Detecting ultralight dark matter gravitationally with laser interferometers in space

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Ultralight dark matter (ULDM) is one of the leading well-motivated dark matter candidates, predicted in many theories beyond the standard model of particle physics and cosmology. There has been increasing interest in searching for ULDM in physical and astronomical experiments, mostly assuming there are additional interactions other than gravity between ULDM and normal matter. Here we demonstrate that even if ULDM has only gravitational interaction, it shall induce gravitational perturbations in solar system that may be large enough to cause detectable signals in future gravitational-wave (GW) laser interferometers in space. We investigate the sensitivities of Michelson time-delay interferometer to ULDM of various spins, and show vector ULDM with mass $m \lesssim 10^{-18}$ eV can be probed by space-based GW detectors aiming at μHz frequencies. Our findings exhibit that GW detectors may directly probe ULDM in some mass ranges that otherwise are challenging to examine.

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I. INTRODUCTION

Dark matter (DM) constitutes the majority of matter in the universe, with supporting evidence from galactic rotational curves, bullet cluster, large-scale structure and cosmic microwave background. However, DM's identity remains unclear because all the confirmed evidence merely suggests DM must have gravitational interaction. Among the leading candidates, ultralight dark matter (ULDM) with mass $\lesssim 10^{-6}$ eV stands out attractively since it may connect to fundamental physics at very high energy [1–6], including quantum gravity [7,8], grand unified theory [9–11], inflation [12–16], etc.

There have been vast efforts and significant progresses in searching for ULDM, either presuming there are additional nongravitational interactions between ULDM and normal matter [17–19] or just gravity. For instance, searching for axionlike ULDM [20–22] involves interactions with photon [23–28], electron [29–32], nucleon [33–38] or neutrino [39–41]. Dark photon ULDM searches assume its mixing with photon or couplings with the baryon/baryon-lepton charge [42–53]. After the detection of gravitational waves (GWs), it was shown that gravitational-wave (GW) experiments can also be very sensitive to some of such interactions [54–59].

Astrophysical methods that only employ ULDM's gravitational interaction are also pushed forward, including probing metric perturbation by pulsar timing array (PTA) [60–70], binary dynamics [71–74], Lyman-α constraints [75–77], 21 cm absorption line [78,79], superradiance around black holes [80–85], and galactic dynamics [86–89]. Such searches can provide complementary information and are largely model-independent unless nongravitational interaction dramatically change the physical contexts.

In this work, we present the searches for local ULDM of various spins by space-based GW laser interferometers. Unlike the scalar case that suffers from velocity suppression, we demonstrate that the gravitational tensor perturbations in solar system caused by vector ULDM can lead to detectable signals, which may be probed by future GW laser inteferomerters in space with arm lengths comparable to the diameter of Mars' orbit. Detection of such a signal would directly suggest the wave nature of DM and its mass range, signifying the fundamental theory of DM.

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II. METRIC PERTURBATIONS AND SIGNAL RESPONSE

Since we are considering the effects of ULDM in the solar system at a timescale of years, we can neglect the

Milky Way Galaxy background and the cosmic expansion, and write the metric with linear perturbations over a flat background, defining scalar metric perturbations Ψ and Φ, and tensor h_{ij} by

$$ds^2 = -(1+2\Psi)dt^2 + [(1-2\Phi)\delta_{ij} + h_{ij}]dx^i dx^j. \quad (1)$$

In the Poisson gauge we have $\partial_i h_{ij} = 0, \delta_{ij}h_{ij} = 0$. The energy-momentum tensor $T_{\mu\nu}$ of ULDM would source metric perturbations through the Einstein equations. For ULDM with mass m, energy density ρ and velocity v, we can estimate the amplitudes of perturbations,

$$\Psi^j \simeq \Phi^j \simeq \pi G \frac{\rho}{m^2} = \frac{7\times 10^{-26}\rho}{0.4\ \mathrm{GeV/cm^3}}\left(\frac{10^{-18}\ \mathrm{eV}}{m}\right)^2, \quad (2)$$

