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Wobbly Dark Matter Signals at Cherenkov Telescopes from Long-lived Mediator Decays

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Imaging Atmospheric Cherenkov Telescope (IACT) searches for dark matter often perform observations in “wobble mode”, i.e. simultaneously collecting data from the signal region and from a corresponding background control region. This observation strategy is possibly compromised in scenarios where dark matter annihilates to long-lived mediators that can traverse astrophysical distances before decaying to produce the gamma rays observed by the IACTs. In this paper, we show that this challenge comes with several interesting features and opportunities: in addition to signal contamination in the background control region, the gamma-ray spectrum changes with the observing direction angle and typically exhibits a hard excess at high energies. Such features represent a significant departure from the canonical picture, and offer novel handles to identify a dark matter signal and to extract underlying dark matter parameters.

INTRODUCTION AND MOTIVATION

Indirect dark matter searches with ground based Imaging Atmospheric Cherenkov Telescopes (IACTs) such as MAGIC [1], HESS [2], and VERITAS [3], which look for TeV-scale gamma rays from dark matter annihilation or decay in dark matter dense astrophysical systems, have been an integral component of the effort to unravel the nature of dark matter. The upcoming Cherenkov Telescope Array (CTA), which offers an order of magnitude improvement in sensitivity over existing telescopes, opens up further possibilities on this frontier [4–6].

IACTs often perform observations in the so called “wobble mode” [7], where the signal region is observed within a solid cone (referred to as the ON region) at an offset angle from the center of the telescope’s field of view, while a diametrically opposite region of the same size and offset provides a background control region (referred to as the OFF region). Wobble mode observations take data from both ON and OFF regions simultaneously, providing concurrent measurement of the background up to statistical uncertainties while minimizing systematic and time-varying effects such as atmospheric changes. A particularly promising class of targets for such observations are dwarf spheroidal galaxies (dSph), for which the angular parameters can be optimized based on the dark matter distribution to facilitate signal detection [8, 9].

However, the nature of dark matter’s microscopic properties remains a complete mystery, and the assumption that the distribution of visible signals of dark matter annihilation or decay follows the dark matter distribution is born out of theoretical prejudice rather than direct observational evidence. In this paper, we study how the wobble mode observation strategy is affected in scenarios where dark matter annihilates into mediator particles that are long-lived and travel astrophysical distances before decaying, producing signal events in the OFF region (see Fig. 1).

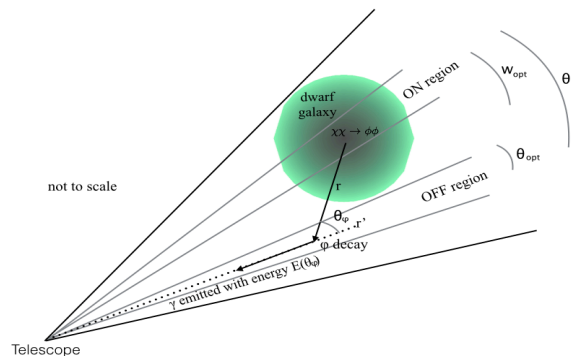


FIG. 1: Schematic representation of the scenario studied in this paper. The telescope performs observations in wobble mode, where the field of view contains two symmetric circular regions: the signal (ON) region, containing the signal source (here, a dwarf spheroidal galaxy), and a background control (OFF) region. We study the effects of dark matter annihilation in the ON region into long-lived mediators, ϕ , that can propagate to and decay in the OFF region.

This study is motivated from both theoretical and experimental considerations. Stringent null results from recent direct and indirect detection efforts are making it increasingly plausible that dark matter resides in some dark or hidden sector that is only very weakly connected to our visible sector (see e.g. Ref. [10] and references therein). In such scenarios, dark matter can annihilate or decay into particles that belong to the dark sector, which can then decay into Standard Model (SM) particles [11–15] with arbitrarily long lifetimes. Here we focus on lifetimes corresponding to boosted decay lengths $\mathcal{O}(\text{kpc})$, for which mediators decay in the OFF regions of IACTs. Dark matter annihilation into mediators with such long lifetimes and the implications for indirect detection have been discussed earlier in the literature, for instance in Ref. [16, 17] in the context of explaining positron excesses.

