

Detecting dark objects in the Solar System with gravitational wave observatories

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Dark objects streaming into the solar system can be probed using gravitational wave (GW) experiments through the perturbations that they would induce on the detector test masses. In this work, we study the detectability of the resulting gravitational signal for a number of current and future GW observatories. Dark matter in the form of clumps or primordial black holes with masses in the range 10^7 – 10^{11} g can be detected with the proposed DECIGO experiment.

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I. INTRODUCTION

Gravitational wave (GW) observatories such as LIGO-Virgo-KAGRA have opened a new window to the Universe by their ability to detect minuscule deformations of spacetime caused by the inspiral and merger of black hole binaries and neutron stars [1–3]. They do so by interfering light beams sent between the detector test masses.

During their operation, GW experiments are subject to a number of different noise sources, some of which lead to movement of the test masses between which the deformations of spacetime are measured. Such perturbations, if they are unpredictable, generally pose a limit to the sensitivity of an experiment [4].

However, the movement of the detector test masses can also lead to a detectable signature. In this work, we are interested in gravitational perturbations induced on the test masses by fast transients of objects passing through the Solar System. These objects could be primordial black holes (PBHs), making up the entire dark matter [5,6]. However, the results from this work generically apply to any object flying through the Solar System unbound, with velocities beyond the escape speed.

Similar analyses have been performed in the past for the case of dark matter clumps [7–12]. References [7,8] were

the first to consider the detectability of dark matter clumps using space-based laser interferometers. Additionally, [9] studied a Yukawa interaction between dark and baryonic matter for the LIGO and LISA detectors. Reference [10] added to existing work by considering both gravitational and nongravitational forces for several detectors, including a novel concept for an asteroid-based detector [13]. In addition, they performed Monte Carlo simulations to account for the full phase space distribution of the dark matter trajectories. Reference [11] expanded previous analyses by also taking into account the Shapiro delay and considering higher-frequency gravitational wave experiments. Reference [12] studied the detectability of dark matter with proposed atom gradiometers. Their detectable mass window ($M \in [10^6, 10^{10}]$ g) is similar to what we find for the planned Big Bang Observer (BBO)/Deci-hertz Interferometer Gravitational wave Observatory (DECIGO) experiments, and their results are thus complementary to our work. Finally, we want to emphasize that there have been numerous other works on the role that dark matter clumps or primordial black holes could have in the Solar System [14,14–20].

Our contribution is summarized in the following. First, we study the general detectability of an object passing through the solar system with any velocity, mass, or distance, regardless of its nature, for a number of current and planned GW detectors. Adding to previous work, we include the proposed detectors BBO and DECIGO with their respective modeled noise curve. Furthermore, a detection threshold based on the false alarm rate based on [21] is used in this work, giving more realistic sensitivities compared to SNR thresholds used in the

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existing literature. Focusing on the case of dark matter clumps, we show that there is an interesting mass range $M \in [10^7, 10^{11}]$ g for which DECIGO could detect the presence of dark matter. In the case of PBHs, this mass range has previously been ignored due to their presumed rapid evaporation. However, recently this view has been challenged by the so-called “memory burden” effect [22–28], giving additional motivation to investigate this parameter space. Nevertheless, we remain agnostic about the nature of the objects passing through the Solar System, demanding only that they can be treated as a point mass in terms of their gravitational influence.

Our paper is structured as follows. We first describe how we compute the signal of the fly-by for a given gravitational wave detector. In the following, we investigate detection prospects in terms of the detection volume of each experiment as well as the interstellar mass density to which they are sensitive. For the case of the DECIGO detector, we additionally perform Monte Carlo simulations to sample a realistic phase space distribution of dark matter trajectories through the Solar System. This allows us to make predictions about the probability to observe the gravitational perturbation from the fly-by of a dark object.

II. COMPUTATION OF THE SIGNAL

In this section, we derive an analytical expression used to estimate the signal detected by a gravitational wave detector from the gravitational force of an object with mass M traversing the solar system with speed v . This is largely analogous to previous considerations in the literature [7–12].