$$h_{ij}^v \propto h_0 \simeq \frac{8}{3}\pi G \frac{\rho}{m^2} = \frac{2\times 10^{-25}\rho}{0.4\ \mathrm{GeV/cm^3}}\left(\frac{10^{-18}\ \mathrm{eV}}{m}\right)^2, \quad (3)$$

and $h_{ij}^s \simeq h_0 v^2/2$. Here the superscript $j = s$ and v stands for contribution from scalar and vector ULDM [90]. Note that h_{ij}^s due to scalar ULDM are suppressed by v^2 (see Supplemental Material [91]). However, the tensor perturbation h_{ij}^v for vector ULDM is not suppressed, which is crucial for the detection by interferometers in space.

Now we derive the signal response of a space-based GW interferometer to the metric perturbations sourced by ULDM. We consider the constellation with three spacecrafts (S/C) as Fig. 1, which is adopted in most space-based GW detectors, including LISA [92], Taiji [93], Tianqin [94], BBO [95], DECIGO [96], μAres [97], LISAmax [98], and ASTROD-GW [99]. The signal is encoded in the fractional frequency shift,

$$y_{rs}(t) \equiv \frac{\delta\nu_{rs}(t)}{\nu_0} \simeq z_\Phi(t) + z_h(t) + N(t), \quad (4)$$

which parameterizes various effects on the single-link frequency shift $\delta\nu_{rs}$ of the transmitted laser light from S/C s to S/C r, including instrumental noises $N(t)$ and geodesic deviations from perturbations Φ and h_{ij}, $z_\Phi(t) + z_h(t)$. The central laser frequency is taken as $\nu_0 \simeq 2.81\times 10^{14}$ Hz as the wavelength of laser light is 1064 nm.

III. INSTRUMENTAL NOISES AND TDI COMBINATIONS

Three main instrumental noises, contributing to $\delta\nu_{rs}(t)$, would limit the detection sensitivity, including frequency noise of lasers $p_i(t)$, acceleration noise of test masses s_{acc}, and noise of optical metrology system s_{oms}. Frequency noise is related to how monochromatic the laser light is, while acceleration noise denotes the deviation of free fall for test mass, and metrology noise represents the displacement uncertainty of optical interferometers.

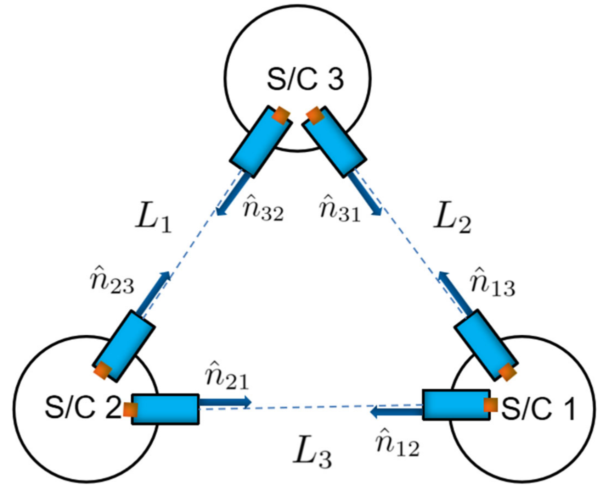

FIG. 1. A schematic of the triangle constellation for LISA-like GW laser interferometers in space. Each spacecraft (S/C) hosts two test masses (orange cubic) and each single-link measurement encodes the distance between two test masses at two ends of an edge. $\hat{n}_{ij}$ denotes the unit direction vector pointing from S/C i to S/C j. The arm lengths L_i are changing over time with percent-level variation.

