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Heavy Dark Matter searches with LHAASO

Andrea Addazi,[1,2,*] Konstantin Belotsky,[3] Vitaly Beylin,[4] Marco Cirelli,[5] Arman Esmaili,[6] Nicolao Fornengo,[7,8] Qingyu Gan,[1] Michael Kachekriess,[9] Maxim Khlopov,[10,3,11] Vladimir Korchagin,[4] Alexander Korochkin,[10] Vladimir Kuksa,[4] Antonino Marciano,[12,2] Andrei Neronov,[10,13] Paolo Panci,[14] Roman Pasechnick,[15] Alexander Sakharov,[16,17] Filippo Sala,[5] Pino Di Sciascio,[18] Dimitri Semikoz,[10,3] Pasquale Dario Serpico[19] and Nikolay Volchanskiy[4,20]

[1] *Center for Theoretical Physics, College of Physics Science and Technology, Sichuan University, 610065 Chengdu, China*

[2] *Laboratori Nazionali di Frascati INFN, Frascati (Rome), Italy, EU*

[3] *National Research Nuclear University MEPHI (Moscow State Engineering Physics Institute), 31 Kashirskoe chaussee, Moscow 115409, Russia*

[4] *Institute of Physics, Southern Federal University Stachki 194, Rostov on Don 344090, Russia*

[5] *LPTHE, CNRS and Sorbonne Université, 4 Place Jussieu, F-75252, Paris, France*

[6] *Departamento de Fisica, Pontificia Universidade Catolica do Rio de Janeiro, Rio de Janeiro 22452-970, Brazil*

[7] *Dipartimento di Fisica, Universita di Torino, Via P. Giuria 1, 10125 Torino, Italy.*

[8] *Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy.*

[9] *Institutt for fysikk, NTNU, 7491 Trondheim, Norway*

[10] *Universite de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France*

[11] *Institute of Physics, Southern Federal University Stachki 194, Rostov on Don 344090, Russia*

[12] *Department of Physics and Center for Field Theory and Particle Physics, Fudan University, 200433 Shanghai, China*

[13] *Astronomy Department, University of Geneve, Ch. d'Ecogia 16, 1290, Versolx, Switzerland*

[14] *Dipartimento di Fisica, Universita di Pisa and INFN, Sezione di Pisa Largo Pontecorvo 3, 56127 Pisa, Italy*

[15] *Department of Astronomy and Theoretical Physics, Lund University, 221 00 Lund, Sweden, EU*

[16] *Experimental Physics Department, CERN, Geneva 23 CH 1211, Switzerland*

[17] *Department of Physics, New York University, New York NY; United States of America.*

[18] *INFN sezione Roma Tor Vergata, I-00133 Rome, Italy*

[19] *LAPTh, Univ. Grenoble Alpes, USMB, CNRS, F-74000 Annecy, France*

[20] *Bogoliubov Laboratory of Theoretical Pjysics, JINR, Dubna, Russia*

E-mail: addazi@scu.edu.cn

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*Presenter

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1. Theoretical motivations and background

Given the universality of the gravitational force, in order to identify the nature of the DM it is required to detect it via some other interaction, if it has any. Candidates for cold DM have been proposed in an extremely wide range of masses and interaction strengths. These parameters notably control the DM average cosmological abundance, now measured to percent precision thanks to Cosmic Microwave Background (CMB) data, which must be correctly reproduced within a specific production mechanism in the early universe.

Despite the huge parameter space, over the past few decades the dominant DM searches have overwhelmingly focused on the so-called WIMP paradigm, which features stable particles with masses in the electroweak scale region (give or take one order of magnitude) and couplings to the SM of electroweak strength, produced as thermal relics in the early universe. This has been promoted especially by

1. The rather predictive thermal freeze-out production mechanism.

2. A widespread theoretical expectation expecting new particle physics (such as Supersymmetry, Extra Dimensions etc.) at or slightly above the weak scale in order to fix the hierarchy problem of the Higgs mass. Such new physics produces (or can easily accommodate) also a WIMP DM particle as a byproduct.

3. The numerous approaches that such a possibility would open for experimental searches, with technologically accessible and mature technologies: via DM recoils in underground experiments (direct detection), via direct searches at colliders, or indirectly detecting the SM byproducts of DM annihilation (the same process setting their relic abundance in the early universe) in space or ground-based observations of astrophysical messengers (indirect searches).

