$ adopted throughout this study.

Limits on F_{PBH} are determined by finding the value for which the theoretical merger rate for EB matches the 90% confidence level upper bounds derived from Equation (8). We constrain F_{PBH} only for EB, since its definition in Equation (11) is specific to this scenario, and merger rate models for LB are more uncertain and less constraining. We adopt the binning in (m_1, m_2) from Section 4, and write the integral in Equation (9) within each bin as

$$\mathcal{R}_{\text{EB}}^{\text{PBH}} = 3.68 \times 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1} \bar{F}_{\text{PBH}} \times \left(\frac{\bar{m}_1 + \bar{m}_2}{M_\odot} \right)^{-32/37}$$

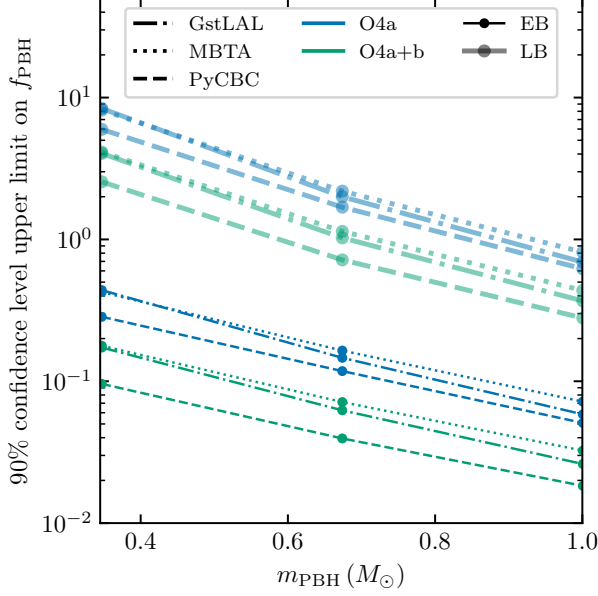


Figure 10. Upper limits on the PBH dark matter fraction f_{PBH} as a function of PBH mass m_{PBH} . Constraints are derived using the merger rate models given by Equation (9) for early binaries, and Equation (10) for late binaries, assuming monochromatic mass functions. Results are shown at the 90% confidence level using the sensitive hypervolumes $\langle VT \rangle$ calculated for GstLAL, MBTA, and PyCBC for the combined O4a+O4b runs. Previous O4a results are also shown for comparison.

$$\times \left[\frac{\bar{m}_1 \bar{m}_2}{(\bar{m}_1 + \bar{m}_2)^2} \right]^{-34/37} \ln \left(\frac{m_1^{\max}}{m_1^{\min}} \right) \ln \left(\frac{m_2^{\max}}{m_2^{\min}} \right), \quad (12)$$

where $m_{1,2}^{\min}$ and $m_{1,2}^{\max}$ denote the bin edges for the component masses, $\bar{m}_{1,2} = (m_{1,2}^{\min} + m_{1,2}^{\max})/2$ is the central value, and $\bar{F}_{\text{PBH}}$ denotes the effective bin-averaged value of F_{PBH} , defined implicitly such that Equation (12) reproduces the exact integral of the merger rate over the bin.

Figure 11 shows the median 90% upper limit on $\bar{F}_{\text{PBH}}$ across all search pipelines, based on the results from the combined runs O4a+b. We find that $\bar{F}_{\text{PBH}}$ is constrained to be less than unity across the entire range of (m_1, m_2) explored in this study, with upper limits a factor two below those obtained from O4a.