The gravitational force exerted by the traversing object leads to a time-dependent acceleration of the detector test mass,

$$\delta a_{ij}(\omega) \approx (a_i(\omega)\hat{\mathbf{a}}_i + a_{i,\parallel}(\omega)\hat{\mathbf{v}} - a_j(\omega)\hat{\mathbf{a}}_j e^{i\omega\Delta t} - a_{j,\parallel}(\omega)\hat{\mathbf{v}} e^{i\omega\Delta t}) \cdot \frac{(\mathbf{r}_i - \mathbf{r}_j)}{L}. \quad (5)$$

Here, $\Delta t = t_i - t_j$ is the difference between the time of closest encounter for each detector test mass and $L = |\mathbf{r}_i - \mathbf{r}_j|$ is the arm length of the detector. By $\hat{\mathbf{a}}_i$, we denote the normalized vector pointing from the position of the test mass to the point of closest encounter. $\hat{\mathbf{v}}$ denotes a normalized vector parallel to the motion of the perturber.

To gain a better understanding of Eq. (5), we consider a single detector arm with two test masses and the particular geometry sketched in Fig. 1, where the dark object moves perpendicular to the axis of the detector arm. For $R \gg L$, this leads to the largest possible perturbation, whereas for $R \lesssim L$ it is representative of a typical signal as we will show below. For the geometry depicted in Fig. 1, we have $\Delta t = 0$, $\hat{\mathbf{v}} \cdot (\mathbf{r}_i - \mathbf{r}_j) = 0$ and Eq. (5) reduces to

$$a(t) = \frac{GMR}{(R^2 + (vt)^2)^{3/2}}, \quad (1)$$

in the direction toward the point of closest encounter at a distance of R . The spectral density of such a signal can be computed analytically to be

$$a(\omega) = \frac{2GM\omega}{v^2} K_1(\omega R/v), \quad (2)$$

where K_1 denotes the first-order modified Bessel function of the second kind. Note that $K_1(x) \approx 1/x$ for $x \ll 1$ and thus $a(\omega) = \frac{2GM}{vR}$ for $\omega \ll v/R$. For $\omega > v/R$, the signal drops exponentially.

There is also an acceleration in the direction parallel to the perturber

$$a_{\parallel}(t) = \frac{GMvt}{(R^2 + (vt)^2)^{3/2}}, \quad (3)$$

with its spectral density given by

$$a_{\parallel}(\omega) = i \frac{2GM\omega}{v^2} K_0(\omega R/v). \quad (4)$$

As $K_0(x) \ll K_1(x)$ unless $x \gtrsim 0.1$ and both drop exponentially for $x > 1$, the contribution from $a_{\parallel}(\omega)$ is small except for $\omega \sim v/R$.

For a detector with multiple test masses i , located at positions $\mathbf{r}_i$, the different masses will be perturbed at a slightly different time t_i and distance of closest encounter R_i . The spectral density of the relative acceleration $\delta a_{ij}(\omega)$ between a pair of test masses i and j can be computed by projection on the vector between the two test masses, $\mathbf{r}_i - \mathbf{r}_j$:

$$\delta a = \frac{2GM\omega}{v^2} (K_1(\omega R/v) - K_1(\omega(R+L)/v)). \quad (6)$$

If the compact object passes within close proximity of the test mass ($R \ll L$, near-field limit), then that mass will be perturbed much stronger than the other one, and we reach a good approximation:

$$\delta a_{\text{near}} = \frac{2GM\omega}{v^2} K_1(\omega R/v). \quad (7)$$

If the distance between the compact object and the test masses is much larger than the detector size ($R \gg L$), we only get a tidal effect, where the perturbation is suppressed by the factor L/R :

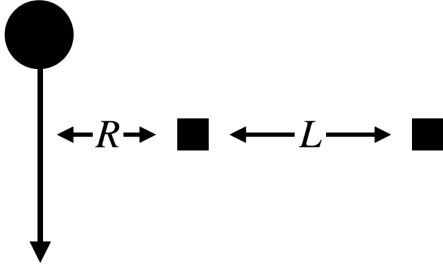


FIG. 1. Visualization of a fly-by at an impact parameter R near a GW detector of arm length L .

$$\delta a_{\text{tid}} \approx \frac{2GM\omega L}{Rv^2} K_1(\omega R/v). \quad (8)$$

A gravitational wave detector usually has more than two test masses. For an L-shaped detector like LIGO with 3 test masses, the measured quantity is actually $\delta a_{12}(\omega) - \delta a_{13}(\omega)$. Here, the index 1 indicates the corner test mass where the signals from the two arms interfere. Therefore, the measured perturbation can in principle be larger by up to a factor of two compared to Eq. (6). It is useful to evaluate the probability distribution $p(\delta a(\omega))$ due to the space of possible geometries of the encounter. Using Monte-Carlo simulations, we sample this distribution for a LIGO-like “L”-shaped detector, as well as for a triangular setup as is planned for LISA, BBO, and DECIGO. We find that the following expression gives an excellent fit to the mean perturbation strength both for $R \ll L$ and $R \gg L$ as long as $\omega < v/R$:

$$\langle \delta a(\omega) \rangle = \frac{2GM\omega L}{v^2(\alpha R + \beta L)} K_1(\omega R/v). \quad (9)$$