Due to the mismatch of time-changing arm lengths, the laser frequency noise in a single-link data stream $y_{rs}(t)$, $p_s(t-L_j) - p_r(t)$, does not cancel and dominates over all other ones by several orders. To suppress laser noise to a negligible level, the usual strategy is to postprocess the acquired data by time-delay interferometry (TDI) algorithm [100], which makes time-shifts and linear combinations of $y_{rs}(t)$, or equivalently constructs virtual equal-arm interferometry. One example for Michelson combination $X(t)$ can be written as follows,

$$\begin{aligned} X(t) = {} & [y_{13}(t) + y_{31}(t-L_2) + y_{12}(t-2L_2) \\ & + y_{21}(t-L_3-2L_2)] - [y_{12}(t) + y_{21}(t-L_3) \\ & + y_{13}(t-2L_3) + y_{31}(t-L_2-2L_3)]. \end{aligned} \quad (5)$$

The combinations in two brackets can be geometrically described in Fig. 2 by the blue and black light paths, respectively. Two paths have almost equal lengths, $2L_2 + 2L_3$, but in different directions, indicated by the arrows. Many other combinations are possible (see Supplemental Material [91]). The laser frequency noise in such combinations can be suppressed and hence neglected in further discussions. Also L_i appearing in all other contributions can be approximately taken as $L_i = L$, the nominal arm length of the triangle constellation.

On the other hand, acceleration noise and metrology noise cannot be suppressed and consequently limit the detection sensitivity. In Table I, we list the noise power spectral density (PSD) for several future laser interferometors in space. To compare with the signal strain in X

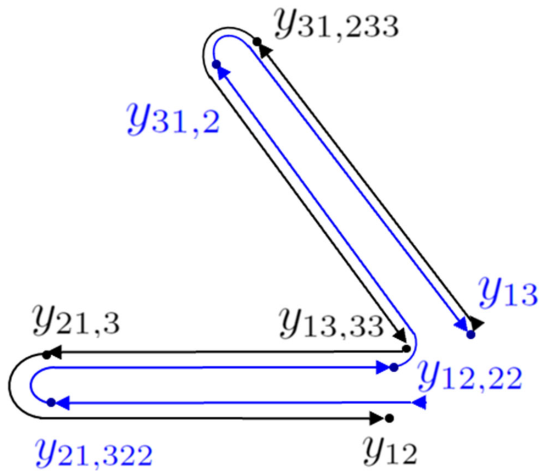

FIG. 2. The schematic of Michelson combination X centered at S/C 1. For time delays, we use the convention, $y_{ij,kl\cdots} = y_{ij}(t - L_k - L_l \cdots)$. The light paths of two colors are nearly equal so that laser frequency noise is effectively suppressed.

directly, we calculate the noise power spectrum in Michelson combination, Eq. (5),

$$N_X(\omega) = 16\sin^2\omega L\left[2(1+\cos^2\omega L)\frac{s_{\rm acc}^2}{\omega^2} + \omega^2 s_{\rm oms}^2\right], \quad (6)$$

where ω is the angular frequency and $\omega = 2\pi f$. It is expected that acceleration noise would dominate at low frequencies due to the ω^{-2} factor while optical metrology noise dominates at high frequencies because of ω^2 term. In the low-frequency limit, $\omega L \ll 1$, we have $N_X(\omega) \simeq 64L^2 s_{\rm acc}^2$, which is frequency-independent for constant $s_{\rm acc}$. At first sight, it seems longer arms would make detectors less sensitive. However, as we shall shown, the signal PSD also depends on L and eventually prefers larger arm lengths.

IV. SENSITIVITIES TO ULDM

To estimate the sensitivity of a laser interferometer to ULDM, we calculate the signal PSD of $X(t)$ in frequency domain, and compare it with the noise PSD, $N_X(\omega)$ in Eq. (6). The ULDM PSD of $X(t)$ in observation duration T is related to the amplitude in frequency domain, $\tilde{X}(\omega)$,

$$S_X(\omega) = |\tilde{X}(\omega)|^2/T = S_\Phi^j + S_h^j, \quad (7)$$

where we have separated the contributions from scalar and tensor metric perturbations into S_Φ^j and S_h^j, respectively, and performed the sky average over the propagation direction of ULDM, and additional average over the polarizations for vector ULDM. We have neglected the cross term $S_{\Phi h}$, which either vanishes after averaging over directions and polarizations, or is subdominant. Parametrizing ULDM as superpositions of plane waves with frequency dispersion $\delta\omega \sim mv^2$, we observe that $S_X(\omega)$ has a nearly monochromatic component at $\omega = 2m$ [102].

