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The Kilometer Square Array (KM2A) of the Large High Altitude Air Shower Observatory (LHAASO) aims at surveying the northern γ-ray sky at energies above 10 TeV with unprecedented sensitivity. γ-ray observations have long been one of the most powerful tools for dark matter searches, as e.g., high-energy γ-rays could be produced by the decays of heavy dark matter particles. In this letter, we present the first dark matter analysis with LHAASO-KM2A, using the first 340 days of data from 1/2-KM2A and 230 days of data from 3/4-KM2A. Several regions of interest are used to search for a signal and account for the residual cosmic-ray background after γ/hadron separation. We find no excess of dark matter signals, and thus place some of the strongest γ-ray constraints on the lifetime of heavy dark matter particles with mass between 10^5 and 10^9 GeV. Our results with LHAASO are robust, and have important implications for dark matter interpretations of the diffuse astrophysical high-energy neutrino emission.

Introduction— Dark matter (DM) is one of the cornerstones of fundamental physics and cosmology, as it accounts for most of the mass of the Universe. So far, DM has evaded all the attempts to detect its non-gravitational interactions [1–3]; the identification of its nature is one of the primary goals in modern science [4, 5]. In this context, DM indirect-detection searches represent a powerful tool that leverages astrophysical data to probe a variety of DM candidates. Among all the astrophysical messengers, high-energy γ-rays have long been an important avenue for achieving some of the best sensitivities in DM searches [6–12]. In this regard, very-high-energy (VHE) γ-rays offer a unique possibility to probe heavy DM particles with masses above 100 TeV.

In recent years, VHE γ-rays have been detected from several Galactic sources [13–17] as well as from the whole Galactic plane [18]. Away from the Galactic plane, upper limits have been placed on the isotropic diffuse γ-ray flux above 100 TeV [19–21]. While the γ-ray emission from extragalactic sources is significantly suppressed due to the cosmic γ-ray absorption, detectable high-latitude VHE γ-rays could be produced through the decays of heavy DM particles in the Galactic halo, as DM annihilations are theoretically disfavored by the unitarity bound in the VHE regime [22]. Decaying heavy DM has been theorized in several models, including WIMPIzil-

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las [23–25], glueballs [26–29], gravitinos [30–32], frozen-in DM [33–36] and other proposals [37–46]. Interestingly, it has also been proposed [47–49] as a source of the diffuse TeV-PeV neutrino flux observed by IceCube [50–52]. Such a scenario has been long studied with multi-messenger observations [53–76]. Nevertheless, DM contributions to the diffuse high-energy neutrino flux remain a viable possibility [67].

The Large High Altitude Air Shower Observatory (LHAASO) [77] is a general purpose, continuously operating air shower cosmic-ray and γ-ray detector located in south-west China, which has completed its construction in 2021. It mainly consists of KM2A (Kilometer Square Array), WCDA (Water Cherenkov Detector Array), and WFCTA (Wide Field of view Cherenkov Telescope Array). Together, it is sensitive to the γ-ray sky from 100 GeV to 1 PeV, and has for the first time detected PeV γ-rays from astrophysical sources [16, 17].

In this letter, we utilize the data from partially-completed KM2A to search for signatures of DM decays.

KM2A Data Analysis— KM2A is a ground-based full-duty extensive air shower (EAS) array dedicated to VHE γ-ray astronomy above 10 TeV. It has an excellent γ/hadron separation capability by using both electromagnetic particle detectors (EDs) and underground muon detectors (MDs). The EDs are plastic scintillation detectors and the MDs are water Cherenkov detectors with 2.5m soil overburden [78]. With a large field of view, $\sim 2\,\mathrm{sr}$, KM2A covers about 60% of the sky daily [79, 80].