For an L-shaped detector, we obtain $\alpha = 1.3$ and $\beta = 1.8$, and for a triangular shape we get $\alpha = 1.5$ and $\beta = 2.0$. The maximum deviation of the fit from the simulated data is observed for $R = L/2$, when the expression above underestimates the mean perturbation strength by a factor of ~ 1.6 . For $\omega \sim v/R$, Eq. (9) typically underestimates the spectral density by a factor of around two, partly as a result of the contribution from $a_{\parallel}(\omega)$. In the following, we will make use of Eq. (9) to obtain estimates of the signal-to-noise ratio (SNR) for existing and planned GW observatories.

To compute the spectral density of the gravitational wave strain $h(\omega)$, we recall that by definition of the metric tensor $L' = \sqrt{1 + h}L$ and thus $\delta x = L' - L \approx h/2$. From this and $\delta x(\omega) = \delta a(\omega)/\omega^2$, we get the strain

$$h(\omega) = \frac{4GM}{\omega v^2(\alpha R + \beta L)} K_1(\omega R/v), \quad (10)$$

which can be used to estimate the SNR for any GW experiment, as

$$\text{SNR} = 2 \left(\int df \frac{h(f)^2}{P_n(f)} \right)^{1/2}, \quad (11)$$

where $P_n(\omega)$ denotes the power spectral density of the detector noise for the respective observatory. Note that, for the case of gravitational waves, $P_n(f)$ is replaced by the spectral strain sensitivity $S_n(f)$. The latter usually accounts for the angular dependence of the response of the detector. In addition, it includes a frequency-dependent suppression for gravitational waves with wavelengths which are comparable or smaller than the arm length of the detector [29]. In our case, this suppression is not applicable and the angular dependence is accounted for in the signal by the factors α and β . Therefore, we can directly use the detector noise $P_n(f)$ to estimate the SNR.

The data for our study is taken from [30] for the detectors aLIGO (design sensitivity), Einstein Telescope (ET), LISA, BBO, and DECIGO. For Cosmic Explorer (CE), we use the updated model for the detector noise from [31]. For the LISA experiment, we include the binary confusion noise presented in [32] for our analysis. This stochastic background will also be relevant for the BBO/DECIGO experiments, but the precise noise spectrum has not been worked out yet and will depend on the exact detector geometry and the ability to subtract individual sources from the background. Therefore, as a conservative choice, we set the lower frequency limit of both detectors to $f = 3 \times 10^{-3}$ Hz where we can expect the noise level to be subdominant (see the dotted gray line in Fig. 2). We found that if we instead extrapolate the detector noise to lower frequencies, including the binary noise as computed for LISA, then our results do not change much. Only if BBO achieves lower detector noise than LISA at frequencies $f \ll 10^{-3}$ do the detection prospects improve notably.

In addition to the noise from the galactic binaries, there are a plethora of other possible sources for GW backgrounds [33,34], from binary black holes to phase transitions. The existence of a GW background can in principle limit the detectability of the perturbations induced by dark objects flying through the solar system. However, there are often large uncertainties in the estimates for the noise level of the GW backgrounds. Therefore, in our analysis, we will assume that detectability is limited only by the detector noise. The only exception to this is the mentioned galactic foreground that is accounted for in the LISA noise curve.

The integrand in Eq. (11) has the form $df/P_n(f)/f^4 = d \log f / P_n(f)/f^3$ for $f \ll v/R$ and decreases sharply for $f \gg v/R$. It is therefore convenient to plot $\sqrt{P_n(f)}f^3$ and $h(f)f^2$ together, as the latter will be constant for $f \ll v/R$ and the area between the two curves will be proportional to the SNR on a log-scaled figure.