Specifically, for scalar ULDM propagating along some direction $\hat{k} = \vec{k}/|\vec{k}|(\vec{k} = m\vec{v})$, we have

$$\begin{aligned} S_\Phi^s(\hat{k}) \simeq v_{\rm osc}^2 T\big|\hat{k}\cdot\hat{n}_{13}\big[1 - e^{-i8mL} - 2e^{-i(2mL+2\vec{k}\cdot\hat{n}_{13}L)} \\ + 2e^{-i(6mL+2\vec{k}\cdot\hat{n}_{13}L)}\big] - \hat{k}\cdot\hat{n}_{12}\big[1 - e^{-i8mL} \\ - 2e^{-i(2mL+2\vec{k}\cdot\hat{n}_{12}L)} + 2e^{-i(6mL+2\vec{k}\cdot\hat{n}_{12}L)}\big]\big|^2, \end{aligned} \quad (8)$$

where $v_{\rm osc} = \kappa^2\rho v/4m^2$, $\kappa \simeq \sqrt{4\pi G}$. And

$$S_h^s(\epsilon_{ij}) \simeq \frac{64}{9}\kappa^4\rho^2 v^4 L^4 T[(\hat{n}_{12}^i\hat{n}_{12}^j - \hat{n}_{13}^i\hat{n}_{13}^j)\epsilon_{ij}]^2, \quad (9)$$

where ϵ_{ij} is the polarization tensor and should be averaged in later numerical evaluations. A quick estimation shows the average of the term in bracket gives an $\mathcal{O}(1)$ factor.

Under the low-frequency approximation, $mL \ll 1$, we average the propagation direction $\hat{k}$ analytically,

TABLE I. Arm lengths and instrumental noises of several planned laser interferometers in space. In the last row we give the sensitivities on vector ULDM with mass 5.0×10^{-19} eV. Here L is the nominal arm length of triangle constellation, while $s_{\rm acc}$ and $s_{\rm oms}$ are the acceleration noise of test mass and noise from optical metrology system, respectively. Note that LISA/LISAmax/Taiji/Tianqin adopt frequency-dependent noise power spectra [101], $s_{\rm acc}^2 \propto [1 + (0.4\times10^{-3}\ {\rm Hz}/f)^2][1 + (f/8\times10^{-3}\ {\rm Hz})^4]$ and $s_{\rm oms}^2 \propto 1 + (2\times10^{-3}\ {\rm Hz}/f)^4$.

	LISA	Taiji	Tianqin	BBO	DECIGO	μAres	LISAmax	ASTROD-GW
L (10^9 m)	2.5	3	0.17	0.05	1×10^{-3}	395	260	260
$s_{\rm acc}$ (10^{-15} $\frac{\rm m/s^2}{\sqrt{\rm Hz}}$)	3	3	1	3×10^{-2}	4×10^{-4}	1	3	3
$s_{\rm oms}$ (10^{-12} $\frac{\rm m}{\sqrt{\rm Hz}}$)	15	8	1	1.4×10^{-5}	2×10^{-6}	50	15	100
$\frac{\rho}{\rho_0}$ (5.0×10^{-19} eV)	7.95×10^2	6.53×10^2	3.82×10^3	2.00×10^2	1.34×10^2	0.44	7.67	4.32

$$S_{\Phi}^{s} \simeq \frac{64}{15}\kappa^4\rho^2 v^2 L^4 T \left[v^2 \sin^2\gamma + 5m^2 L^2 \sin^2\frac{\gamma}{2} \right], \tag{10}$$

where γ is the angle between two arms of the triangle, $\gamma \simeq \pi/3$. When $mL \simeq 0.75 \times (\frac{m}{5.0\times 10^{-19}\ \mathrm{eV}})(\frac{L}{3.0\times 10^{11}\ \mathrm{m}}) \gg v \simeq 10^{-3}$, the second term in bracket would be dominant and $S_{\Phi}^{s} \propto m^2 v^2 L^6$. Otherwise, $S_{\Phi}^{s} \propto v^4 L^4$ and comparable to S_h^s. In both cases, longer arms give larger signal PSD.