Cosmological constraints, while in some cases extremely strict for long mediator lifetimes (see e.g. [18–21]), allow for such possibilities provided the abundance of such mediator particles is sufficiently small in the early Universe. This can occur in several realistic scenarios: Possible mechanisms include efficient mediator pair-annihilation into lighter dark sector species [16, 17], an injection of entropy after the mediator freeze-out, or exotic scenarios involving late dark matter production (e.g.[22]).

Independent of such theoretical considerations, from an observational point of view it is important to consider plausible scenarios that can lead to departures from the standard search strategies at IACTs in order to better understand both caveats to existing results and possible new observational opportunities.

FORMALISM

We consider a simplified model where the dark matter particle, χ , annihilates via the process $\chi\chi \rightarrow \phi\phi$, where ϕ is the mediator particle. We consider ϕ to have a boosted decay length l_d in the Galactic frame, with decay into the final state $\phi \rightarrow \gamma\gamma$ ¹. The three parameters m_χ , m_ϕ , and l_d represent the free parameters of our simplified model.

The photon spectrum is monochromatic in the ϕ frame with $E_\gamma = m_\phi/2$, and gets boosted into a box-shaped spectrum in the Galactic frame,

$$\frac{dN_\gamma}{dE_\gamma} = \frac{2}{\beta_\phi m_\chi} \quad \text{for } |E_\gamma - \frac{m_\chi}{2}| \leq \frac{\beta_\phi m_\chi}{2}, \quad (1)$$

where $\beta_\phi = (1 - m_\phi^2/m_\chi^2)^{1/2}$ is the mediator velocity. In the Galactic frame, the photon energy E_γ is correlated with the angle θ_ϕ between the directions of propagation of the mediator and the photon (see Fig. 1):

$$E_\gamma = \frac{m_\phi^2/(2m_\chi)}{1 - \beta_\phi \cos \theta_\phi}. \quad (2)$$

For our dark matter source, we consider a dwarf spheroidal galaxy with dark matter density profile [32]

(see also [33–35])

$$\rho(r) = \frac{\rho_S}{\left(\frac{r+r_{\text{cutoff}}}{r_S}\right)^\gamma \left[1 + \left(\frac{r}{r_S}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}, \quad (3)$$

where r is the distance from the center of the dwarf galaxy, and r_S is the halo scale radius, inside which the dark matter density rises as $r^{-\gamma}$ down to a cutoff scale r_{cutoff} . The origin of r_{cutoff} could lie in baryonic effects [36], or self-interactions [37]. We consider an observationally motivated range for r_{cutoff} , from 0.05 to 0.5 kpc [38]; our final results are largely insensitive to such details, since the long-lived mediators tend to smear out the signal distribution.

The gamma ray flux along a line of sight (*l.o.s*) at an angle θ from the direction to the dwarf galaxy as viewed by the telescope (see Fig. 1), following the formalism of Ref. [39], is

$$\Phi_\gamma(\theta, E_\gamma) = \frac{1}{4\pi} \frac{\langle\sigma v\rangle_{\chi\chi \rightarrow \phi\phi}}{m_\chi^2} \frac{dN_\gamma}{dE_\gamma} J_{\text{eff}}(\theta, E_\gamma). \quad (4)$$

$J_{\text{eff}}(\theta)$ represents the effective source term in the direction θ . For prompt ϕ decays, this would simply be the familiar integral over $\rho(r)^2$ along the *l.o.s*. Due to displaced decays of ϕ , gamma rays at a particular point can originate from dark matter annihilations elsewhere in space, hence [39]

$$J_{\text{eff}}(\theta, E_\gamma) = \int_0^\infty dr' \int_0^{2\pi} \frac{d\phi}{2\pi} \int_0^\infty dr \frac{e^{-r/l_d}}{l_d} \rho_\chi^2(\vec{x}(r, r', \phi, \theta, E_\gamma)). \quad (5)$$