Figure 2 shows the rescaled spectral noise of current, planned, and proposed GW observatories. This plot can be used to easily read off the signal-to-noise ratio for any of the experiments displayed by the area between the signal,

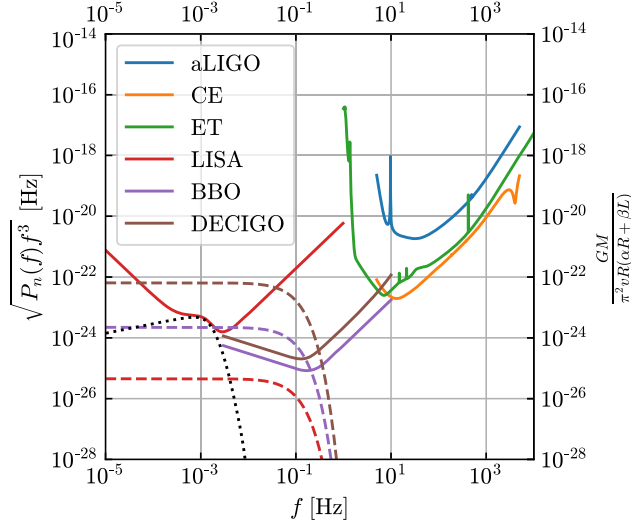


FIG. 2. Strain sensitivity of various existing and proposed GW experiments. The y-axis has been rescaled such that the signal of an encounter with given parameters M , R , and v would appear as a horizontal line for $f < v/R$, dropping quickly for $f > v/R$. The area between it and any sensitivity curve is proportional to the signal-to-noise ratio for that experiment. Note that, in the limit of a close encounter, $R < L$, the signal amplitude is dependent on the detector arm length and must be computed for each experiment separately. The dashed lines show the signal for an object with $M = 10^{10}$ g, $v = 300$ km s $^{-1}$, and $R = 10^3$ km for the detectors LISA, BBO, and DECIGO in the same colors as the strain sensitivity. The dotted black line indicates the binary confusion noise, taken from [32].

based on the right-side y-axis and the noise curve. The axis has been rescaled such that the signal will be represented by a horizontal line with an amplitude of $\frac{GM}{\pi^2 v R (\alpha R + \beta L)}$ that extends up to a frequency $f = v/R$ and drops sharply thereafter. Note that in the limit $R \ll L$ the amplitude is dependent on the arm length of each detector, and thus, the signal must be computed for each experiment individually.

As a first step, we remain agnostic about the orbital parameters of the perturber and compute for a range of values of M and velocity v the distance of the encounter R to which each experiment is sensitive. We will present the results of this in the following section.

As a second step, we study the feasibility of detecting objects with a given interstellar mass density ρ at the location of the solar system. If primordial black holes of a given mass M make up all of the dark matter, they will have $\rho \sim \rho_{\text{DM}} = 7 \times 10^{-25}$ g cm $^{-3} \approx 0.4$ GeV cm $^{-3}$ and an rms velocity of $v \sim 300$ km s $^{-1}$ [35,36]. While our results apply to PBHs, they can also be used more generally as a way to constrain any kind of interstellar objects flying through the solar system.

Fixing the density of the perturbers implies a number of encounters with impact parameters smaller than R within a time t , given by

$$N = \frac{\pi R^2 \rho v t}{M}. \quad (12)$$

Therefore, the probability distribution of the distance R to the closest encounter by Poisson statistics is

$$p(R) = p(N) \frac{dN}{dR} = \frac{2\pi R \rho v t}{M} \exp\left(-\frac{\pi R^2 \rho v t}{M}\right), \quad (13)$$

which implies that the 90th percentile distance of the closest encounter to occur within a time span t is given by

$$R_{\text{min},90} = \sqrt{\frac{M \ln(10)}{\rho v t}}. \quad (14)$$

Using this as an estimate for the value of R , we employ Eqs. (10) and (11) to evaluate the SNR for a given interstellar density ρ , mass M , and velocity v of the perturbers. The choice of $R_{\text{min},90}$ implies that there is a 90% probability to observe at least one event with the given SNR in that time period.

Previous studies of “burst”-like GW signals have found SNRs of around 8 sufficient for the LIGO observatory [21,37]. For a lower SNR, the false alarm rate (FAR) will be too large. Using Eq. (30) from [21], we compute the FAR for any other GW detector using the spectral density $h(\omega)$ of the signal:

$$\text{FAR} = \sqrt{\frac{C_2 - C_1^2}{2\pi}} \xi e^{-\xi^2/2}. \quad (15)$$

Here, ξ denotes the signal-to-noise ratio according to Eq. (11) and C_k are defined as

$$C_k = \frac{4}{\xi^2} \int df (2\pi f)^k \frac{h(f)^2}{P_n(f)}. \quad (16)$$

As the detectors considered in this work are generally most sensitive at lower frequencies compared to LIGO, the resulting false alarm rates are generally lower and so is the required SNR. Using the false alarm rate as a detection threshold provides more realistic estimates for the sensitivity of individual detectors and is generally more conservative compared to the SNR thresholds used in previous work. We will use $\text{FAR} < 10^{-3}$ yr $^{-1}$ throughout this work but note that due to the exponential dependence in Eq. (15) the precise value is not important.

