Searches for binary mergers including sub-solar mass compact objects in data from the first part of LIGO-Virgo-KAGRA’s fourth observing run

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Structure

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Purpose of the paper

ABSTRACT

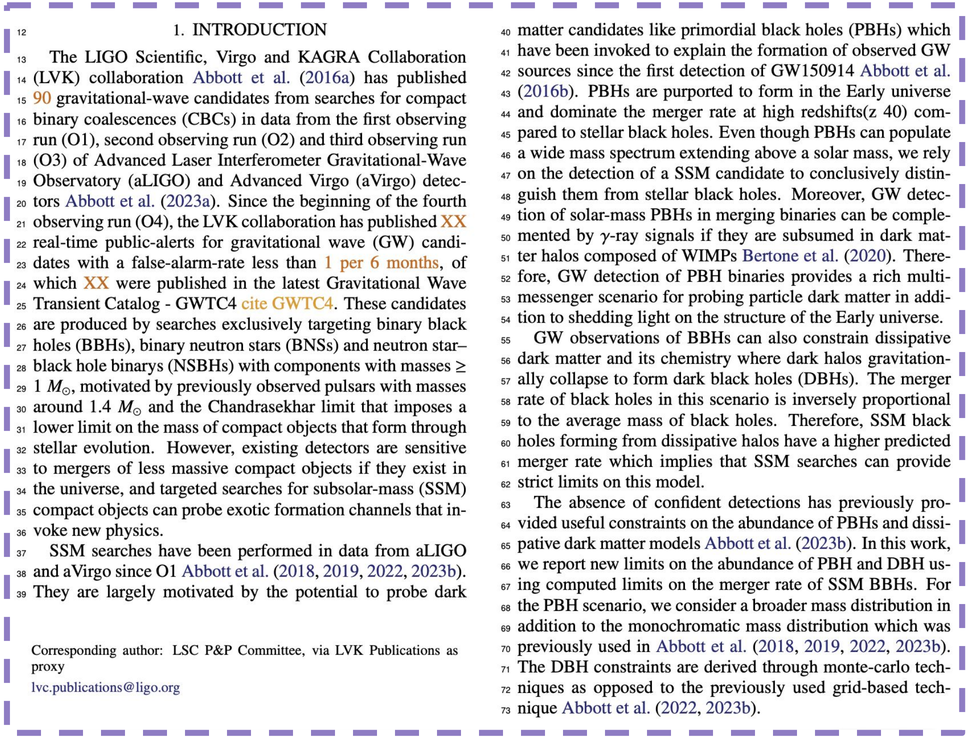
We present results from searches for compact binary coalescesnces including at least one sub-solar mass compact object conducted by three search algorithms. Information about significant triggers. We also perform sensitivity studies for the population of sub-solar mass black hole binaries targeted by this search while extending th4 scope to include low-mass neutron star binaries. Using the sensitivity estimates, we constrain the rate of these mergers. Statement about merger rate limits. Furthermore, we constrain dark matter models that predict the formation of sub-solar mass compact objects. Statement about PBH constraints and DBH constraints.

→ Search for SSM

→ Estimate of the VT for ‘BBH’ and ‘BNS’

→ Constrain dark matter model

Introduction



1. INTRODUCTION

The LIGO Scientific, Virgo and KAGRA Collaboration (LVK) collaboration Abbott et al. (2016a) has published 90 gravitational-wave candidates from searches for compact binary coalescences (CBCs) in data from the first observing run (O1), second observing run (O2) and third observing run (O3) of Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) and Advanced Virgo (aVirgo) detectors Abbott et al. (2023a). Since the beginning of the fourth observing run (O4), the LVK collaboration has published XX real-time public-alerts for gravitational wave (GW) candidates with a false-alarm-rate less than 1 per 6 months, of which XX were published in the latest Gravitational Wave Transient Catalog - GWTC4 cite GWTC4. These candidates are produced by searches exclusively targeting binary black holes (BBHs), binary neutron stars (BNSs) and neutron star–black hole binarys (NSBHs) with components with masses ≥ 1 $M_\odot$, motivated by previously observed pulsars with masses around 1.4 $M_\odot$ and the Chandrasekhar limit that imposes a lower limit on the mass of compact objects that form through stellar evolution. However, existing detectors are sensitive to mergers of less massive compact objects if they exist in the universe, and targeted searches for subsolar-mass (SSM) compact objects can probe exotic formation channels that invoke new physics.