Here, dr' corresponds to the *l.o.s* specified by θ . Gamma rays along this *l.o.s*, and with energy E_γ , can only be produced by mediators incident at an angle θ_ϕ , as specified by Eq. (2). The integrals over ϕ and r integrate over production of mediators along the cone defined by $\theta_\phi(E_\gamma)$. The factor $e^{-r/l_d}/l_d$ represents the probability distribution function for a mediator to decay at distance r from its point of production. This gamma-ray flux can then be integrated over the relevant ON and OFF regions of the IACT.

RESULTS

For our benchmark scenario, we take $m_\chi = 1$ TeV and $m_\phi = 400$ GeV. We use as a concrete example the Draco dSph, using Eq. (3) with $\alpha = 2.01, \beta = 6.34, \gamma = 0.71, \log_{10}(r_S/\text{pc}) = 3.57$ [33] for the dark matter profile. The overall normalization of the signal is left as a free parameter (*i.e.*, ρ_S and $\langle\sigma v\rangle_{\chi\chi \rightarrow \phi\phi}$ are left unspecified – the scaling with these parameters is trivial). We use the telescope specifications anticipated for CTA, using the optimized values for CTA observations of Draco as reported in [8]:

$$w_{\text{opt}} = 0.6^\circ, \quad \theta_{\text{opt}} = 0.3^\circ, \quad (6)$$

¹ We choose the final state $\gamma\gamma$ for simplicity. The analysis in this paper holds for any other decay channel with a monochromatic photon, such as $\gamma\nu$, as occurs for decays of sterile neutrinos, which can naturally be long-lived when part of a secluded sector [23–27]. Likewise, although we choose the process $\chi\chi \rightarrow \phi\phi$ for our studies, the phenomenon is more general and can be realized in a wide variety of dark matter frameworks, such as frameworks with dark matter annihilation into different mediators (e.g.[28]), semi-annihilating dark matter (e.g.[29]), coannihilation in the dark sector (if there are multiple dark matter candidates) (e.g.[30]), or with decaying dark matter (e.g.[31]).

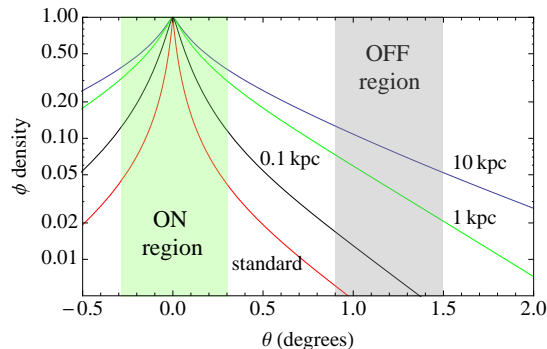


FIG. 2: The density of mediator particles as a function of θ , normalized to 1 at the center of Draco ($\theta = 0$), for instantaneous decay of the mediator in red, and decay lengths $l_d = 0.1, 1, 10$ kpc in black, green, and blue, respectively, using $r_{\text{cutoff}} = 0.05$ kpc. The green and grey bands represent the optimized ON and OFF regions ($w_{\text{opt}} = 0.6^\circ$, $\theta_{\text{opt}} = 0.3^\circ$) for CTA observations of Draco [8].

where w_{opt} is the optimal offset angle (wobble distance) of the center of the ON region from the pointing direction of CTA, and θ_{opt} is the optimal angular radius of the ON and OFF regions. Since Draco is at a distance of ≈ 76 kpc [33], for the above parameters, the OFF region is ~ 1.2 kpc away from the center of Draco at its closest approach.