III. DETECTION PROSPECTS

Figure 3 displays the minimum fly-by distance required to have a signal with $\text{FAR} < 10^{-3}$ yr $^{-1}$, which corresponds to SNRs between 5 and 8 for the experiments considered. We display the detection volume as a function of the perturber mass and velocity for LISA and DECIGO

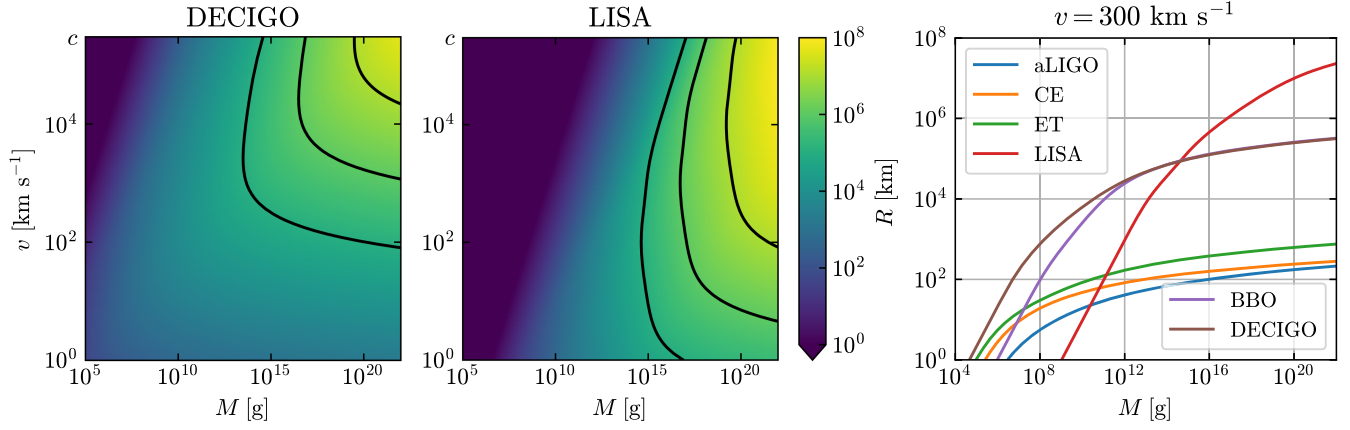


FIG. 3. Maximum distance for which GW experiments are sensitive to a fly-by of a perturber. Left: results for DECIGO/LISA as a function of the mass and velocity of the perturber. Contours for $R = [10^5, 10^6, 10^7]$ km are shown as black lines. Right: results for all GW experiments as a function of the mass of the perturber for $v = 300$ km s $^{-1}$. Detectability is defined as $\text{FAR} < 10^{-3}$ yr $^{-1}$.

and additionally show the results for all detectors for $v = 300$ km s $^{-1}$.

A limitation for each GW detector is the minimum frequency $f_{\min}$ to which it is sensitive, as it sets the maximum distance observable to $R_{\max} \sim v/f_{\min}$. For this reason, LISA has the largest detection range for the most massive objects due to its susceptibility at low frequencies. For objects of smaller mass or higher velocity, where the limiting factor is the sensitivity of the experiment, DECIGO achieves a larger detection volume due to its superior design sensitivity compared to LISA.

We note that the large detection radius for LISA in principle opens the possibility to measure the masses of asteroids or comets whose trajectory and velocity are known, should they pass close enough to the detector. The recently discovered interstellar object 3I/ATLAS [38–40] has a minimum intersection distance with Earth’s orbit of 0.37 AU. Assuming a mass of 10^{16} g, corresponding to a diameter of the nucleus of 1–2 km, the closest approach to LISA would have to be at a distance below 0.002 AU in order to be detectable. However, there are assumed to be many more smaller bodies, some of which could come close enough to a GW observatory for detection. Computing the likelihood for such an event is left for future work.

The results presented in Fig. 3 for aLIGO, ET, and LISA agree reasonably well with those presented in Fig. 1 of [10] for the same choice of parameters. We find somewhat larger sensitivity at higher masses for aLIGO and ET due to the approximations made in their heuristic sensitivity estimate.