In this work, we consider data from the partially completed KM2A, including 340 days from the 1/2-KM2A (2365 out of 4901 EDs and 578 out of 1188 MDs, covering an area of $0.432\,\mathrm{km}^2$), from December 27, 2019 to November 30, 2020, and 230 days from the 3/4-KM2A (3978 out of 4901 EDs and 917 out of 1188 MDs, covering an area of $0.727\,\mathrm{km}^2$), from December 1, 2020 to July 19, 2021. We employ the same data quality cuts, event selection, and detector simulation as in Ref. [80] for both 1/2-KM2A and 3/4-KM2A. The angular and energy resolution of the two data sets are similar, with the latter being slightly better. At 100 TeV, the angular and energy resolutions are about 0.3 degrees and 20% [80], respectively.

The field of view of LHAASO covers the celestial northern sky (Fig. 4 in Ref. [79]). Given that the DM signal is expected to be higher with smaller galactocentric radius, and to reduce the potential diffuse astrophysical emission from the northern Fermi bubble and the Galactic plane, we consider one fiducial search region of interest (ROI), labeled as ROI_0, around $15^\circ \leq b \leq 45^\circ$ and $30^\circ \leq \ell \leq 60^\circ$. We also consider four control regions (labeled $\mathrm{ROI}_1 - \mathrm{ROI}_4$) away from ROI_0 for the purpose of constraining the isotropic cosmic-ray background. These regions are selected to avoid the Fermi bubbles and the Galactic plane as well.

TABLE I. Residual events after γ/hadron separation in the search (ROI_0) and control ($\mathrm{ROI}_1 - \mathrm{ROI}_4$) regions with an observations of 340 days with 1/2-KM2A and 230 days with 3/4-KM2A.

Energy bin $[\log_{10}(\frac{E}{\mathrm{GeV}})]$	N_{ROI_0}	N_{ROI_1}	N_{ROI_2}	N_{ROI_3}	N_{ROI_4}
5.0 – 5.2	1209	1210	1112	1160	1157
5.2 – 5.4	150	147	148	150	153
5.4 – 5.6	51	58	51	41	43
5.6 – 5.8	15	13	14	6	9
5.8 – 6.0	7	7	2	1	7
6.0 – 6.2	1	0	3	1	2

Importantly, we also require $\mathrm{ROI}_1 - \mathrm{ROI}_4$ to have the same declination and angular size (0.274 sr) as ROI_0. This ensures that all the ROIs have the same detector responses, eliminating potential systematics in the declination dependence of the detector response. Following these criteria, $\mathrm{ROI}_1 - \mathrm{ROI}_4$ are chosen by shifting ROI_0 along the RA direction by 90, 135, 240, and 285 degrees, respectively. The exposure time for ROI_0 to ROI_4 are 523, 510, 523, 527, and 529 days, respectively. Due to being shifted to larger galactocentric radii, the expected DM γ-ray fluxes from $\mathrm{ROI}_1 - \mathrm{ROI}_4$ are a factor of a few smaller than the one from ROI_0. For more details see Supplemental Material I.

We partition the data from 10^5 to $10^{6.2}$ GeV with 6 energy bins in logarithmic space, which are wider than the energy resolution of the detector [80]. The γ/hadron separation is then applied by considering the ratio of the detected muons and electrons (see Eq. (7) in Ref. [80]). To further reduce the background, we adopt a more stringent γ/hadron cut parameter than the one in point-source analyses [80]. In this analysis, the γ-ray survival rate is lowered to be at least 50% of the injected gamma-ray events in detector simulation, with the cosmic-ray survival rate further lowered down to 1.86×10^{-6} around 1 PeV in the observed data (see Supplemental Material II for details and validation of the cut). Even with such a strong cut, we still expect that most of the residual events are mis-identified cosmic-ray events. Table I shows the events after γ/hadron separation.