As an alternative to searches at point 3. WIMP candidates may be much heavier than the electroweak scale, notably above the kinematical production threshold of collider searches. There is thus a renewed interest of traditional WIMP searches in the multi-TeV range, where both forthcoming Imaging Cherenkov Telescopes (notably CTA) and the Large High Altitude Air Shower Observatory (LHAASO) may contribute. [1]

On the other hand, in recent years the trend has been to tackle the DM problem on its own, exploring alternatives to the baseline production mechanism 1., to break more and more free from the "theoretical injunction" 2. in building DM models, and to explore alternative detection strategies, channels and energy windows, compared to the more limited framework of point 3. above. In that sense, the window roughly spanning the energies 0.1-10 PeV has become an interesting new target for DM modeling, for a variety of reasons such UV models [1–4] models explicitly built to account DM [5] and models inspired by phenomenological puzzles in the 0.1-10 PeV energy range, notably the origin of the IceCube astrophysical neutrino flux [6–31].

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[1]While LHAASO can also target the tens of TeV range, it is our opinion that in that respect one has to carefully assess for which BSM models and astrophysical targets, if any, LHAASO offers a real advantage if compared to CTA, when coming to WIMPs.

2. Phenomenology and numerical expectations

The number of particles of type i per unit energy E per unit volume per unit time injected at position $\mathbf{x}$ at time t via the annihilation for self-conjugated DM particles writes

$$Q_i(\mathbf{x},t) = \frac{\langle\sigma v\rangle}{2}\frac{\rho^2_{\rm DM}(\mathbf{x},t)}{m^2_{\rm DM}}\frac{{\rm d}N_i(E)}{{\rm d}E}\,. \tag{1}$$

For a decaying species X with lifetime $\tau_{\rm DM} = \Gamma^{-1}_{\rm DM}$,

$$Q_i(\mathbf{x},t,E) = \frac{\rho_{\rm DM}(\mathbf{x},t)}{\tau_{\rm DM}\,m_{\rm DM}}\frac{{\rm d}N_i(E)}{{\rm d}E}\,. \tag{2}$$

In general, knowing the signal at the emission point is not enough, since we need the flux detectable at the Earth. For charged particles, one key difficulty is that they do not retain directionality due to deflections in interstellar magnetic fields: CR trajectories are similar to random-walks typically described via a diffusion-loss equation. Although we will not cover this channel in detail, note that it is of some interest for LHAASO as well, since at very least energetic $e^{\pm}$ final states are responsible for *secondary* gamma-rays, notably via Inverse-Compton up-scattering of background photons.

The best sensitivity for indirect searches of DM is naively expected from telescopes with the largest "grasp" $G = A\Omega$ [31–34], with A being the area and Ω the solid angle field of view. The current HAWC and, especially, the forthcoming LHAASO are the detectors with the largest grasp in the very-high-energy γ-ray band and are therefore well suited for the DM search.

Different strategies are possible for the search of the DM decay signal. The analysis by the HAWC collaboration [35] has adopted an approach in which a signal from the direction around the Galactic Center (more precisely, the region of the Fermi Bubble) is searched for, and the rest of the sky is considered for the background estimate. An alternative possibility is to search for a somewhat weaker (by a factor of two, on average) signal, but extending across the entire sky. An advantage of the latter approach is the larger exposure available for the full-sky search, while a disadvantage is the stricter requirements on the charged-particle vs. gamma-ray separation, due to the modest if not negligible angular variation of the signal.

Intriguingly, the birth of high-energy neutrino astronomy provides a benchmark region in parameter space to search for a possible DM decay signal. The IceCube experiment, completed in 2011, continues observing a flux of high energy ($\gtrsim 10$ TeV) neutrinos significantly in excess with respect to the expected background from atmospheric neutrinos and muons [6–11]. The source(s) of these neutrinos is yet unknown, although based on their almost uniform angular distribution an extragalactic origin or a galactic halo origin is favored. Directional analyses with various classes of astrophysical objects and catalogs are not showing any correlation leading to the conclusion that the contribution of well-known objects, such as blazars, to the observed diffuse neutrino flux is $\lesssim O(10\%)$ [36]. In this context, it has been quite natural to consider unconventional sources for these neutrinos. Also, since neutrinos provide for the first time a window on the 0.1-10 PeV Universe, it may not be so bizarre that new classes of sources can pop up. The potential to answer long-standing problems such as the nature of DM by investigating this energy regime has only recently been entertained.