5.2. Dissipative Dark Matter

The method to constrain the fraction of dissipative dark matter in the binary dark matter budget is nearly identical to that used in the analyses of Abac et al. (2026c), but with a key change in that we now report upper limits on f_{DBH} conditional on $M_{\min}$, and the complementary bound on $M_{\min}$ conditional on f_{DBH} , rather than a two-dimensional credible region. Each conditional bound therefore depends only on the posterior at the given value of $M_{\min}$ (or f_{DBH}), not on how the posterior behaves elsewhere in the parameter space. In this

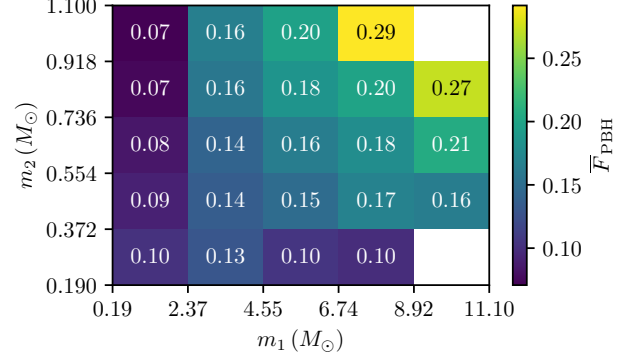


Figure 11. Upper limits on $\bar{F}_{\text{PBH}}$, Eq. (11), as a function of the PBH binary component masses m_1 and m_2 . Constraints are derived using the early binary merger rate model of Equation (12). We show the median 90% upper limit across GstLAL, MBTA, and PyCBC calculated using their sensitive hypervolumes $\langle VT \rangle$ in the combined O4a and O4b runs.

section, we reiterate the methods and update the constraints with the search pipeline sensitivity, which combines results from the SSM search in O4a data and O4b data.

Dissipative dark matter is a class of models which posit that dark matter may have complex particle interactions similar to those of the Standard Model, including dissipative processes. Whenever there is a fermion in the model, dark matter has a Chandrasekhar limit analogous to that of the Standard Model, but with a value that depends on the dark matter particle mass(es) (Mohapatra & Teplitz 1999; D’Amico et al. 2018; Shandera et al. 2018; Choquette et al. 2019; Chang et al. 2019; Bramante et al. 2024). In dissipative scenarios, particle interactions allow energy to be transported away from gravitationally bound systems such as dark matter halos. These dissipative interactions become more efficient in denser regions, and some dense regions may dissipate energy efficiently enough for gravity to dominate, leading to the formation of ultra-compact objects made of dark matter. When those are sufficiently massive, above the dark Chandrasekhar limit, they are dark black holes. Therefore, GW signals from DBH binaries provide a way to probe the microphysics of dissipative dark matter even if it is not coupled to the Standard Model beyond gravity, or if the coupling is too weak to be detectable in the near future.

Although the fragmentation scale of the dark gas depends on the chemistry of the dark sector, the dynamical processes that lead to the formation of compact objects are analogous to those in star formation. While simulation of such small-scale phenomena in novel dark matter scenarios remains challenging, it is reasonable to expect that the initial mass function and binary fraction of DBHs are qualitatively similar to that of baryonic objects. For the particular worked example of atomic dark matter (Ackerman et al.

2009; Kaplan et al. 2011; Cyr-Racine & Sigurdson 2013), where cooling and compact object formation has been extensively studied (Rosenberg & Fan 2017; Ryan et al. 2022a; Gurian et al. 2022; Ryan et al. 2022b), there is a close parallel between DBH formation and Population III star formation that further supports this statement. Thus, we use a truncated power-law mass model characterized by a minimum mass $M_{\min}$, power $-b$, and ratio of maximum mass to minimum mass $r = M_{\max}/M_{\min}$, and assume a binary fraction of $f_{\text{binary}} = 0.26$ (Shandera et al. 2018) in our analysis. The total number of DBHs in this population is set by $f_{\text{DBH}} \equiv \rho_{\text{DBH}}/\rho_{\text{DM}}$ where ρ_{DBH} and ρ_{DM} are the densities of DBHs and dark matter, respectively. The rate of DBH binaries merging in this population, $\mathcal{R}$, is computed as (Singh et al. 2021)

$$\frac{d\mathcal{R}(\mathcal{M} | f_{\text{DBH}}, \theta)}{d\mathcal{M}} = \left[p(\mathcal{M} | t_m, \theta) p(t_m | \theta) \right]_{t_m=10 \text{ Gyr}} \times \left(\frac{f_{\text{DBH}} \rho_{\text{DM}} f_{\text{binary}}}{\langle M \rangle} \right), \quad (13)$$