Figure 4 shows the SNR resulting from a fixed density of the dark objects of $\rho \sim \rho_{\text{DM}} = 7 \times 10^{-25}$ g cm $^{-3} \approx 0.4$ GeV cm $^{-3}$. The distance to the perturber is set by Eq. (14), implying that there is 90% probability to observe at least one event with at least the given SNR. The future detectors BBO and DECIGO show the most promising results, achieving large SNRs for a sizable part of the

parameter space, even at nonrelativistic velocities. LISA, CE, and ET reach SNRs close to or slightly above one at relativistic velocities. However, such parameter regions are likely ruled out by other constraints, either from structure formation in the case of dark matter or from collisions with solar system bodies in general.

Focusing on the case of compact objects such as PBHs as dark matter, we adopt a velocity of $v = 300$ km s $^{-1}$ and compute the lowest density ρ for which the closest encounter at the 90th percentile within a period of $T = 10$ yr produces a signal with a false alarm rate below 10^{-3} yr $^{-1}$. The results are displayed in Fig. 5. The curves can be easily adopted for different periods of observation T by noting that $\rho \sim 1/T$. Our results demonstrate that the planned BBO and DECIGO experiments have the potential to probe scenarios where the dark matter is in the form of compact objects with a mass of $M \in [10^7, 10^{11}]$ g. It is commonly assumed that PBHs of such masses cannot make up the dark matter due to their rapid evaporation. However, the so-called “memory burden” effect [22,23] could significantly suppress the evaporation, opening a new window for light PBHs as a dark matter candidate [24–27]. It is therefore highly interesting that GW experiments could be used to probe their existence purely by their gravitational interaction as they pass through the solar system. By pure coincidence, DECIGO is also able to probe PBHs of similar mass through the GW emission associated with their formation [41]. Independent of the nature of dark matter, it is highly interesting that GW detectors in the decihertz regime show the potential to probe a region in the parameter space of massive dark matter that is otherwise difficult to access.

The noise spectrum of future gravitational wave detectors has to be estimated, which implies some degree of uncertainty. In Fig. 5, we show how an uncertainty in the detector noise $\sqrt{P_n(f)}$ of a factor of two affects the resulting densities which can be probed. For lower masses,

