

Multimessenger astroparticle physics: The first constraint on light millicharged dark matter via time-delay analysis of GRB GW170817A

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Multimessenger astroparticle physics provides a new approach to probe new physics beyond the Standard Model. We propose to probe the light dark matter which can interact via the electromagnetic force. To be concrete, we derive the new constraint on the millicharged dark matter from the multimessenger observations of GW170817. In the neutron star merger event GW170817, the first detection of a γ -ray burst delayed by approximately 1.7 seconds relative to the gravitational wave emission was observed. Utilizing this delay, we constrain the parameter space of the millicharged dark matter within the large-scale structure of the Universe. For dark matter mass below 10^{-17} eV, the parameter ϵ is constrained to be less than 10^{-14} , representing the most stringent limits achieved to date.

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I. INTRODUCTION

The advent of multimessenger astronomy has inaugurated a new era in fundamental physics, enabling unprecedented probes of the Universe through the correlated detection of gravitational waves (GWs), photons, and neutrinos. Each messenger carries complementary information, and their combined analysis provides a powerful tool for testing the Standard Model and exploring new physics. In this work, we introduce a novel astroparticle phenomenology framework—multimessenger astroparticle physics—that leverages temporal correlations between different cosmic messengers to search for particle dark matter (DM). To be concrete, we propose to probe the light

DM which can interact via the electromagnetic force, for instance, millicharged dark matter, axions, and dark photons, etc. In this paper, we concentrate on the millicharged dark matter. The millicharged particles, which carry a fraction of electron charge, $Q = \epsilon e$, serve as probes of the violation of the charge-quantization hypothesis and are predicted by the superstring theories [1,2] and grand unified theories [3,4]. The dark sector provides a natural scenario for weakly breaking the $U(1)$ electromagnetic symmetry through interactions with hidden photon fields [5–7]. The interaction between millicharged DM and the Standard Model is mediated by a kinetically mixed dark photon [8–11], effectively introducing a feeble $U(1)$ coupling. For wavelike dark matter with mass below 10^{-10} eV, terrestrial detectors such as the milliQan experiment [12], colliders [13–15], fixed-target experiments [16–18,18–20], and neutrino experiments [21–23] face challenges due to the ultralight particle's macroscopic de Broglie wavelength [24], necessitating probes via spectral distortions in astrophysical [11] or cosmological transient events [14]. Various mechanisms exist for the production of

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ultralight dark matter in the early Universe, such as the misalignment mechanism and nonthermal freeze-in [25], which can lead to distinct charge distributions of the dark matter species, including both symmetric (neutral) [26,27] and asymmetric [28,29] distributions of millicharged dark matter. In this paper, we propose a novel detection scheme that is applicable to dark matter candidates originating from nonthermal production. This scheme remains valid regardless of the specific charge distribution of the dark matter. This approach leverages the observed time delay between the short γ -ray burst (sGRB) and gravitational wave emission from the neutron star merger event [30–32] GW170817 [33–35]. By treating the ubiquitous millicharged dark matter in the cosmos as a homogeneous medium—analogous to light propagation in water where photon scattering with the medium slows the effective phase velocity—we analyze how interactions between photons and millicharged dark matter could induce a measurable delay in high-energy photon arrival times.

The sGRB 170817A [34,36–38] serves as an ideal candidate for probing light dark matter in the Universe due to two key characteristics:

- (i) Extreme propagation distance: the source is located 40 Mpc away from the Earth, making the DM distribution along the path approximately homogeneous. In addition, the vast distance amplifies cumulative effects from photon–dark matter interactions.
- (ii) Breakthrough in time-delay measurement: the event provided the first precise measurement of the propagation time difference (~ 1.7 s) between the sGRB and gravitational wave signals, establishing a novel pathway to constrain dark matter parameters via multimessenger time-delay analysis.

The sGRB originated from relativistic jets driven by accretion disks [39–41] around black holes formed in the aftermath of compact binary mergers. Considering the non-zero jet breakout time, the actual delay of γ -ray photons during propagation is actually less than 1.7 s. However, due to the difficulty in precisely calculating the jet breakout duration, we adopt the most conservative scenario in this work and focus on translating the observational time delay into constraints on the millicharge parameter, assuming the photon propagation delay approximates the full 1.7 s. Crucially, if the true delay is smaller than 1.7 s, the derived upper limit on the millicharge parameter would be further strengthened. With this delay, we constrain the millicharge parameter of dark matter within the large-scale structure of the Universe. For dark matter mass below 10^{-15} eV, the millicharge parameter e is constrained to be less than about 10^{-14} , representing the most stringent limits achieved to date.