where $p(\mathcal{M} | t_m, \theta)$ is the distribution of chirp mass with a time of merging t_m , $p(t_m | \theta)$ is the probability distribution of times-to-merger (these two factors evaluated at $t_m = 10$ Gyr), $\rho_{\text{DM}} = 3.3 \times 10^{19} M_{\odot} \text{ Gpc}^{-3}$ (Aghanim et al. 2020), and $\langle M \rangle$ is the average component mass of the DBH binaries. The merger times are calculated using Peters' formula for coalescing binaries (Peters & Mathews 1963).

We use a Bayesian analysis to constrain this population of DBHs by modeling the number of detected binaries with a Poisson distribution in each of 99 uniformly spaced chirp mass bins spanning $0.16 M_{\odot} \leq \mathcal{M} \leq 2.72 M_{\odot}$. With the non-detection of significant SSM candidates, the likelihood in the i -th chirp-mass bin is $P(0 | \mathcal{R}_i, \langle VT \rangle_i, \mathcal{M}) = e^{-\mathcal{R}_i \langle VT \rangle_i}$, where the rate $\mathcal{R}_i$ is determined by integrating Equation (13) over the width of the i -th chirp mass bin, and the sensitive hypervolume VT_i is informed by this SSM search. To ensure an overall non-detection result, which will be applicable to each chirp mass bin, we adopt a more stringent FAR threshold of 0.01 yr^{-1} when estimating the pipeline-specific $\langle VT \rangle_{\text{O4a+b}}$ for this analysis. Additionally, we are discarding S241229bq which has a FAR below 0.01 yr^{-1} due to it being consistent with noise as detailed in Section 2.4.

We use priors consistent with previous analyses (Abbott et al. 2022, 2023b): uniform in log-space priors on $M_{\min}$ over the interval $[10^{-3}, 3.1] M_{\odot}$, and f_{DBH} over the interval $[10^{-10}, 1]$, and a log-uniform prior on r over the interval $[2, 1000]$, as well as a uniform in linear-space prior on b over the interval $[-1, 2]$. From Bayes' theorem, the log-posterior is then

$$\ln p(f_{\text{DBH}}, M_{\min}, r, b) = - \sum_i \mathcal{R}_i(f_{\text{DBH}}, M_{\min}, r, b) \langle VT \rangle_i - \ln r + C, \quad (14)$$

where C is a normalization constant.

Analyses through the end of O3b evaluated the posterior distribution using a grid-based method (Abbott et al. 2022, 2023b), while we use the Markov chain Monte Carlo (MCMC) sampler EMCEE (Foreman-Mackey et al. 2013) to explore the parameter space for faster convergence in this analysis. We marginalize over r and b to constrain f_{DBH} and $M_{\min}$. The resulting posterior is two-dimensional; we then compute the one-dimensional probability density over f_{DBH} conditioned on $M_{\min}$ and use this to obtain the 90% upper bound $f_{\text{DBH},90\%}(M_{\min})$ by solving

$$\int_0^{f_{\text{DBH},90\%}(M_{\min})} p(f_{\text{DBH}} | M_{\min}) df_{\text{DBH}} = 0.9 \quad (15)$$

for each $M_{\min}$, where $p(f_{\text{DBH}} | M_{\min}) = p(f_{\text{DBH}}, M_{\min}) / \int p(f_{\text{DBH}}, M_{\min}) df_{\text{DBH}}$. Both integrals are evaluated as sums over the f_{DBH} bins of the two-dimensional sample histogram. The $\langle VT \rangle$ values are updated relative to Abac et al. (2026c) by incorporating $\langle VT \rangle_{\text{O4a+b}}$, and the $\langle VT \rangle_{\text{O4a}}$ constraints quoted here are recomputed from the corresponding posterior samples using this method, so they differ from the values reported there. Figure 12 shows $f_{\text{DBH},90\%}(M_{\min})$ derived from $\langle VT \rangle_{\text{O4a}}$ and from the combined $\langle VT \rangle_{\text{O4a+b}}$ for GstLAL, MBTA, and PyCBC individually. As described in Section 3, the combined $\langle VT \rangle_{\text{O4a+b}} > \langle VT \rangle_{\text{O4j}}$ where $j = a, b$. Hence, the combined analysis provides the most stringent constraint.