In Fig. 2, we plot the density of mediator particles, which is the effective source term for the gamma-ray signal, as a function of θ (normalized to 1 at the center of Draco, corresponding to $\theta = 0^\circ$) for various choices of the decay length, l_d . Here the mediator density is calculated along a radial line perpendicular to the direction to the detector, and we use $r_{\text{cutoff}} = 0.05$ kpc for this plot. For prompt mediator decay, this distribution reverts to the standard dark matter profile $\rho(r)^2$, for which the contribution in the OFF region is negligible (red curve), justifying the optimized choice of parameters in Eq. (6). The effect of increasingly larger decay lengths l_d is to progressively smear out the sharp peak at the center, as mediators stream out of the central region and decay further away. In particular, for $l_d \gtrsim 1.2$ kpc, a significant fraction of the mediators produced in the central region reach the OFF region without decaying, and we see that the contribution in the OFF region can grow to $\mathcal{O}(10\%)$ of the density at the center (blue curve). Therefore, *long-lived mediators can significantly contaminate the background control region of IACTs with signal events*, affecting the efficiency of wobble mode observations.

Next, in Fig. 3 we plot the photon flux $\Phi_\gamma(\theta, E_\gamma)$ as defined in Eq. (4) as a function of θ and E_γ , normalized to the flux from the center of Draco. For this plot, we have chosen $l_d = 10$ kpc and $r_{\text{cutoff}} = 0.5$ kpc [40]. This plot clearly demonstrates that the energy spectrum of the signal changes across the field of view, with the distortion getting stronger as the *l.o.s* moves away from the center

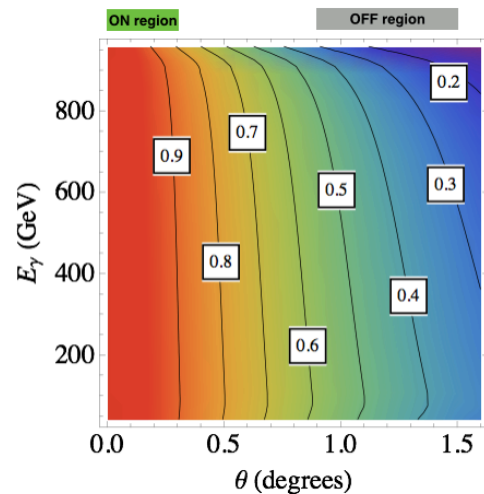


FIG. 3: Contours of the ratio $\Phi(E_\gamma, \theta)/\Phi(E_\gamma, \theta = 0)$, i.e., flux of photons of energy E_γ from direction θ relative to the center of Draco, normalized to the flux from the dwarf center, for $m_\chi = 1$ TeV, $m_\phi = 400$ GeV, $l_d = 10$ kpc, and $r_{\text{cutoff}} = 0.5$ kpc.

of the dwarf galaxy. There are, in particular, three salient features:

- (i) at large θ , the photon flux gets strongly suppressed at the highest energies,
- (ii) the OFF/ON ratio exhibits a peak around $E_\gamma \approx 80$ GeV, and
- (iii) the flux in the OFF region can be sizable compared to the flux in the ON region, rising to over 50% at lower energies (see the contours under the OFF region label in Fig. 3).

These effects can be understood from the correlation between E_γ and the angle θ_ϕ between the mediator and photon propagation directions (Eq. (2)). The highest E_γ correspond to vanishing θ_ϕ , i.e. to gamma rays emitted along the same direction as the mediator. For sufficiently large θ away from the dwarf center, such mediators therefore cannot originate from the central region of the dwarf (see Fig. 1), resulting in a suppression of the flux at these high energies. In contrast, lower E_γ can be produced by mediators coming in at larger θ_ϕ angles, which can originate from the core of the dwarf, enhancing the flux at these energies. The peak at $E_\gamma \approx 80$ GeV maximizes this effect: this energy (for the parameters chosen) corresponds to $\theta_\phi = \pi/2$, so that the contribution from the center of the dwarf is received at the point on the *l.o.s* that is closest to the dwarf center (see again Fig. 1), where the density of mediators is maximal. Due to this enhancement of intermediate/low energy photons in the OFF region, the flux in this part of the spectrum can therefore rise to over 50% of the corresponding flux in the ON region.