II. LIGHT VELOCITY IN DM MEDIUM AND CONSTRAINTS FROM THE SGRB GW170817A

Given that time-delay effects are significantly enhanced for dark matter with mass below $\mathcal{O}(1)$ eV, we specifically

focus on millicharged dark matter within the sub-eV mass range. The light dark matter must be bosonic due to the large average number of particles in a de Broglie volume, $\lambda_{dB}^3 = (\frac{2\pi}{mv})^3$, as follows:

$$N_{dB} \sim \left(\frac{34 \text{ eV}}{m}\right)^4 \left(\frac{250 \text{ km/s}}{v}\right)^3. \quad (2.1)$$

The effective refraction index, which is related to the group velocity for a particle in a homogeneous medium is [42]

$$n = 1 + \frac{\rho_N}{4m\omega^2} \mathcal{M}(k, p, \lambda \rightarrow k, p, \lambda), \quad (2.2)$$

where $\rho_N = \rho_\chi/m$ is the dark matter number density, m is the dark matter mass, and ω is the photon energy. For a nonuniform dark matter distribution, the homogeneous factor $\rho_\chi L$ should be understood as the line-of-sight dark matter column density

$$\mathcal{D}_\chi \equiv \int_0^L \rho_\chi(s) ds,$$

or equivalently as an effective density

$$\rho_\chi^{\text{eff}} \equiv \frac{1}{L} \int_0^L \rho_\chi(s) ds.$$

In the numerical bounds quoted in this work, we use

$$\mathcal{D}_\chi = \bar{\rho}_\chi L,$$

with $\bar{\rho}_\chi = 2.1 \times 10^{-30} \text{ g cm}^{-3}$, namely the cosmological mean dark matter density. This choice does not include the additional dark matter column density from the Milky Way, the host galaxy, or possible intervening halos. Therefore, the resulting limits should be interpreted as conservative large-scale-structure limits.

The amplitude, $\mathcal{M}(k, p, \lambda \rightarrow k, p, \lambda)$, corresponds to the forward Compton scattering event with λ indicating the photon polarization. This value is calculated in the dark-matter rest frame with $p = (m, 0)$. One can show that the amplitude vanishes unless the photon polarization direction is unchanged. For millicharged scalars with electric charge e , the Lagrangian relevant to interactions with SM photon is $\mathcal{L} \supset |\mathcal{D}_\mu \phi|^2$, where $\mathcal{D}_\mu = \partial_\mu - ieA_\mu$ with e the scalar millicharge. Three channels including s-, u- and $\phi\phi A_\mu A^\mu$ direct interaction channels are included as shown in Fig. 1. This amplitude is given by $|\mathcal{M}| = 2e^2 e^2$, demonstrating that the detection mechanism is independent of charge symmetry and depends solely on the magnitude of the dark matter's millicharge.

One might assume that the DM as a Bose-Einstein condensate [43–46] would lead to a significant

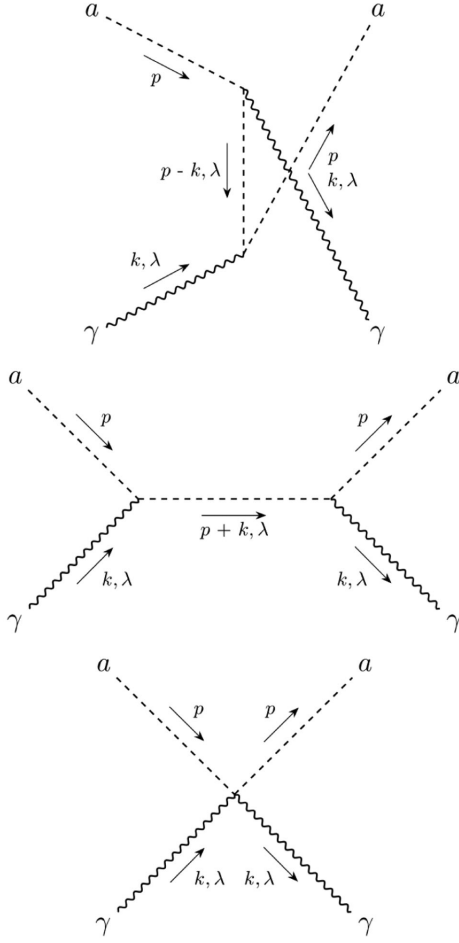


FIG. 1. Feynman diagrams for the forward scattering process involving γ photons.