Applied to $\langle VT \rangle_{\text{O4a}}$ alone, the 90% upper limit reaches $f_{\text{DBH}} = (1.8\text{--}2.5) \times 10^{-5}$, where the range arises from the differing sensitivities of the search pipelines. Including O4b tightens this by nearly a factor of 2, with the combined $\langle VT \rangle_{\text{O4a+b}}$ giving $f_{\text{DBH}} = (1.0\text{--}1.1) \times 10^{-5}$. These are reached at $M_{\min} \approx (0.65\text{--}0.80) M_{\odot}$ and $(0.65\text{--}0.85) M_{\odot}$ for O4a and O4a+b, respectively. These limits on f_{DBH} are consistent with the dissipative dark matter scenario as the formation channel requires efficient cooling, which only occurs in regions dense in dark matter. We exclude limits where $M_{\min} > 1 M_{\odot}$ as an SSM detection necessitates the minimum mass to be smaller than $1 M_{\odot}$. Conditioning instead on f_{DBH} and integrating over $M_{\min}$ gives the complementary statement that for $f_{\text{DBH}} = 1$ the analysis excludes $M_{\min} > (4.2\text{--}4.8) \times 10^{-2} M_{\odot}$ using $\langle VT \rangle_{\text{O4a}}$ alone, tightening to $M_{\min} > (4.2\text{--}4.4) \times 10^{-2} M_{\odot}$ with the combined $\langle VT \rangle_{\text{O4a+b}}$. These constraints appear weaker than those of Abac et al. (2026c), where the exclusion region was reported to extend as low as $f_{\text{DBH}} = (0.9\text{ to }1.2) \times 10^{-5}$ at $1 M_{\odot}$ and $M_{\min} > 0.020 M_{\odot}\text{--}0.021 M_{\odot}$ at $f_{\text{DBH}} = 1$, respectively. Those bounds were obtained from a global two-dimensional

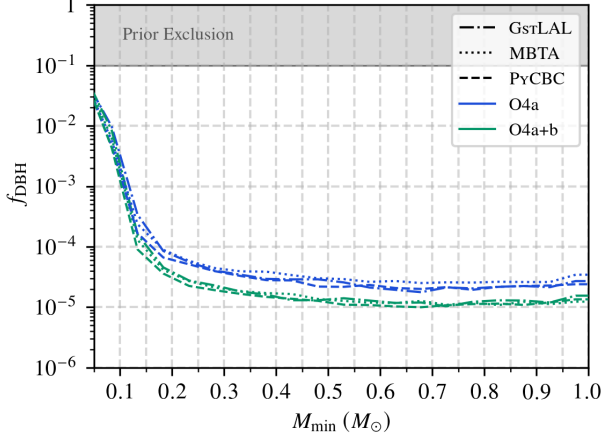


Figure 12. Conditional 90% upper limits on f_{DBH} as a function of M_{min} for the atomic dark matter model, after marginalizing over the ratio of maximum to minimum mass and the slope of the black hole population. The samples are binned in the $f_{\text{DBH}}-M_{\text{min}}$ plane, and within each M_{min} bin the posterior is normalized and integrated in f_{DBH} following Equation (15); values of f_{DBH} above each curve are excluded. The shaded band marks the 90% quantile of the f_{DBH} prior, shown for reference as the level a limit approaches where the data is uninformative. Constraints are shown for the GStLAL, MBTA, and PyCBC pipelines, derived from $\langle VT \rangle_{\text{O4a}}$ and from the combined $\langle VT \rangle_{\text{O4a+b}}$, each evaluated with a FAR threshold of 0.01 yr^{-1} . The improvement from $\langle VT \rangle_{\text{O4a}}$ to $\langle VT \rangle_{\text{O4a+b}}$ is roughly a factor of two across the range where the data best constrains f_{DBH} .