For vector ULDM, S_{Φ}^{v} is at the same level as S_{Φ}^{s}. However, in this case the dominant contribution actually comes from the tensor perturbation,

$$S_h^v(\epsilon_{ij}) \simeq \frac{256}{9}\kappa^4\rho^2 L^4 T [(\hat{n}_{12}^i \hat{n}_{12}^j - \hat{n}_{13}^i \hat{n}_{13}^j)\epsilon_{ij}]^2. \tag{11}$$

Note that S_h^v is significantly larger than S_{Φ}^v, at least by a factor of $1/v^2 \sim 10^6$ when $mL \gg v$.

It is now evident that larger arm length L gives larger power spectrum S_X, which suggests that at the same noise level GW detectors in space with longer arms would have better sensitivity to ULDM. To estimate the sensitivity quantitatively, we define it as the value of density ρ with which the signal-to-noise ratio (SNR) reaches unity,

$$\mathrm{SNR} = \frac{S_X(\omega)}{N_X(\omega)} = 1. \tag{12}$$

At low frequencies we have $\rho \propto \kappa^2 s_{\mathrm{acc}}/L\sqrt{T}$. When the sensitivity ρ of some detector is less than or equal to DM's local density $\rho_0 \simeq 0.4\ \mathrm{GeV/cm^3}$, namely $\rho/\rho_0 \lesssim 1$, such a detector would be able to probe local ULDM in solar system.

In Fig. 3 we plot the sensitivities of various GW detectors to scalar and vector ULDM. For scalar ULDM, the most sensitive range is around $m \sim 10^{-18}$ eV by μAres [97], which is aiming at detecting μHz GWs. The sensitivity surpasses that from planetary ephemerides in solar system [71], reaching $\rho/\rho_0 \sim 10^3$. This large value also suggests that, unless there are huge improvements on instrumental noises by several orders of magnitude or there are DM clumps near solar system, it is difficult to probe local scalar ULDM gravitationally through GW detectors in space.

Interestingly, for vector ULDM with $m \lesssim 10^{-18}$ eV μAres is able to probe $\rho/\rho_0 \simeq 0.4$, indicating the possibility to detect local DM gravitationally. In this case, at low frequencies the flat behavior of sensitivities from μAres, ASTROD-GW, DECIGO and BBO as well, results from the frequency independence of $N_X(\omega)$ and S_h when $\omega L \ll 1$. For LISA, Taiji, Tianqin and LISAmax, the adopted acceleration noises s_{acc} have nontrivial frequency dependence, making them less sensitive at lower frequencies. The plot demonstrates that at low frequencies the sensitivity goes as $\rho \propto L^{-1}$, which is quite different from the scalar ULDM case where $\rho \propto L^{-2}$ for $1 \gg mL \gg v \sim 10^{-3}$, indicated by Eq. (10). It also exhibits that all discussed GW detectors in space would surpass planetary ephemerides in some mass ranges of vector ULDM. These findings extend the scientific objects for future GW detectors in space.