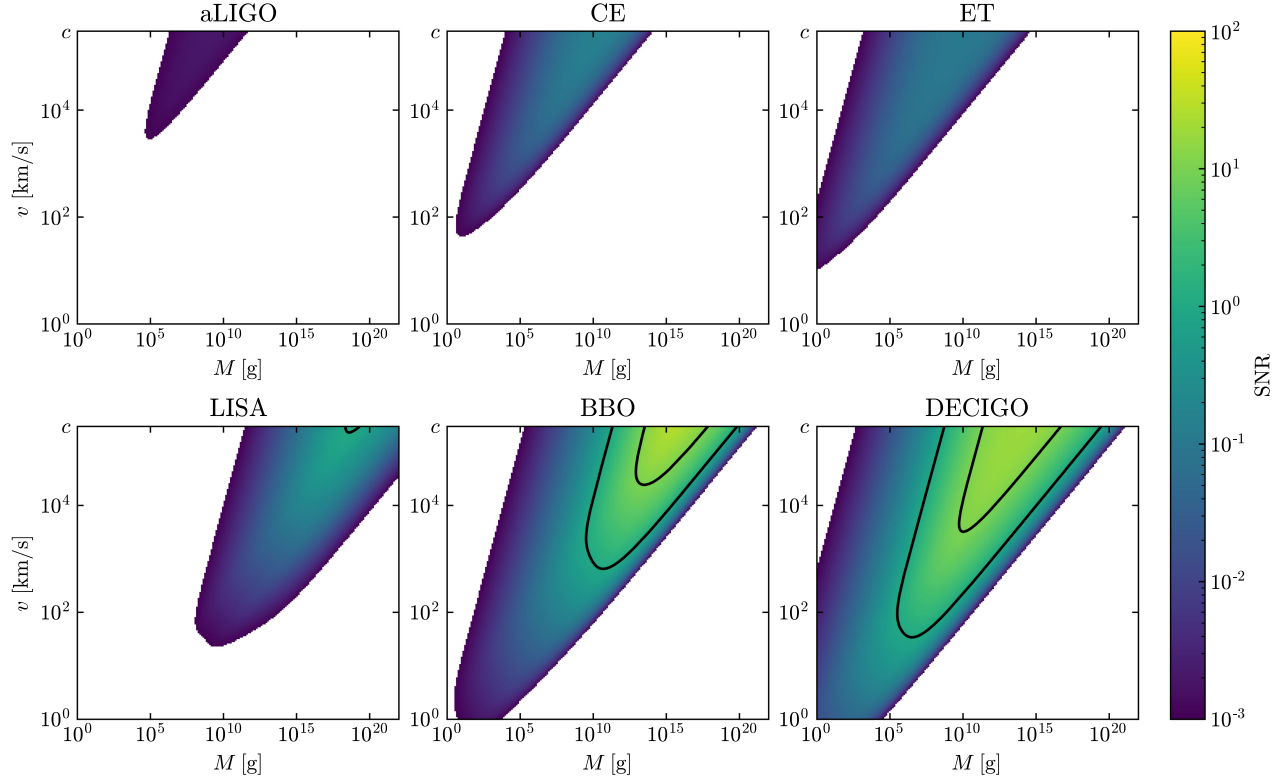


FIG. 4. Signal-to-noise ratio from the closest encounter at the 90th percentile expected within an observation time $T = 10$ yr for density $\rho = \rho_{\text{DM}} = 7 \times 10^{-25} \text{ g cm}^{-3}$. The SNR is shown for several GW experiments as a function of the mass M and velocity v of the perturber. In the white area, the SNR is lower than 10^{-3} . The black lines indicate the contours for which $\text{SNR} = [1, 10]$.

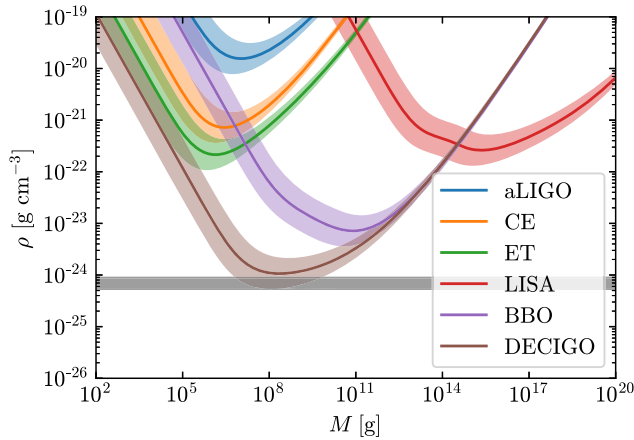


FIG. 5. Density for which each experiment is sensitive to at least one perturbation within a period of $T = 10$ yr at 90th percentile. A velocity of $v = 300 \text{ km s}^{-1}$ is assumed, as expected for dark matter. The detection threshold is $\text{FAR} < 10^{-3} \text{ yr}^{-1}$ which implies SNRs between 5 and 8 for the various detectors. The colored shaded area indicates the resulting range implied by an uncertainty in the detector noise $\sqrt{P_n}$ of a factor of two. The gray shaded area corresponds to the range of the latest observational estimates of the local dark matter density $\rho_{\text{DM}} \in [0.3, 0.5] \text{ GeV cm}^{-3}$ [35].

where the detection is limited by the noise level of the observatory, one has $\rho \sim P_n(f)$ as $h(f) \sim 1/R \sim \sqrt{\rho}$. At higher masses, where the limit is set by the frequency range of the detector, the results are not very sensitive to the exact noise level.

We can compare our results for the sensitivity of aLIGO, ET, CE, and LISA with those shown in Fig. 3 of [11] for the same choice of parameters. Overall, our results agree quite well with some deviations due to methodological differences and the fact that in their work they use $S_n(f)$ for the computation of the SNR instead of $P_n(f)$ which gives a somewhat worse sensitivity. We found a notable deviation for ET at low masses which seems to come from an erroneous value for the arm length in [11] giving a sensitivity that is two orders in magnitude too low. We also want to note that the sensitivities of LISA, BBO, and DECIGO presented in Fig. 1 of [8] are significantly more optimistic compared to ours, owing to their assumption of a flat spectrum of the detector noise $P_n(f)$ which is only true in a certain frequency range.