90% highest posterior density region, considering the joint posterior across the full $(M_{\text{min}}, f_{\text{DBH}})$ parameter space. That construction introduces a non-local dependence on both parameters: the location of the 90% contour in a given region of parameter space depends on how strongly the posterior is constrained elsewhere in the joint distribution. (For example the quoted bound on M_{min} at $f_{\text{DBH}} = 1$ depends on how strongly the population is constrained near $M_{\text{min}} = 1 M_{\odot}$.) In contrast the bounds we quote here are conditional on a given value of M_{min} or of f_{DBH} , hence are independent of how the posterior behaves elsewhere.

The range of dark fermion masses m_{χ} probed by this search is set by M_{min} via dark Chandrasekhar mass, $M_{\text{Chandra}}^{\text{Dark}} \propto M_{\text{Planck}}^3 / (\mu^{\text{Dark}} m_{\chi})^2 \leq M_{\text{min}}$, where $\mu^{\text{Dark}} m_{\chi}$ is the mass per degenerate fermion (Chandrasekhar 1931). We derive a bound on the ratio of m_{χ} to the mass of the Standard Model proton m_p by taking the ratio of the stellar Chandrasekhar mass to the dark Chandrasekhar mass as

$$\mu^{\text{Dark}} \frac{m_{\chi}}{m_p} = 2 \sqrt{\frac{1.4 M_{\odot}}{M_{\text{Chandra}}^{\text{Dark}}}} \geq 2 \sqrt{\frac{1.4 M_{\odot}}{M_{\text{min}}}}, \quad (16)$$

where we set the stellar Chandrasekhar mass to $1.4 M_{\odot}$ and the corresponding μ^{Stellar} to 2.

Previous searches (Abbott et al. 2023b) used the Standard Model value of $\mu^{\text{Dark}} = 2$, but we report the bound leaving

μ^{Dark} unspecified to cover a broader range of dissipative dark matter models, as done in Abac et al. (2026c). The lower end of the range is 2.4, set by the largest minimum mass considered, $M_{\text{min}} = 1 M_{\odot}$, and is common to both analyses. Using $\langle VT \rangle_{\text{O4a}}$ alone, the search probed $\mu^{\text{Dark}} m_{\chi} / m_p$ up to (10.8–11.5), extending to (11.3–11.7) with the combined $\langle VT \rangle_{\text{O4a+b}}$, where the spread arises from the differing sensitivities of the search pipelines. Again, these bounds appear weaker than those reported in Abac et al. (2026c), which reported to probe $\mu^{\text{Dark}} m_{\chi} / m_p$ up to 16.5–16.6, because the bound is obtained directly from the corresponding constraint on M_{min} . A future detection would be able to put a direct bound on the microphysics of dissipative dark matter.

6. CONCLUSION

We present results from searches for SSM compact objects in data of the second part of the fourth observing run of the LIGO–Virgo–KAGRA Collaboration. No significant candidate is reported by any of the three participating search pipelines. Outlier candidates identified by the GStLAL pipeline and the MBTA pipeline do not reach a sufficient level of significance to provide evidence for detection, and are consistent with noise fluctuations. Given the null detection result, we report updated upper limits on the merger rates for SSM BBHs with masses greater than $0.2 M_{\odot}$ using the estimated search sensitivity.

Using the inferred sensitive hypervolume and limits on the merger rate of SSM BBHs, we update the constraints on two dark matter models: PBHs, and DBHs that form in a dissipative dark matter model. While both models can populate the sub-solar and super-solar regimes, we turn to the SSM parameter space for clear evidence of such objects because no known astrophysical channel produces SSM black holes.