The detector responses of the ROIs are obtained by tracking the ROIs through the sky and comparing with detector simulations. To handle the large ROIs and their potential non-uniform exposure, the exposure of each ROI is obtained by tracking 67 subpixels (each $\simeq (3.7\mathrm{deg})^2$) within each ROI and then combined. We note that even though we expect the detector response are the same for each ROI, their response are computed separately to take into account differences in lifetime and pointing efficiencies. The detector performance of 1/2-KM2A has been thoroughly validated with a precise measurement of the Crab Nebula [17, 80, 81]. Details are presented in Ref. [80], and in Supplemental Material III. For 3/4-KM2A, we use the same data selection cuts, reconstruction series, and γ/hadron separation parameters as those in 1/2-KM2A. Our results are subject to the same systematic uncertainties as discussed in Ref. [80], which is estimated to be about 7% for the flux inference and mainly comes from the variation of event rate during the operational period due to seasonal and daily changes. Furthermore, to assess the systematic uncertainties due to the γ/hadron separation procedure, we find that the flux would change by about 20% if the cut condition were changed to a 30% γ-ray survival rate. The inferred DM decay rate results are thus also subject to these uncertainties.

Decaying dark matter formalism— DM decaying into various Standard Model states could give rise to a diffuse flux of VHE γ-rays. In the PeV energy range, the dominant γ-ray components are the prompt component generated directly from Galactic DM decays as well as the secondary component from Inverse Compton (IC) scattering of electrons and positrons produced by DM particles [56, 82, 83]. Other contributions, such as bremsstrahlung and synchrotron radiation, are either subdominant or contribute at much lower energies. Moreover, due to the cosmic γ-ray attenuation and the related electromagnetic cascade processes, extragalactic DM decays are relevant only at energies smaller than $\sim 10^4$ GeV [84]. Thus, neglecting these contributions is conservative, and does not impact our results.

The prompt γ-ray intensity (flux per solid angle) due to DM decay from a certain Galactic latitude (b) and longitude (ℓ) is given by

$$\frac{\mathrm{d}I_\gamma^{\mathrm{prompt}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi\, m_{\mathrm{DM}}\tau_{\mathrm{DM}}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}D(E_\gamma, b, \ell)\,, \qquad (1)$$

where m_{DM} and τ_{DM} are respectively the mass and the lifetime of DM particles, $\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ is the photon energy spectrum per DM decay, and $D(E_\gamma, b, \ell)$ is the so-called D-factor. The photon energy spectrum is computed by using the `HDMSpectra` package [85], which includes the electroweak radiative corrections. The D-factor is given by the integral of the DM halo density profile ρ_h over the line-of-sight s, including the effect of Galactic γ-ray attenuation,

$$D(E_\gamma, b, \ell) = \int_0^\infty \mathrm{d}s\, \rho_h\left[r(s, b, \ell)\right] e^{-\tau_{\gamma\gamma}(E_\gamma, \vec{x})}\,, \qquad (2)$$

where $\tau_{\gamma\gamma}$ is the total optical depth due to pair production ($\gamma\gamma \to e^+e^-$) with background photons [56]. The photon targets are the Cosmic Microwave Background (CMB), Galactic starlight (SL), and infrared (IR) radiation. The SL+IR background is extracted from the `GALPROPv54` code [86] (see also Ref. [87]). While the CMB photons are homogeneous, the SL+IR radiation depends on the position $\vec{x}$ in the Galaxy, which is expressed in terms of (s, b, ℓ). In particular, SL+IR dominates over CMB near the Galactic center and in the Galactic plane. Nevertheless, the angular dependence of the D-factor stems mainly from the DM halo density profile, for which we consider the commonly-adopted Navarro-Frenk-White (NFW) distribution [88]