A decaying DM scenario has gained some attention, mainly due to its minimal assumptions and its testability in future gamma-ray experiments. Interestingly, the whole observed flux of neutrinos by

IceCube can be interpreted in this scenario, as proposed in [12, 13] soon after the first observation of diffuse neutrinos, although a multi-component flux arising from both the conventional astrophysical sources and DM also has been investigated [16]. In a phenomenological approach, the properties of the required DM particle can be deduced from a fit to the neutrino data. In this case, the free parameters are the decay lifetime, the mass and the branching ratios of the DM decay to various standard model particles. The ballpark lifetime is $\sim 10^{27} \div 10^{28}$ s and the mass has to be $\gtrsim$few PeV in order to interpret the highest energy observed events in IceCube (obviously, assuming the multi-component neutrino flux, the DM mass can take any value in our range of interest $\gtrsim 10$ TeV). The highest energy events are typically accounted for via 'hard' leptonic final states, while lower energy events are fitted via soft channels including e.g. gauge bosons and quarks. Part of the flux can also be accommodated via some astrophysical component.

For any decay channel of PeV-scale DM particles explaining or contributing to the IceCube neutrino flux, gamma rays are unavoidably associated decay products, and their Galactic fraction can be observed by LHAASO. The following processes contribute to the expected gamma ray flux at Earth: i) A prompt flux is at very least due to the electroweak corrections for a semi-analytical inclusion of electroweak corrections into the final yield of decay products). ii) A secondary flux is induced by the unavoidable prompt (as well as secondary) charged leptons, via the Inverse-Compton process onto the CMB and star-light which leads to a spectrum of high energy gamma rays where the Galactic part of it contribute to the total flux. Of course the exact spectral shape of the flux depends on the magnitude and profile of the magnetized halo in our Galaxy, which are yet not known very well.

Figure 1, from Ref. [30], shows the spectrum of gamma ray yield from the decay of DM with mass 4 PeV and final state branching ratios given by: $\ell^\pm W^\mp : \overset{(-)}{\nu}_\ell \, Z : \overset{(-)}{\nu}_\ell \, h = 1 : 2 : 2$. The solid curves show the prompt flux accounting for γ-ray absorption, to be compared with the dot-dashed curves where the absorption is neglected; different colors represent different directions in the sky. We see that even this Galactic flux suffers from absorption due to the pair production on CMB and star-light, with the suppression reaching $\sim 70\%$ for the Galactic center line of sight. Dashed curves show the flux due to inverse-Compton photons, for various assumptions for the constant halo magnetic field, $B_{\rm halo}$, possibly pervading the thick diffusive halo of the Galaxy up to large distances. While uncertain, it is particularly important in the range above 100 TeV. Note how upper bound from two-decade old experiments CASA-MIA [37] and KASCADE [38] are within one order of magnitude of the expected flux (even less, if they had been sensitive to regions closer to the Galactic center).

Note that bounds on this scenario can also be obtained thanks to diffuse gamma-ray data by Fermi-LAT in the GeV band, se e.g. [41], exploiting the cascading effect on the extragalactic part of the flux previously mentioned. However, such constraints are rather indirect, depending on the datasets used, the final state considered, and the different assumptions for the contributions to the astrophysical background. LHAASO would allow one to probe the scenario directly and unambiguously, achieving great sensitivity. This was explicitly illustrated in Ref. [39], where the authors estimated the LHAASO sensitivity reach for the decaying DM search, following the approach of Ref. [35].

In each energy bin, they compared the DM decay flux levels for different values of m_{DM}, τ_{DM} with the residual charged particle background levels and calculated by how much the χ^2 of the fit of

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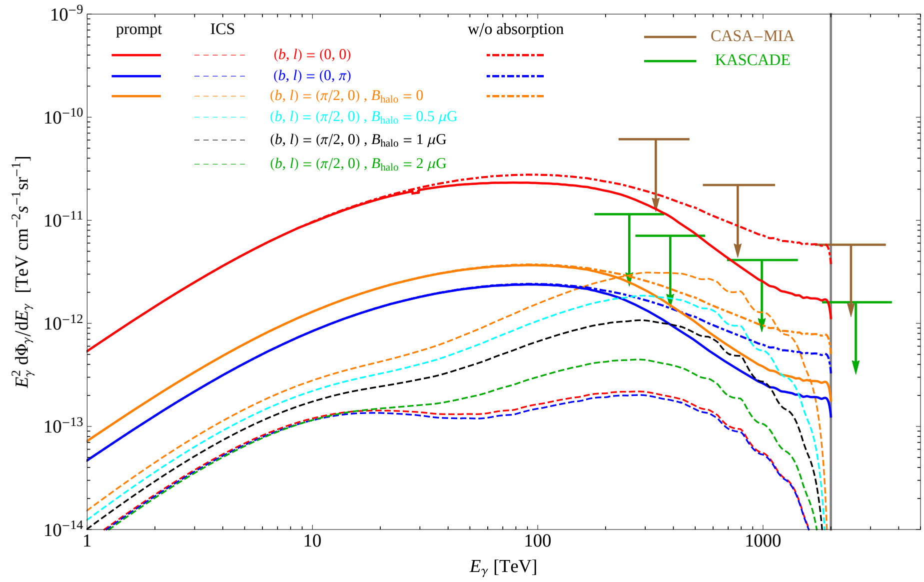