Our estimates based on Eq. (10) show that DECIGO has the greatest potential to detect perturbations from dark matter in the form of compact objects streaming through the solar system. We therefore study this case in more detail

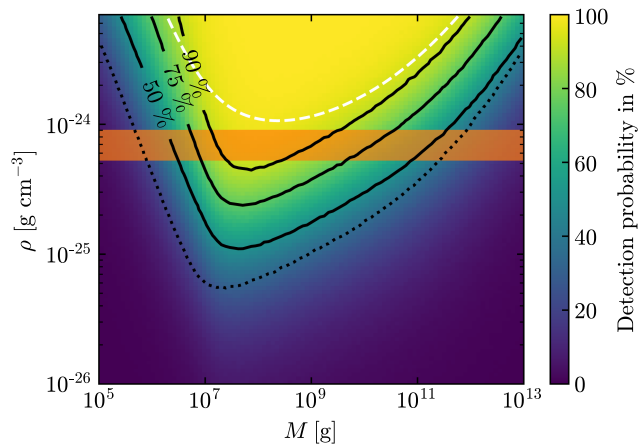


FIG. 6. Probability for DECIGO to detect at least one signal from the fly-by of compact objects, shown as a function of their mass M and density ρ . We assume an observation time of $T = 10$ yr. A successful detection is defined as having $\text{FAR} < 10^{-3} \text{ yr}^{-1}$, which roughly corresponds to $\text{SNR} > 6$. The orange shaded area corresponds to the range of the latest observational estimates of the local dark matter density $\rho_{\text{DM}} \in [0.3, 0.5] \text{ GeV cm}^{-3}$ [35]. Contours of constant probability are displayed as solid black lines. The dotted black line indicates a contour of 50% probability given a reduction in the detector noise level by a factor of two. The estimate from Fig. 5 for the DECIGO experiment is shown as a dashed white line and should be compared to the contour of 90% probability.

and relax previous approximations. For a more accurate assessment of detection prospects, we compute the signal using Eq. (5) by performing Monte Carlo simulations over the space of possible geometries of the encounter. The velocity for each encounter is obtained by adding a random component with $v_{\text{rms}} = 270 \text{ km s}^{-1}$ to the proper motion of the Sun around the Galactic Center (DM wind) with $v_{\odot} = 220 \text{ km s}^{-1}$ [36]. We neglect the small nonisotropy in the angular distribution of the velocity and sample the orientation uniformly on a sphere. These simulations are performed for a range of different masses M and densities ρ , and the probability of a successful observation in a period of $T = 10$ yr is determined as the fraction of simulations for which $\text{FAR} < 10^{-3} \text{ yr}^{-1}$ is obtained.

Figure 6 shows the results. Notably, there is a wide range of masses M for which the probability of observing the gravitational signal is high. In other words, should the dark matter be in the form of compact objects with mass $M \in [10^7, 10^{11}] \text{ g}$, there is a good chance that it will perturb the DECIGO detector enough to lead to a detectable signal at least once within 10 yr of observation. This agrees reasonably well with the estimate presented before in Fig. 5 that is also shown as a white dashed line in Fig. 6. Our more careful analysis results in slightly better sensitivity compared to the estimate based on Eq. (9), which underestimates the mean spectral density for $\omega \sim v/R$ as we have mentioned before.

The nondetection of a gravitational signal of this kind allows in principle one to put constraints on the dark matter

density for the same range of masses. Our results indicate that these constraints would rule out that all the dark matter is in objects with a mass $M \in [10^7, 10^9] \text{ g}$ at 90% confidence.

The sensitivity to the perturbations depends on the exact level of DECIGO's detector noise. We highlight this in Fig. 6 by an additional dashed line which indicates the contour for a 50% probability of observation in a scenario where the detector noise is lower by a factor of two. Notably, if the “Ultimate DECIGO” detector [42] is realized, which is only limited by quantum noise, then the detection prospects could increase by several orders of magnitude, expanding the range of masses to which it would be susceptible. Conversely, the detection prospects can diminish if detector noise is greater than anticipated or in the presence of irremovable gravitational wave backgrounds. We find that an increase in the noise level by a factor of six reduces the probability for an observation to below 50% for any mass of the perturber. Finally, we want to note that the densities which are observable or that can be constrained scale with observation time as $\rho \sim 1/T$.

IV. SUMMARY

We have studied the feasibility of gravitationally probing the streaming of dark objects through our solar system. The detection method relies on the perturbation of the test masses of gravitational wave detectors, which leads to a burstlike signal in the experiment.

We have computed the distances of encounters to which the different types of current and future GW experiments are sensitive, which can reach several million kilometers for LISA, BBO, and DECIGO. The main limitation of each experiment is the frequency range to which it is sensitive. In order for the encounter to be detectable, the fly-by must be sufficiently close or fast in order for $f \sim v/R$ to be large enough.

If the solar system is penetrated by dark objects with a halo density $\rho \sim \rho_{\text{DM}}$, then the proposed GW experiment DECIGO offers the best prospects to detect dark matter and it will be sensitive to the range of masses $M \in [10^7, 10^{11}] \text{ g}$.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [43].

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