$$\rho_h(r) = \frac{\rho_s}{(r/r_s)\,(1 + r/r_s)^2}\,, \qquad (3)$$

which is a function of the Galactocentric radial coordinate

$$r = \sqrt{s^2 + R_\odot^2 - 2\, s\, R_\odot \cos b \cos \ell}\,, \qquad (4)$$

with $R_\odot = 8.3$ kpc being the Sun position. At the scale radius $r_s = 20$ kpc we take $\rho_s = 0.33$ GeV/cm^3, which yields a local DM density $\rho_\odot \simeq 0.4$ GeV cm^{-3} [89–91]. The local DM density is found to be generally around $0.3 - 0.6\,\mathrm{GeV/cm^3}$ [92] and our DM decay results scale linearly with it. In the energy range considered, the averaged energy-dependent D-factor in Eq. (2) in the search region (ROI$_0$) is larger by a factor ranging from 1.6 to 2.3 than those in the control regions (ROI$_1$ − ROI$_4$). This ensures a higher DM intensity in ROI$_0$ with respect to the other selected regions. Moreover, the DM γ-ray flux depends only slightly on the choice of the density profile for the extended DM Galactic halo and our results are robust against density profile choices, see Supplemental Material IV.

The secondary Galactic IC component is computed by solving the stationary diffusion-loss equation for the electrons and positrons injected in the Galaxy by DM decays. At high energies, however, the electron/positron distribution is completely dictated by the energy losses [56]. Hence, by neglecting the marginal effect of diffusion, the galactic IC component takes the following expression [56, 82]:

$$\frac{\mathrm{d}I_\gamma^{\mathrm{IC}}}{\mathrm{d}E_\gamma} = \frac{1}{2\pi E_\gamma m_{\mathrm{DM}}\tau_{\mathrm{DM}}}\int_0^\infty \mathrm{d}s\, \rho_h(r) e^{-\tau_{\gamma\gamma}(E_\gamma, \vec{x})} \times \int_{E_\gamma}^{\frac{m_{\mathrm{DM}}}{2}} \mathrm{d}E_e\, \frac{P_{\mathrm{IC}}(E_\gamma, E_e, \vec{x})}{b(E_e, \vec{x})}\int_{E_e}^{\frac{m_{\mathrm{DM}}}{2}} \mathrm{d}E_e'\, \frac{\mathrm{d}N_e}{\mathrm{d}E_e'}\,. \qquad (5)$$

Here, P_{IC} is the IC radiated power, $b(E_e, \vec{x})$ is the energy loss coefficient comprising IC and synchrotron processes, and $\mathrm{d}N_e/\mathrm{d}E_e'$ is the injected electron spectrum computed with `HDMSpectra`. For the synchrotron energy losses we adopt the regular Galactic magnetic field model with a local strength of 4.78 μG as reported in Ref. [93]. For more details on the DM signal computation and its uncertainties, see Supplemental Material IV.

Likelihood analysis— We perform a joint-likelihood analysis on the ROIs that takes into account the DM angular distribution. The likelihood function for the k-th ROI is given by

$$\ln \mathcal{L}_k(\tau_{\mathrm{DM}}, b) = \sum_i N_k^i \ln n_k^i - n_k^i\,, \qquad (6)$$

where N_k^i is the number of observed events in each energy bin, i, and n_k^i is the modeled number of events, given by

$$n_k^i(\tau_{\mathrm{DM}}, b) = \left(b^i + s_k^i\left(\tau_{\mathrm{DM}}\right)\right)\mathcal{E}_k^i \Delta\Omega\,, \qquad (7)$$