SSM searches have been performed in data from aLIGO and aVirgo since O1 Abbott et al. (2018, 2019, 2022, 2023b). They are largely motivated by the potential to probe dark matter candidates like primordial black holes (PBHs) which have been invoked to explain the formation of observed GW sources since the first detection of GW150914 Abbott et al. (2016b). PBHs are purported to form in the Early universe and dominate the merger rate at high redshifts(z 40) compared to stellar black holes. Even though PBHs can populate a wide mass spectrum extending above a solar mass, we rely on the detection of a SSM candidate to conclusively distinguish them from stellar black holes. Moreover, GW detection of solar-mass PBHs in merging binaries can be complemented by γ-ray signals if they are subsumed in dark matter halos composed of WIMPs Bertone et al. (2020). Therefore, GW detection of PBH binaries provides a rich multi-messenger scenario for probing particle dark matter in addition to shedding light on the structure of the Early universe.

GW observations of BBHs can also constrain dissipative dark matter and its chemistry where dark halos gravitationally collapse to form dark black holes (DBHs). The merger rate of black holes in this scenario is inversely proportional to the average mass of black holes. Therefore, SSM black holes forming from dissipative halos have a higher predicted merger rate which implies that SSM searches can provide strict limits on this model.

The absence of confident detections has previously provided useful constraints on the abundance of PBHs and dissipative dark matter models Abbott et al. (2023b). In this work, we report new limits on the abundance of PBH and DBH using computed limits on the merger rate of SSM BBHs. For the PBH scenario, we consider a broader mass distribution in addition to the monochromatic mass distribution which was previously used in Abbott et al. (2018, 2019, 2022, 2023b). The DBH constraints are derived through monte-carlo techniques as opposed to the previously used grid-based technique Abbott et al. (2022, 2023b).

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→ Discuss the motivations for this search

- Detect mergers with a sub-solar component (**no stellar formation channel known**)
  → Primordial black holes (PBHs)
  → Dissipative dark matter…

- Detect EM-bright signals
  → Multimessenger astronomy

Search : presentation of the pipelines

2. SEARCH

Description of the search: Participating pipelines and template bank design

Three pipelines – GstLAL, MBTA, and PyCBC —- analyzed data collected during the first half of the fourth observing run, covering the period from 24 May 2023 to 16 January 2024. These pipelines use matched-filtering techniques, correlating the data with a bank of simulated CBC waveforms (hereinafter referred to as "templates" for simplicity) with identical parameter space coverage across all pipelines. The template bank is designed to detect CBCs with primary masses between $0.2M_\odot$ and $10.0M_\odot$, and secondary masses between $0.2M_\odot$ and $1.0M_\odot$ in the detector frame. The binary mass ratio, $q = m_2/m_1$ ($m_2 \leq m_1$), is restricted to values between 0.1 and 1.0 to maintain a manageable number of templates in the bank. Aligned spin effects are included, with the absolute value of the spin magnitude limited to 0.9 for components exceeding $0.5M_\odot$ and to 0.1 for smaller masses. To enhance signal recovery while controlling computational cost, a minimal match of 0.97 is ensured, and data analysis begins at 45 Hz.

The three pipelines are independent and have specific features in their analyses, which are outlined below.

2.1. *GstLAL*

GstLAL Messick et al. (2017); Sachdev et al. (2019) is a Gstreamer-based Inspiral pipeline searching for gravitational wave from CBC. The detailed methods and detection statistic that GstLAL applies can be found at[cite GWTC4 method paper section 3.2] Hanna et al. (2020); Cannon et al.

sick et al. (2017). Several improved ranking statistic and gating is added to GstLAL search since Abbott et al. (2023b): 1. advanced mass-model [cite paper in prep] which weights the template bank due to the characteristic of expected population. As O3a SSM paper, we estimate the weight by assuming uniform mass distribution in SSM population. 2. new SVD grouping Sakon et al. (2024) 3. improved ranking statistic including changes to dtdphi model Tsukada et al. (2023) 4. In O4a offline analysis, we re-apply the loud-noise gating (which we took off in O3 SSM), while we didn't use iDQ algorithm Huxford et al. (2024) for data quality as O3 SSM.