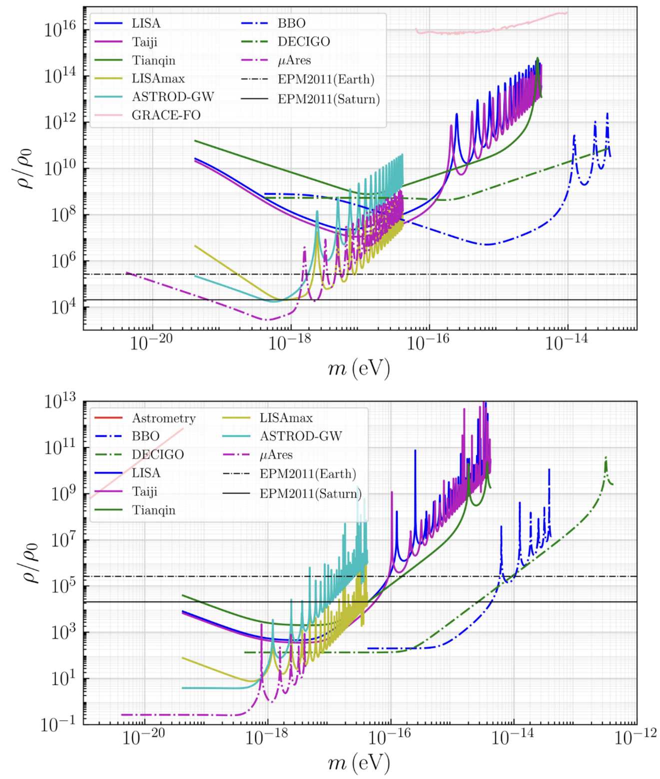

FIG. 3. Upper: sensitivities to ρ for scalar ULDM. Lower: sensitivities to ρ for vector ULDM. We assume one-year observation time for LISA, Taiji, Tianqin, BBO, DECIGO, LISAmax and ASTROD-GW, ten years for μAres and 13 days for GRACE-FO (pink curve). For comparison, we also show the constraints (horizontal lines) derived from the solar system planetary ephemerides [71] and the estimated astrometric detection threshold (the red line in lower panel).

We have conducted the above numerical analysis by employing the first-generation time-delay interferometry (TDI), which assumes static arm lengths. However, the sensitivities and conclusions do not change if we use the second-generation TDI with time-changing arm lengths, which doubles the terms in $X(t)$ and the light paths in Fig. 2. The resulting noise and signal PSDs would be modified by the same factor $4\sin^2(2mL)$ and cancel out in the signal-to-noise ratio. Furthermore, we have only used the Michelson channel. Many other channels are possible, which can provide additional information of the signal, like the spin of ULDM (Supplemental Material [91]).

For comparison, we show the inferred limit from the GRACE-FO satellite project [103], which has validated the laser metrology to be deployed in LISA. There are only two spacecrafts in GRACE-FO whose separation is monitored by laser interferometers. Although not capable to detect GW or ULDM, the overall noise level in the collected data can still give a constraint, shown as the pink curve in the upper plot. Similar to GWs, the metric perturbations sourced by ULDM also lead to a distortion of the apparent angular positions of stars, a rough estimation for its detectability with Gaia-like astrometric accuracy (see Supplemental Material [91]) is shown in the lower plot for vector ULDM. Both limits are considerably weaker than that from planetary ephemerides, and GW detectors in space.

V. CONCLUSION AND OUTLOOK

We have elucidated that future space-based GW laser interferometers can provide new insights into detecting ULDM and extend the scientific objectives. Without assuming any additional interactions between ULDM and normal matter, the gravitational perturbations caused by vector ULDM with mass $m \lesssim 10^{-18}$ eV in solar system is able to perturb the geodesics of test masses at a detectable level if the arm length of the triangle constellation is comparable to the diameter of Mars' orbit. For scalar ULDM, although not capable to make a detection, GW detectors would probe the mass range around 10^{-18} eV that other experiments are challenge to explore. This investigation highlights the unique advantage of GW detectors in space. Detection of such a signal would directly suggest the wave nature of DM and its mass and spin, indicating the fundamental theories of DM.

To distinguish the ULDM signal from GW events from compact binaries nearby galaxies, it is necessary to go beyond the power spectral density and perform matched filtering in time domain or even joint observation with multiple detectors. A more sophisticated treatment would be comparing the outcome of various TDI combinations, which at low frequencies have different sensitivities to ULDM of different spins and GWs. The anisotropic distribution of such GWs would also be distinct. Dedicated investigations are warranted in future work.

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