enhancement of scattering amplitudes due to high occupancy within one de Broglie wavelength volume, rendering single-particle scattering amplitude calculations inapplicable. However, the fact is that this enhancement effect has already been accounted for in refractive index calculations involving multiple scattering. We employ the method described in Ref. [47] to describe dark matter as a multi-particle wave packet, and the result is equivalent to the modification of the propagator presented in Ref. [46]. To make this explicit, we need to reformulate Eq. (2.2) as a relation between the time delay and the single-collision amplitude in general,

$$\Delta t = \frac{L}{4m\omega^2} \sum_i \mathcal{M}_i(k, p, \lambda \rightarrow k, p, \lambda), \quad (2.3)$$

where the $\sum_i \mathcal{M}_i$ is the amplitude counted for per unit volume. The subscript i stands for the i th forward Compton process within a unit volume. L is the distance between the observer and the source.

Similarly, the ultralight dark matter comprises multiple Bose-Einstein condensates (BECs), indexed by i . The i th

BEC consists of a macroscopic number N_i of identical bosonic particles occupying a single quantum state, with their momentum differences lying below experimental resolution. Such an occupation number follows the Bose-Einstein distribution and has the relationship $\rho_N = \sum_i N_i$.

A BEC composed of N_i particles—each described by a wave packet—forms a collective background field. When this field participates in scattering processes, the interaction evolves from single-particle scattering to N_i -wave-packet scattering, reflecting a macroscopic quantum enhancement. Our derivation establishes that in Feynman diagrams with two external legs of axionlike particles (ALPs), the BEC-mediated scattering amplitude and the single-particle amplitude obey the relation

$$\mathcal{M}_i = N_i \mathcal{M}(k, p, \lambda \rightarrow k, p, \lambda). \quad (2.4)$$

The detailed calculations are provided in Appendix A. From Eqs. (2.4) and (2.3), one can directly see that the refractive index formula satisfies Eq. (2.2). It should be noted that our calculations do not depend on the specific occupation numbers within the coherent state, i.e., they are independent of the explicit form of N_i . This is because we address a specialized process that depends solely on the total ALP particle number, and the enhancement factor for individual scattering events coincides exactly with N_i .

According to the experimental observations of GW170817A [36,37], the sGRB detected by the Fermi satellite exhibited a frequency distribution spanning 8 keV to 300 keV. The time lags between different frequency bins showed no significant frequency dependence [33–35]. However, a time interval of approximately 0.27 ± 0.05 s [36] was observed between the arrival times of γ rays in the (8, 50) keV and (100, 300) keV energy ranges. Based on the above results, we consider the following two scenarios:

- (i) Scenario 1: neglecting the arrival time differences between different frequency bands and assuming the photon delay approximates the full 1.7 s, we adopt the central frequency of 100 keV as the reference frequency. This scenario provides the most conservative constraints on the millicharge parameter. In this case, the millicharge parameter can be expressed as

$$\epsilon_{\max} \simeq 7.90 \times 10^3 \times \left(\frac{m}{1 \text{ eV}} \right) \left(\frac{10^{-6} \text{ GeV/cm}^3}{\rho_\chi} \right)^{\frac{1}{2}} \times \left(\frac{\omega}{100 \text{ keV}} \right). \quad (2.5)$$

- (ii) Scenario 2: assuming the time lag ~ 0.27 s between (8, 50) keV and (100, 300) keV photons arriving at Earth is induced by scattering with dark matter. In this case, the sGRB and gravitational waves are not produced simultaneously—the sGRB emission lags

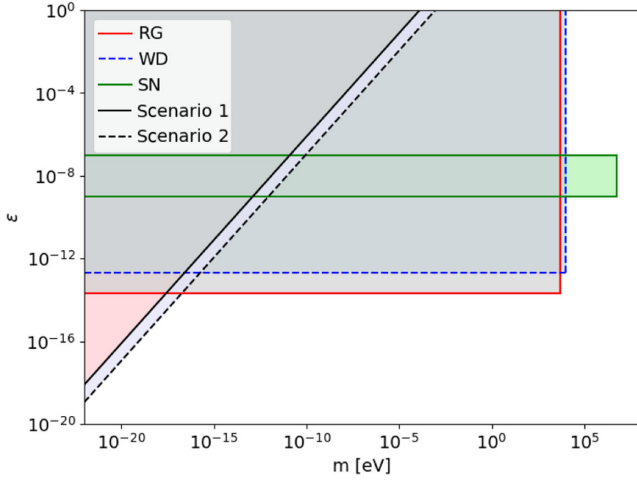


FIG. 2. Upper limit from cosmological observables from a red giant (RG) [48], white dwarf (WD) [49], and supernova (SN) [50,51] as well as the sGRB 170817A. The colored area is excluded by the corresponding observables.