The solid curves in Fig. 4 show the energy flux integrated over the ON and OFF regions described by

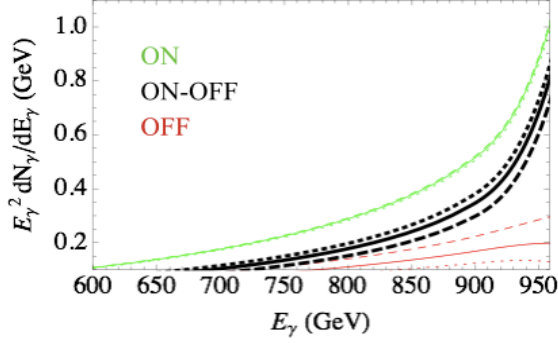


FIG. 4: Signal from the ON region (green), OFF region (red), and the resulting background subtracted (ON-OFF) signal (black), with an arbitrary overall normalization, for $m_\chi = 1$ TeV, $m_\phi = 400$ GeV, $l_d = 10$ kpc, and $r_{\text{cutoff}} = 0.5$ kpc. The dashed, solid, and dotted curves show results for $w_{\text{opt}} = 0.5^\circ, 0.6^\circ, 0.7^\circ$ respectively.

$w_{\text{opt}}, \theta_{\text{opt}}$ in Eq. (6), as well as the difference between the two, choosing an arbitrary normalization. For comparison, the dashed (dotted) curves show the corresponding fluxes for $w_{\text{opt}} = 0.5^\circ (0.7^\circ)$. As anticipated previously, the flux in the OFF region can be $\mathcal{O}(10)\%$ of the flux in the ON region. Note that the signal from the ON region exhibits a sharp peak at the highest energies – these correspond to photons emitted in the direction of the mediator, so that all the photons produced from mediators emitted in the direction of the detector reach the detector. On the other hand, the spectrum from the OFF region gets suppressed at the highest energies, as these are not sensitive to mediators produced in the central region of the dwarf, as described above. The net effect of subtracting the OFF region from the ON region is that the overall signal count gets reduced, but the peak at the highest energies becomes sharper. Furthermore, the strength of this effect varies as the separation between the ON and OFF regions is varied, as indicated by the differences between the dashed, solid, and dotted curves in the figure.

Fig. 4 corresponds to $m_\chi = 1$ TeV, $m_\phi = 400$ GeV, and $l_d = 10$ kpc. We find that changing these parameters changes the above plots quantitatively but not qualitatively. For instance, for smaller m_ϕ/m_χ , the mediators receive greater boost, so that the same energies correspond to smaller angles θ_ϕ (as can be inferred from Eq. (2)); this effectively stretches the curves in Fig. 4 along the x -axis, so that the peak gets broader. Likewise, as l_d is decreased, the spectrum approaches the standard box-shaped spectrum from instantaneous decay. However, we find that the generic qualitative features discussed above – the presence of a peak at the highest energies and distortion of the energy spectrum as a function of direction – remain robust.

Fig. 4 represents the theoretically predicted energy

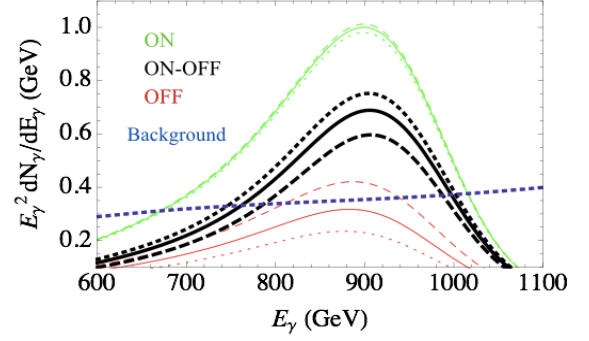


FIG. 5: Same as Fig. 4, but with CTA instrumental effects taken into account (see text for details). Also shown (blue dotted curve) is the expected shape of the background (arbitrary normalization).