2.2. *MBTA*

The Multi-Band Template Analysis (MBTA) Aubin et al. (2021) is a matched-filtering-based pipeline that searches for gravitational waves from compact binary coalescences (CBCs) in data from the LIGO-Virgo-KAGRA collaboration. For the first time, MBTA conducts a low-latency search for sub-solar mass compact objects in addition to the archival search presented in this paper. MBTA stands out by its approach of splitting the matched-filtering process across multiple frequency bands to optimize computational efficiency.

The template bank used by MBTA is the same as the one employed in the low-latency analysis Brown et al. (2013). It comprises 2,253,561 templates, covering the parameter space described above, and was generated using a geometric placement algorithm. This frequency-band splitting approach significantly reduces the computational cost associ-

→ One subsection per pipeline (GstLAL, MBTA, PyCBC – *Spiir status unknown*)

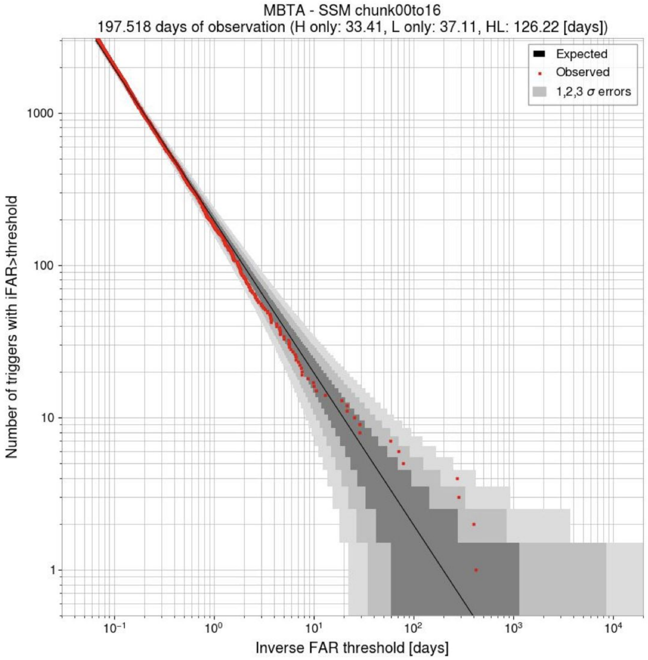
Presenting parameter space, template banks and configuration for the O4a Offline Analysis

Each pipeline present its specificities

Search : sub-section for the results

2.4. *Results*

Table 1 shows the triggers that three independent searches recover with a false-alarm-rate lower than 6.34×10^{-8} Hz (2 per year). Comment on the statistical probability of searches producing reported triggers from noise. The three independent searches recover no confident SSM candidates in this data. The only significant trigger in all searches corresponds to the gpstime and chirp mass of the published NSBH signal, GW230529_181500 Abac et al. (2024). Interestingly, the second most significant trigger in GstLAL's results had a timestamp of 2023-05-28 11:07:32 UTC, and was recovered with the same component masses as GW230529_181500. Although this trigger was recovered with a false alarm rate (FAR) less than 2 per year by GstLAL, it is consistent with the expected number of noise events at this FAR in the GstLAL search. MBTA and PyCBC recover this trigger with higher FARs. The conventional all-sky searches by all pipelines recovered a trigger in real-time with the same gpstime with a less significant FARs. Given the increased significance in offline SSM searches and its coincidence in mass with GW230529_181500, this trigger was jointly followed up with GW230529_181500 to investigate the possibility of a lensed signal. We concluded that it is unlikely a lensed counterpart of GW230529 due to the following reasons: 1. Parameter estimation of the two triggers indicated that the mass ratio of S230528 is much smaller than GW230529_181500, with the chirp mass matching within $\sim 0.5\%$, indicating that it was quieter than GW230529 near the merger if the two have the same intrinsic parameters. 2. A joint parame-



→ **No detection.**

→ Discussion about a **GW lensing candidate seen by GstLAL :** second trigger is **not a lensed counterpart.**

Rates

Using the absence of detection to set upper-limits on the merger rate of SSM BBH.