behind the GWs by approximately 1s, which is consistent with predictions from jet formation models for sGRBs. The time lag induced by the millicharged DM is no longer than ~ 0.27 s. Approximately, adopting 30 keV and 200 keV as representative energies for (8, 50) keV and (100, 300) keV bands respectively, we derive

$$\epsilon_{\max} \simeq 1.13 \times 10^3 \times \left(\frac{m}{1 \text{ eV}} \right) \left(\frac{10^{-6} \text{ GeV/cm}^3}{\rho_\chi} \right)^{\frac{1}{2}}. \quad (2.6)$$

The upper limit of the millicharge parameter derived from the two scenarios is shown in Fig. 2.

We emphasize that the relevant measure of an inhomogeneous dark matter distribution is not a volume filling factor alone, but the density-weighted line-of-sight column density. If a localized region occupies a path-length fraction $f_L = L_{\text{loc}}/L$ and has an average density $\langle \rho_\chi \rangle_{\text{loc}}$, its fractional contribution relative to the homogeneous cosmological component is

$$\eta_{\text{loc}} \equiv \frac{1}{\bar{\rho}_\chi L} \int_{\text{loc}} \rho_\chi(s) ds = f_L \frac{\langle \rho_\chi \rangle_{\text{loc}}}{\bar{\rho}_\chi}.$$

Thus, a small geometric filling factor by itself does not necessarily imply a small contribution if the density contrast is large. In the present work, we do not attempt to model these local structures. Instead, we quote the conservative bound obtained from the homogeneous cosmological component alone. If local halos are included, the total column density becomes

$$\mathcal{D}_\chi = \bar{\rho}_\chi L (1 + \eta_{\text{loc}}),$$

and the upper bound on the millicharge rescales as

$$\epsilon_{\max} \rightarrow \frac{\epsilon_{\max}}{\sqrt{1 + \eta_{\text{loc}}}}.$$

Therefore, possible positive contributions from local galaxies or halos would strengthen, rather than weaken, the limits reported here. A dedicated modeling of the Milky Way, the host galaxy, and possible intervening halos is beyond the scope of the present work, and our quoted limits should be regarded as conservative bounds based on the homogeneous cosmological dark matter component.

III. DISCUSSION

We have presented a new astroparticle detection strategy that utilizes time-delay measurements between gravitational waves and electromagnetic signals from neutron star mergers to search for light millicharged dark matter. By analyzing the GW170817/GRB 170817A event, we derived competitive constraints on the millicharge parameter ϵ for ultralight DM—in some mass regimes, surpassing existing limits from laboratory or astrophysical probes.

In this work, we investigate constraints on the millicharged DM deriving from the time delay between the gravitational wave event and its electromagnetic counterpart. To address uncertainties in the relative timing of jet emission and gravitational wave generation during the neutron star merger, we adopt the most conservative scenario by attributing the entire observed 1.7-second delay to dark matter-induced refraction.

By utilizing the connection between the refractive index in a homogeneous dark matter medium and the forward Compton scattering amplitude, our preliminary calculations reveal that GRB 170817A provides the most stringent constraints on ϵ within the ultralight mass regime ($m_{\text{DM}} \lesssim 10^{-15}$ eV).

When further incorporating the BEC effects of ultralight dark matter, we demonstrate that—under cosmological large-scale structure conditions—the refractive index modification caused by single-particle Compton scattering amplitudes becomes equivalent to the collective effect of multiparticle BEC condensates. This equivalence enables us to derive the most robust conservative bounds on the millicharged dark matter parameter space.

A critical theoretical aspect of our constraints is the stability of the millicharged DM condensate against depletion via parametric resonance (PR) annihilation into photons in the early Universe, as pointed out in recent literature [52]. For the parameter space probed in this study, the Mathieu parameter governing the resonance,

$$Q \simeq \frac{\epsilon^2 e^2 \rho_{\text{DM}}}{2m_{\text{DM}}^4}, \quad (3.1)$$

can be exceptionally large, potentially leading to rapid fragmentation of the DM field in the minimal setup.

However, this possible depletion is model dependent, and our phenomenological constraint can be embedded in frameworks in which the condensate is stable. We highlight two viable scenarios. First, in a mass-protected symmetric dark matter framework mediated by a kinetically mixed dark photon, PR depletion can be kinematically blocked if the photon mode into which the condensate would resonantly decay has an effective plasma mass m_{plasma} . Here, m_{plasma} denotes the in-medium effective mass of the photon/dark-photon propagation eigenmode in the early Universe plasma, not the dark matter mass. When

$$m_{\text{plasma}} \gg 2m_{\text{DM}},$$

the resonant production of two on-shell photon modes is kinematically forbidden, and the corresponding Floquet exponent becomes imaginary. Consequently, the parametric resonance channel is shut off.

