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Constraints on heavy dark matter annihilation and decay from electron and positron cosmic ray spectra

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Abstract

Annihilation or decay of dark matter (DM) could contribute to the electron and positron cosmic-ray flux, allowing for constraints on DM parameters from its measurement. CALET is directly measuring the energy spectrum of electron+positron cosmic rays up into the TeV region most important for studying heavy DM, while AMS-02 provides a positron-only spectrum below the TeV range. Limits on DM annihilation and decay well into the TeV mass range have been derived from a combined analysis of both data-sets with an astrophysical background model including pulsars as the origin of the positron excess and individual nearby supernova remnant sources.

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1 Introduction

Limits on DM annihilation and decay are derived from the all-electron (electron+positron) spectrum measured by CALET [1], and the positron spectrum from AMS-02 [2]. The astrophysical background for the positron spectrum is limited to pulsars and secondary particles, but it reaches only up to 1 TeV, while the background for the all-electron spectrum which extends up to 4.8 TeV includes also SNRs. Based on previously established methods [3–5], this study focuses on TeV-mass-range DM, with an improved background model treating the nearby SNRs Vela, Monogem and Cygnus Loop, which dominate the TeV-region [6], as individual sources.

Table 1: Propagation model parameters, see text for explanation.

parameter	D_0 [10^{28}cm^2/s]	$D_{0(@sol)}$ [10^{28}cm^2/s]	R_0 [GV]	L [kpc]	v_a [km/s]	γ_l	R_{bi} [GV]	s_{bi}	γ_i	R_{cut} [TV]
value	1.295	5.064	4	6	9.9	2.0	7.81	0.224	2.2642	27

r_n [kpc]	r_s [kpc]	z_n [kpc]	z_s [kpc]	δ_l	R_{bl} [GV]	s_l	δ	R_{bh} [GV]	s_h	δ_h
2	4.62	0.15	2.68	0.3126	12.3284	0.0535	0.574	914.5	0.3262	0.053

2 Method

2.1 Propagation model and calculation of dark matter signal

The calculation of DM signals and background flux requires an underlying model of cosmic ray propagation. The model used in this work is founded on the hypothesis that all primary nuclei species have a common source spectrum, a power law with index γ_l below, and γ_i above the break at R_{bi} with softness s_{bi}, and with an exponential cut-off at R_{cut}. Spectral differences between the nuclei species are attributed to propagation with a rigidity and position dependent (increasing with galactic radius r and distance from the disk z) diffusion coefficient as given by equation 1 and diffusive re-acceleration with Alven speed v_a.

$$D(r,z,R) = D_0 \max\left\{e^{(r-r_n)/r_s},1\right\} \max\left\{e^{(z-z_n)/z_s},1\right\} \left(\frac{R}{R_0}\right)^{\delta_l} \left(1+\left(\frac{R}{R_{bl}}\right)^{\frac{\delta_l-\delta}{s_l}}\right)^{s_l} \left(1+\left(\frac{R}{R_{bh}}\right)^{\frac{\delta-\delta_h}{s_h}}\right)^{-s_h}. \quad (1)$$

The parameters of the model were determined by comparing nuclei spectra calculated with DRAGON [7] to experimental proton [8–10], helium [11–13] (including low-energy Voyager data [14]), carbon, oxygen spectra [15], and B/C [16, 17], ^{3}He/^{4}He [18] ratios. By a random walk scan of the parameter space, the parameters listed in table 1, which fit the combined nuclei spectra data with χ^2/ndof < 1, were found. Using these parameters, the propagation of the DM annihilation/decay spectra obtained with PYTHIA was calculated in DRAGON, taking a NFW halo profile and a local DM density of 0.3 GeV/cm^3.