Figure 1: The γ-ray flux from DM decay from various directions, with $m_{\rm DM} = 4$ PeV and $\tau_{\rm DM} = 10^{28}$ s, and branching ratios reported in the text. The solid curves show the prompt flux, including the absorption of γ-rays, while in the dot-dashed curves the absorption is neglected; different colors represent different directions in the sky. The dashed curves show the IC flux, for various assumptions for the constant halo magnetic field, $B_{\rm halo}$, possibly pervading the thick diffusive halo of the Galaxy up to large distances. The green and brown bar lines show the upper bound on γ-ray flux from CASA-MIA [37] and KASCADE [38], respectively.

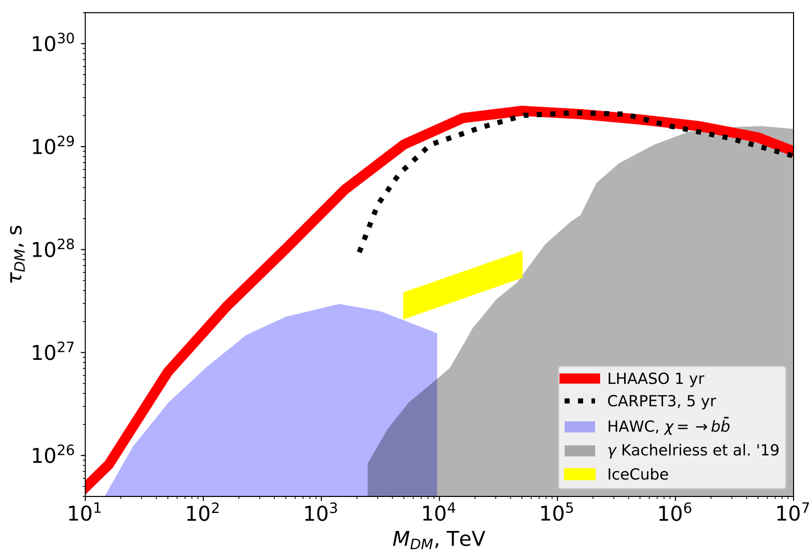

Figure 2: Sensitivity of LHAASO for the measurement of dark matter decay time (for DM decaying into quarks). Yellow band shows the range of decay times for which DM decays give sizable contribution to the IceCube neutrino signal [39]. Blue and gray shaded regions show the existing bounds imposed by HAWC [35] and ultra-high-energy cosmic ray experiments [40]. and dashed curves are from the HAWC search of the DM decay signal in the Fermi Bubble regions [35]. From [31].

the signal+background data is inconsistent with the background-only model in all energy bins. In this way they found the minimal detectable DM decay flux as a function of the DM mass for the model of Ref. [39] of DM decaying into quark-antiquark pair, in turn converted into a maximal measurable DM decay time. The results are shown in Fig. 2. It clearly illustrates how LHAASO will explore DM lifetimes up to $\tau_{DM} \sim 3 \times 10^{29}$ s over a wide DM mass range $m_{DM} > 10$ PeV. In the mass range 10 TeV$< m_{DM} < 10$ PeV LHAASO will provide a factor of 3-to-10 improvement of sensitivity compared to HAWC. In any case, LHAASO will fully test models where a non-negligible fraction of the IceCube astrophysical neutrino flux is generated by DM decays.

3. Conclusions and remarks

In this proceeding, we showed preliminary estimations on the impact of the next VHE gamma rays data from LHAASO to Heavy Dark Matter searches. Heavy dark matter is motivated by several extensions of the Standard Model, including gauge-mediated SUSY models, hidden strong gauge sectors, Homeopathic DM and so on. In particular, we show how LHAASO can be the best probe for tests of Heavy Dark Matter decays from diffuse gamma rays measurements. Finally, LHAASO can sharply test PeV-scale HDM models which may explain the IceCube observations in a genuine multi-messenger strategy.

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