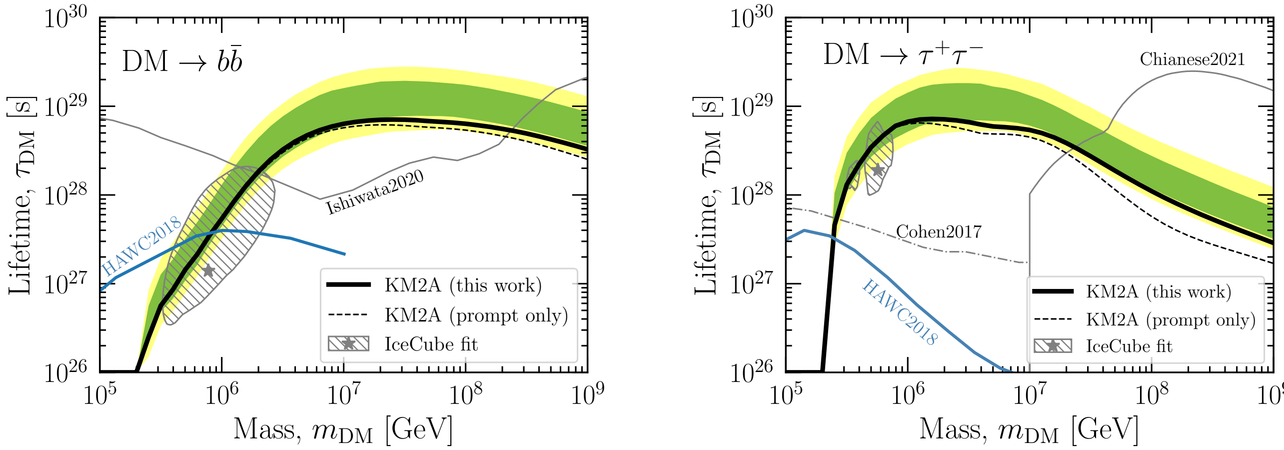

FIG. 1. 95% one-sided lower limits on DM lifetime obtained with the profile likelihood analysis (thick black lines), for DM decaying into b quarks (left) or τ leptons (right). The black dashed line shows the limit obtained if we only consider prompt DM contribution only. The green and yellow bands correspond to the expected 68% and 95% limit ranges from Monte Carlo simulations with the background-only hypothesis. Previous limits [59, 69, 76] and those from HAWC [11] are shown with gray and blue lines. The hatched regions show the 1-σ DM parameter space favored by IceCube high-energy neutrino flux [67].

where b^i is the background model, $s^i_k(\tau_{\rm DM})$ is the total integrated DM intensity for the specific ROI,

$$s^i_k(\tau_{\rm DM}) = \frac{1}{\Delta\Omega}\int {\rm d}\Omega {\rm d}E_\gamma \left(\frac{{\rm d}I^{\rm prompt}_\gamma}{{\rm d}E_\gamma} + \frac{{\rm d}I^{\rm IC}_\gamma}{{\rm d}E_\gamma}\right), \quad (8)$$

$\mathcal{E}^i_k$ is the detector exposure on the ROI, and $\Delta\Omega$ is the solid angle of the ROIs.

Importantly, the DM intensity is different in different ROIs due to the different D-factor and secondary contributions, while all ROIs have the same underlying background model (b^i) due to the isotropic cosmic-ray background distribution. This breaks the signal-background degeneracy between different ROIs, and thus $\mathrm{ROI}_1 - \mathrm{ROI}_4$ are included to constrain the background contribution. The background is expected to be isotropic, as the intrinsic cosmic-ray anisotropy is only ~0.1% [94, 95], much smaller than the statistical uncertainties. We consider the joint-likelihood for all 5 ROIs: $\ln\mathcal{L}(\tau_{\rm DM},\hat{b}) = \sum_{k=0}^{4}\ln\mathcal{L}_k$, with the "hat" signaling that the background b^i has been treated as a nuisance parameter and fitted over to maximize the likelihood [96]. For the background model, b^i, we conservatively assume complete ignorance of their values in each energy bin, and thus they can take any non-negative values during the fit.

We search for the presence of a DM signal by scanning through the DM mass from 10^5 to 10^9 GeV for each decay channel, assuming a 100% branching fraction. We find no significant detection of DM signals, which would correspond to a peak in the likelihood function against $\tau_{\rm DM}$. Therefore, we obtain the one-sided 95% lower limit on the DM decay lifetime, $\tau_{\rm DM,95}$, for each DM mass and decay channel by finding $-2\ln[\mathcal{L}(\tau_{\rm DM,95})/\hat{\mathcal{L}}] = 2.71$ [97], where $\hat{\mathcal{L}}$ is the best-fit likelihood with respect to both $\tau_{\rm DM}$ and b.