2.2 Astrophysical base model and limit calculation

Limit calculation is based on the reduction of the fit quality when adding the DM signal to a purely astrophysical base model. In the base model, the primary electron spectrum from distant SNR is represented by a power-law function with a low-energy spectral break and exponential cut-off. The nearby SNRs and pulsars are treated as individual point sources with free source-spectrum parameters, with the propagated spectrum calculated following ref. [19]. Position and age of the point sources are taken from the Green (SNR) [20] and ATNF (pulsar) [21] catalogs. The secondary particle fluxes are taken from DRAGON nuclei spectra calculations with a free re-scale parameter. To the fit of this model to the CALET and AMS-02 data as shown in fig. 1, the flux from DM annihilation/decay is added with a scale-factor increased in iteratively smaller steps under readjustment of all free parameters. The relative limit is set where χ^2 increases by 3.841 from the base model, disfavoring the addition of DM at 95% CL, while an absolute limit can be set where χ^2 exceeds the 95% CL threshold for the fit's number of degrees of freedom, excluding the model including the DM flux. Examples are shown in fig. 2. The base model is over-fitted (χ^2/ndof « 1), thus only the absolute limit should be considered conservative. However, the reliability of the relative limit may be increased by studying a variation of background model cases giving a good fit (χ^2/ndof $\approx$ 1) and taking the worst limit. To this end, the fixed cut-off energy parameters in the base model were varied, for the parameterized distant SNR spectrum between [0.5, 1, 2] TeV and for the

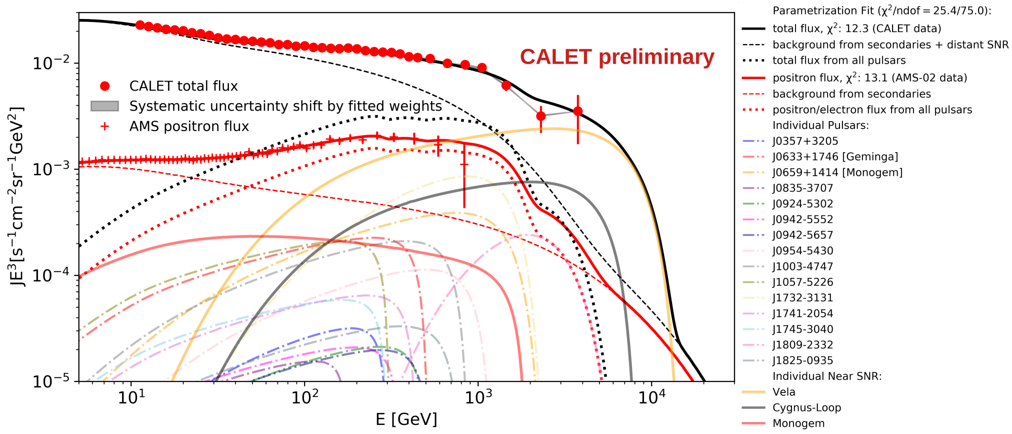

Figure 1: Base model fit with contributions of individual astrophysical sources shown.

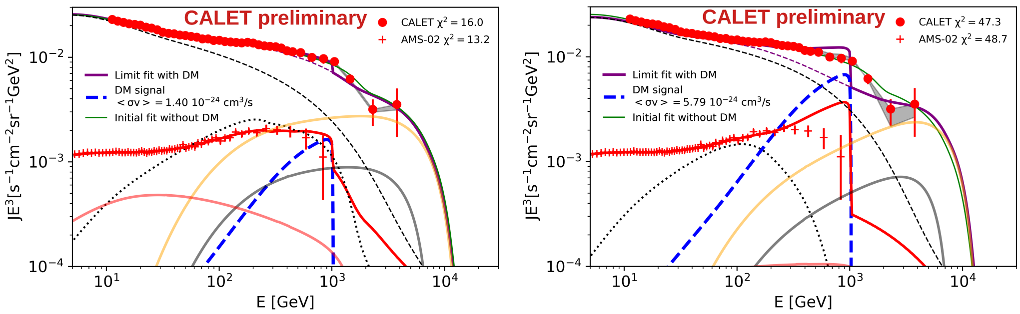

Figure 2: Left: Relative limit fit for 10 TeV DM annihilation to $e^+ + e^-$, for explanation of lines representing the background, see legend of fig. 1. Right: Absolute limit fit.

near SNR source spectrum between [10,20,50,100] TeV. Furthermore, two values of 3.75 μG and 7.50 μG were used for the turbulent magnetic field strength. It was found that indeed the relative limit varies with the background model parameter choices, but the absolute limit is nearly constant.