Second, one can consider a decoupled multicomponent dark sector framework to avoid cosmic magnetic-field constraints on large-scale charge asymmetries. In this scenario, the dark sector consists of two mutually decoupled subsectors carrying opposite millicharges $+ee$ and $-ee$. We denote their macroscopic number densities by n_+ and n_- , respectively. The condition

$$n_+ = n_-$$

is imposed to ensure vanishing net electric charge density on cosmological scales. This condition should not be confused with the electron number density n_e in an ordinary plasma. Because the two subsectors do not share common gauge bosons, direct annihilation between the two components is absent or strongly suppressed in this setup, while the Universe remains electrically neutral.

Crucially, since the forward Compton amplitude and hence the refractive-index correction scale as the square of the millicharge, $(ee)^2$, the time-delay effect depends on the total number density of charged dark matter particles,

$$n_{\text{tot}} = n_+ + n_-,$$

rather than on the net charge density $n_+ - n_-$. Therefore, the contributions from the $+ee$ and $-ee$ components add constructively to the photon time delay, while the net cosmological charge can remain zero.

Our results highlight the potential of multimessenger timing as a novel experimental tool, complementary to traditional particle detection methods. This approach is inherently cross-disciplinary, bridging gravitational-wave

physics, γ -ray astronomy, and particle phenomenology. Looking ahead, the growing catalog of neutron star mergers from advanced GW detectors will provide a statistically robust dataset to which our method can be applied systematically. Future events with better-resolved emission timelines and broader multimessenger coverage—including neutrinos—will further sharpen the probe and may even enable discovery.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX

In this Appendix, we will discuss the BEC effect and demonstrate that the BEC enhancement effect is equivalent to the multiple scattering processes experienced by high-energy photons propagating through a dark matter medium.

We employ multiparticle wave packets to characterize the incoming or outgoing states of ultralight dark matter particles, where the BEC background field is generated by n wave packets [47], as follows:

$$|n\rangle = \frac{(a_a^\dagger)^n}{\sqrt{n!}} |0\rangle, \quad (\text{A1})$$

where the $a_a^\dagger$ is the wave packet generating operator that is expressed as

$$a_a^\dagger = \int \frac{d^3 p}{(2\pi)^3} \frac{\tilde{a}(p)}{\sqrt{2E_p}} a^\dagger(p), \quad (\text{A2})$$

with the wave function renormalization condition

$$\int \frac{d^3 p}{(2\pi)^3} \frac{|\tilde{a}(p)|^2}{2E_p} = 1. \quad (\text{A3})$$

The field operator $a(x)$ is expressed as

$$\phi(x) = \int \frac{d^3 p}{(2\pi)^3} \frac{1}{\sqrt{2E_{p_i}}} [a(p)e^{-ipx} + a^\dagger(p)e^{ipx}]. \quad (\text{A4})$$

The amplitude associated with the creation and annihilation of the ALP in the background of BEC fluid can be simplified as

$$\begin{aligned} \overline{\langle N_i | \phi(y) \phi(y) \phi(x) \phi(x) | N_i \rangle} &= \frac{N_i^2}{N_i!} \prod_{j,k=1}^{N_i-1} \int \frac{d^3 p_j}{(2\pi)^3} \int \frac{d^3 q_k}{(2\pi)^3} \frac{\tilde{a}(p_j) \tilde{a}^*(q_k)}{2E_{p_j} 2E_{q_k}} \langle q_k | p_j \rangle \overline{\langle q | \phi(y) \phi(y) \phi(x) \phi(x) | p \rangle} \\ &= N_i \langle q | \phi(y) \phi(y) \phi(x) \phi(x) | p \rangle. \end{aligned} \quad (\text{A5})$$

Here, we omit the field operators unrelated to the creation or annihilation of ALPs. Field operators connected by contraction lines must undergo contraction, while those without contraction symbols participate in the creation and annihilation of initial and final state particles. In the second line, the factor, N_i^2 , arises from the number of momentum eigenstates p and q selected from the initial and final states.

The last line in Eq. (A5) is obtained by using $\langle q_k | p_j \rangle = (2\pi)^3 (2E_{p_j}) \delta^3(q_k - p_j)$. After integrating over the momentum variables q_k , this term acquires an $(N_i - 1)!$ factor stemming from the permutation symmetry of the BEC particles' momenta between the initial and final states and finally leaves an enhancement factor of N_i .

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