Results— Figure 1 shows the constraints for the DM $\to b\bar{b}$ and DM $\to \tau^+\tau^-$ channels obtained in this work (thick black lines). Other decay channels are discussed in Supplemental Material V. To validate our results, we perform the same joint-likelihood analysis with mock data for the ROIs using the best-fit null-hypothesis ($\tau_{\rm DM}\to\infty$) background model and assuming a Poisson probability distribution. The 68% and 95% limit range from such Monte Carlo simulations are shown in Fig. 1. We find that the actual constraints are within the 95% expected range, but are close to the bottom range. This is caused by a small and statistically insignificant event excess in ROI_0 (The highest local significance found is about $1.4\,\sigma$ for $\tau^+\tau^-$ channel at ~ 8 PeV.). The agreement with the Monte Carlo simulation also validates the common background hypothesis for the ROIs. This implies that potential anisotropic astrophysical components in the ROIs, such as diffuse emission and point sources, are subdominant. In Fig. 1 we also show the limits obtained considering only the prompt contribution to highlight the robustness of our constraints with respect to potential uncertainties in the secondary components.

For comparison, we also show the best previous limits on DM lifetime obtained with γ-rays for both channels [59, 69, 76], including those from HAWC [11]. Hence, the present analysis leads to a significant improvement in the DM constraints. For the $b\bar{b}$ channel, our results are about 5 times better than [69] around 10 PeV, while for the $\tau^+\tau^-$ channel, they are more than 10 times better than [59] at 10 PeV. For DM masses higher than $\mathcal{O}(10^8$ GeV), our constraints are in general weaker than those obtained with KASCADE, etc, [76]. Recently, new DM constraints [73, 74] were obtained by considering the

Tibet-ASγ data along the Galactic plane [18]; our constraints are generally stronger by about one order of magnitude than their model-independent limits. We emphasize that we do not consider any potential astrophysical contributions in the ROIs. Doing so will improve our constraints, but makes our results dependent on the astrophysical models.

Our limits are subject to overall systematic uncertainties, estimated to be 21%, which is a quadrature sum of uncertainties from the detector response ($\sim$7%) and γ/hadron separation procedure ($\sim$20%), and mentioned above. In addition, even with the most conservative DM density profile assumption, our limit only weakens by about 5%. These uncertainties would not affect physical interpretations of our results, as evident from Fig. 1.

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DM decays can also produce high-energy neutrinos that can be searched for with neutrino telescopes [53, 54, 57, 65–68, 72, 75]. Our constraints are generally more stringent than those obtained with IceCube data (e.g., in Refs [66, 67]), except in neutrino channels. These searches are therefore highly complementary. Remarkably, our results highly constrain the hypothesis of decaying DM as a source of high-energy neutrinos. The limits reported in Fig. 1 disfavor a large portion of the 68% CL DM parameter space (hatched regions) and the best-fit scenario (black stars) inferred with the latest IceCube data [67]. We note that the DM interpretation of the IceCube data is not significant ($< 2\sigma$), and the IceCube data is still compatible with an isotropic spatial distribution.

Conclusions and outlook— In this letter, using 340 days of 1/2-KM2A and 230 days of 3/4-KM2A data, we obtain some of the strongest γ-ray limits on heavy decaying DM particles. This analysis shows that, even with just partial KM2A data, LHAASO already offers unprecedented sensitivity in DM indirect-detection searches, with an immediate impact on the DM interpretation of IceCube high-energy neutrino events.

This analysis uses a data-driven method to estimate the residual cosmic-ray background through the ROIs, which allows us to obtain strong yet robust constraints on the DM lifetime. In the future, with the completion of the full KM2A array, considering more sky data and longer collection time, the effective exposure can be enhanced dramatically. Considering any underlying astrophysical components would also reduce the allowed DM contribution. Furthermore, with the full LHAASO detectors (KM2A+WCDA+WFCTA), the γ/hadron separation power is expected to be further improved, with the energy range extended. Together, we expect the DM sensitivity will be significantly improved, offering new possibilities for a potential detection of DM.

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