4. RATES

Given the absence of a detection of SSM BBH, we use the loudest event statistic formalism Biswas et al. (2009) to derive the upper limit on the merger rate of BBHs in this range of masses. The sensitive volume obtained in the previous section is translated to merger rate limits in each mass bin using

$$R_{90,i} = \frac{2.3}{\langle VT_i \rangle} \qquad (4)$$

Rates will be reported as a function of chirp mass and component masses.

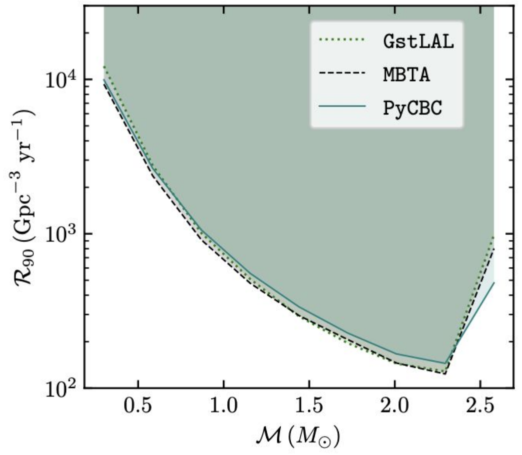


Figure 2. Merger rate limits as function of the source frame chirp mass of the binary system, in data from the full O3. The dotted, dashed and solid lines represent the 90% confidence limits obtained by GstLAL, MBTA and PyCBC, respectively.

Figure taken from the O3b paper →

[arXiv:2212.01477v2]

Constraining Dark Matter

5.1. *Primordial Black Holes*

In the literature, numerous PBH models have been proposed , each predicting different PBH abundances, which is characterized by the fraction of the dark matter cosmological density composed of PBHs, defined as $f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$. Constraining $f_{\rm PBH}$ robustly using gravitational wave (GW) observations is challenging because, for a given $f_{\rm PBH}$, the predicted binary merger rates at the present epoch vary significantly across models. These variations primarily arise from differences in the initial mass distributions and clustering properties of PBHs. Moreover, the merger rate predictions remain highly uncertain, as they are strongly influenced by complex phenomena such as many-body interactions and non-linear gravitational effects, which are difficult to model accurately.

PBH binaries are typically considered to form in two scenarios, Early Binaries (EBs) and Late Binaries (LBs). EBs form shortly after PBH formation, as pairs of PBHs decouple from the universe's expansion and form eccentric binaries through tidal interactions with nearby PBHs. Consequently, EB merger rates are strongly influenced by initial PBH clustering and mass distribution. In contrast, LBs form in dense halos through dynamical interactions, with merger rates shaped by local density and halo properties.

5.2. *Dark black holes*

We consider a pragmatic model of dissipative dark matter, atomic dark matter. This model posits the existence of two fermions, one much more massive than other, charged under a dark U(1) symmetry with interactions mediated via a massless photon. These particles form hydrogen-like bound states that cool via atomic and molecular radiative processes. 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 creation of dark black holes. We assume these black holes follow a truncated power-law mass distribution and calculate the upper bound on the fraction of dark matter in dark compact objects ($f_{\rm DBH} \equiv \Omega_{\rm DBH}/\Omega_{\rm DM}$) as a function of the minimum mass of dark black holes, marginalizing over the slope and maximum mass of the power-law. Appendix (PLACEHOLDER) covers the details of this method.

Presenting the models to constrain in this paper (PBH and DBH briefly introduced before) and present results using the O4a data

Useful links

- Skeleton circulation
- Paper Repository
- Where to leave comments

⚠ Deadline for comments:
Feb 25, 2025 (Tomorrow!)