In the PBH scenario, we set informative constraints on the fraction of dark matter in PBHs f_{PBH} in late-forming binaries, as done previously in Abac et al. (2026c): we infer that $f_{\text{PBH}} < 1$ at the 90% confidence interval for $m_{\text{PBH}} \gtrsim (0.62\text{--}0.74) M_{\odot}$. For early-forming PBH binaries, adopting a conservative model that accounts for binary disruption, we obtain f_{PBH} upper limits between (0.10–0.18) and (0.018–0.032) over the range of PBH masses probed by the searches for SSM systems in O4a and O4b. For the dissipative dark matter scenario, where SSM DBH are assumed to form with some minimum possible mass, we bound the fraction of the total dark matter density in the Universe in DBHs; our most restrictive limit, for a minimum mass (0.65–0.85) $M_{\odot}$, is $(1.0\text{--}1.1) \times 10^{-5}$.

The SSM searches using O4a data provided the sensitivity of LVK SSM searches to binaries containing low-mass neutron stars for the first time by including tides in the simulated signals. In this paper, we updated the sensitivity for this region using our SSM analyses of O4b data. We find

the typical sensitive hypervolume to be $\langle VT \rangle \sim 10^{-3} \text{ Gpc}^3 \text{ yr}$ for populations of BNSs with at least one SSM neutron star. These searches can also provide insight into matter at high densities given the overlap of the neutron star and SSM parameter space, serving as motivation for low-latency SSM searches (All  n   et al. 2025; Hanna et al. 2024) which started to release alerts on March 4, 2025, and continued through the end of O4.

The LIGO and Virgo detectors continued observations in the O4c with similar sensitivities to O4b, and were joined by the KAGRA detector for parts of the remainder of O4. The increase in observing time is expected to increase our search sensitivities, leading to improvements to the constraints we can place on the merger rates of SSM BBHs. O4 ended on November 18, 2025, and the next data collection period is planned to begin in late 2026, with subsequent runs expected to approach the design sensitivity of the detector network.³ These advances will provide more stringent limits on the fraction of dark matter in SSM compact objects, or possibly detect a GW signal originating from the merger of SSM compact objects. Such a detection would have deep implications for fundamental physics.

DATA AVAILABILITY

All strain data analysed as part of this publication are publicly available through Gravitational Wave Open Science Center (GWOSC). The details of this data release are described in detail in Abac et al. (2026). Associated data release includes trigger files for candidates reported in Table 1, BBH sensitive volume-time, and injection results used in the calculation of sensitive volume-time reported in this paper (LIGO–Virgo–KAGRA Collaboration 2026).

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³ Current observing plans are maintained at <https://observing.docs.ligo.org/plan/>.

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Facility: LIGO

Facility: Virgo

Software: Calibration of the LIGO strain data was performed with a GstLAL-based calibration software pipeline (Viets *et al.* 2018). Data-quality products and event-validation results were computed using the DMT (Zweizig 2006), DQR (LIGO Scientific Collaboration and Virgo Collaboration 2018), DQSEGDB (Fisher *et al.* 2021), GWDETCAR (Urban *et al.* 2021), HVETO (Smith *et al.* 2011), IDQ (Essick *et al.* 2020), OMICRON (Robinet *et al.* 2020), PEMCHECK (Helmling-Cornell *et al.* 2024) and PYTHON-VIRGOTOOLS (Virgo Collaboration 2021) software packages and contributing software tools. Analyses relied upon the LALSUITE software library (LIGO-Virgo-KAGRA Collaboration 2018; Wette 2020). The identification of the signal candidates and subsequent significance evaluations in this paper were performed with the GstLAL-based inspiral software pipeline (Messick *et al.* 2017; Sachdev *et al.* 2019; Hanna *et al.* 2020; Cannon *et al.* 2021), with the MBTA pipeline (Adams *et al.* 2016; Aubin *et al.* 2021), and with the PyCBC pipeline (Usman *et al.* 2016; Nitz *et al.* 2017; Davies *et al.* 2020). Sensitive Hypervolume calculations were performed using GWPOPULATION (Talbot *et al.* 2025). Plots were prepared with MATPLOTLIB (Hunter 2007), SEABORN (Waskom 2021) and GWPY (Macleod *et al.* 2021). NUMPY (Harris *et al.* 2020), SciPy (Virtanen *et al.* 2020) and PANDAS (pandas de-

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