spectra, without taking instrumental effects into account. We now perform a more realistic treatment of instrumental effects using CTA’s publicly available data on its expected baseline performance [41]. We use the effective collection area as a function of gamma ray energy as provided in [41], the relative off-axis sensitivity (accounting for reduced efficiency of the telescope towards the edges of the field of view) from [8], and angular and energy resolutions of 0.05° and 7%, respectively (approximate numbers for $E_\gamma = 1$ TeV from [41]). The resulting curves are plotted in Fig. 5; these are analogous to the corresponding curves from Fig. 4 (with a different arbitrary normalization) with the above instrumental effects included. The most important instrumental aspect is the finite energy resolution of the telescope, which smears the sharp peak rising to the cutoff energy ($E_\gamma \approx 960$ GeV) seen in Fig. 4: the size of the peak gets reduced, the location of the peak shifts to a lower energy ($E_\gamma \approx 900$ GeV), and there are events with $E_\gamma > m_\chi$ in the spectrum. Nevertheless, the generic qualitative features from the presence of long-lived mediators – a peak at high energies, and a direction dependent energy spectrum – continue to persist.

In this plot, we also show the expected shape of the post-analysis residual cosmic-ray background as reported by CTA [41], with arbitrary normalization (dotted blue curve). Note that this background is expected to be eliminated up to statistical uncertainties thanks to the wobble mode strategy, and depends on the size of the sample (i.e., observation time). For our benchmark scenario and the above parameters, using $\log_{10}(\rho_S/M_\odot \text{pc}^{-3}) = -1.74$ [33] and $\langle \sigma v \rangle_{\chi\chi \rightarrow \phi\phi} = 10^{-24} \text{cm}^3/\text{s}$, we estimate that CTA can get 2σ sensitivity, $S/\sqrt{B} > 2$, with ~ 35 hours of observation.

DISCUSSION

The efficacy of the wobble mode observing strategy at IACTs hinges on a clean isolation of the signal source within the ON region, with the OFF region providing a reliable background control region. Using the Draco dwarf spheroidal galaxy and the Cherenkov Telescope Array (CTA) as concrete, realistic examples, we studied a scenario where dark matter annihilates into mediators that are sufficiently long-lived that they can travel from the ON region to the OFF region before decaying into visible states, endangering the above assumption. We demonstrated several interesting features in this setup:

- The OFF region can receive a significant contribution of signal events ($\mathcal{O}(10)\%$ of the flux from the ON region, up to 50% at low energies).
- A consequence of the long lifetime of the mediators is that the gamma ray spectrum features a hard excess at the highest available energies instead of being box-shaped (Fig. 4).
- The gamma-ray spectrum varies across the field of view of the instrument. In particular, relative to the spectrum from the center of the dwarf, the emission predicted at larger angles away from this direction feature an increasingly suppressed flux at the highest energies (Fig. 3). Due to this distortion, the subtraction of the background as measured in the control (OFF) region suppresses the overall signal strength but enhances the peak feature.
- The above features persist even when realistic instrumental effects are taken into account.

These features offer both challenges and opportunities. While the contamination of the OFF region, which provides background control, with signal events is a cause for concern, the above features also offer novel handles to identify the signal and extract the underlying dark matter parameters. The change of spectrum from a box-shape to a hard excess at high energies, which is further enhanced when the “background” measurement from the OFF region is subtracted, can aid in identifying the dark matter contribution. The variation of the energy spectrum across the field of view of the instrument offers a challenging but tantalizing possibility – if this effect can be reliably measured with enough statistics, it can be used to both identify the existence of long-lived mediators as well as extract information about the underlying parameters such as the mediator mass and decay length.

Such “wobbly” dark matter signal features therefore offer far richer possibilities beyond canonical dark matter setups and could reveal highly non-trivial information on a possibly complex dark sector. Given the vastness of possibilities in dark matter and dark sectors, as well as

nonstandard signatures and features beyond the canonically studied ones that our current and future instruments could be sensitive to, it becomes crucial to explore and understand the possibilities offered by such exotic scenarios in order to cast as wide a net as possible in our quest for a glimpse into the nature of dark matter.

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