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CONSTRAINING COMPACT DARK-MATTER OBJECTS IN THE TON MASS RANGE WITH LIGO-VIRGO-KAGRA

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ABSTRACT

I show that dark matter objects in the ton mass range could have produced detectable gravitational pulses over the past decade in each of the gravitational wave interferometers, LIGO, VIRGO or KAGRA. The predicted temporal profile of the signal can be isolated from background noise and should appear in only one of these interferometers. A search for the template signal can be used to constrain the nature of dark matter.

1. INTRODUCTION

The nature of dark matter remains unknown. So far, gravitational microlensing had been used to exclude the smallest compact dark matter objects with masses $M \gtrsim 10^{23}$ g (Carr & Kuhnel 2025). Here, I show that the tidal gravitational signal of compact objects in the ton ($M \sim 10^6$ g) mass range is potentially detectable by the LIGO-Virgo-KAGRA (LVK) interferometers (Abbott et al. 2023; Abac et al. 2024). This opens a new window for dark matter searches.

2. TEMPLATE GRAVITATIONAL SIGNAL

Consider a compact dark matter object moving at a speed $v \sim 300$ km s^{-1}, within a distance of closest approach, b, from one of the LVK detectors. At closest approach, the object generates a tidal gravitational signal over a time period of order b/v, corresponding to a frequency,

$$f \equiv \left(\frac{v}{b}\right) = 100 \text{ Hz} \left(\frac{v/300 \text{ km s}^{-1}}{b/3 \text{ km}}\right) , \tag{1}$$

which falls within the frequency sensitivity of the LVK interferometers (Cahillane & Mansell 2022).

The gravitational tide of the passing object induces a differential acceleration between the mirrors at the ends of each interferometer arm. We define the effective strain amplitude h as the fractional shift in the mirror separation $h = \delta\ell/\ell$, induced by a point mass M at a distance $R(t) \gtrsim \ell$. The tidal gravitational signal satisfies the equation,

$$\frac{\partial^2 h}{\partial t^2} = \frac{GM}{R(t)^3}\left(3\cos^2\alpha(t) - 1\right) , \tag{2}$$

where α is the angle between the object-detector axis and the detector arm. For steady motion of the object along a straight line, equation (2) admits the temporal template solution,

$$h(t) = \frac{GM}{bv^2}\left(1 + f^2t^2\right)^{-1/2} = 2.5 \times 10^{-22}\left(\frac{[M/10^6 \text{ g}]}{[b/3 \text{ km}][v/300 \text{ km s}^{-1}]^2}\right)\left(1 + f^2t^2\right)^{-1/2} , \tag{3}$$

where $t = 0$ is the time of closest approach with $R(t = 0) = b$, and f is given by equation (1). This solution can be used as a template for isolating signal events from background noise. Owing to the small value of b under consideration, the signal is expected to appear only in one of the LVK interferometers. Searching for it requires a new dedicated analysis of the LVK data stream that was documented over the past decade. The purpose of this *Research Note* is to motivate a dedicated search for the template signal in equation (3) as a new method for constraining dark matter.

For a population of dark matter objects with a number density, n, and an isotropic velocity distribution, the rate of tidal pulses within a distance b from one of the LVK interferometers is given by,

$$n \times \frac{v}{\sqrt{3}} \times [4\pi b^2] . \tag{4}$$

The lack of a detected signal over a total observing period of $t_{\rm obs} \sim 10$ yr for three detectors, implies the upper limit on the number density, and correspondingly the mass density $\rho = mn$, of dark matter objects,

$$\frac{\rho}{\rho_{dm}} \lesssim 0.5 \left(\frac{M}{10^6 \text{ g}}\right) \left(\frac{v}{300 \text{ km s}^{-1}}\right)^{-1} \left(\frac{b}{30 \text{ km}}\right)^{-2} \left(\frac{t_{\rm obs}}{10 \text{ yr}}\right)^{-1}, \quad (5)$$

where we adopted $\rho_{dm} \approx 10^{-24}$ g cm^{-3} as the local dark matter mass-density (Sivertsson et al. 2022).

The requirement that the object be smaller in radius than b translates to the condition that its internal mass density exceeds $\sim (M/\frac{4}{3}\pi b^3) = 9 \times 10^{-12}$ g cm$^{-3}(M/10^6$ g$)(b/3$ km$)^{-3}$, allowing values that are well below the densities of air, solids or primordial black holes in the same mass range.

3. CONCLUSIONS

Equation (5) implies that the search for the template gravitational signal in equation (3) for one of the LVK interferometers, can be used to constrain the existence of compact dark matter objects in the ton mass range. Future gravitational wave observatories, such as LISA (Colpi et al. 2024), will be able to extend the constraints to other object masses.

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