3 Limits on dark matter annihilation and decay parameters

The obtained limits on the annihilation cross-section are presented in fig. 3, top panel, with a comparison to limits from γ-ray observation of dwarf galaxies with VERITAS [22] and Fermi-LAT [23]. The limits on DM lifetime (fig .3, middle panel) are comparable to the most conservative EGRB limits from [24] which assume no astrophysical background, however based on specific astrophysical background models much stricter limits of O(10^{28} s) have been published (e.g. ref [25]). In addition, limits on the lifetime of topological defect DM (Skyrmions [26]) decaying through a π+lepton channel [27] are shown in the bottom panel of fig. 3.

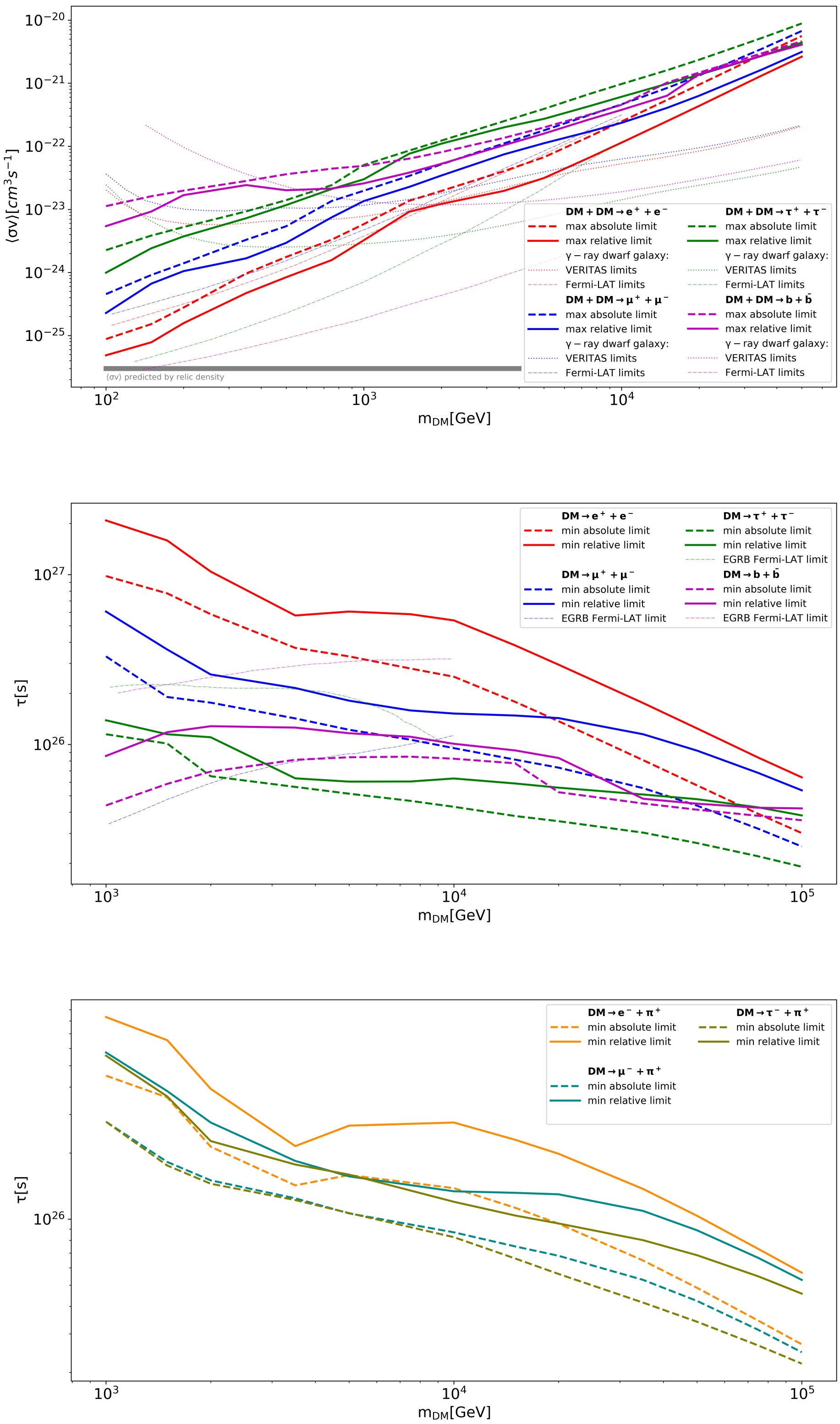

Figure 3: Top: 95% CL limits on $\langle\sigma v\rangle$ as a function of DM mass. Middle: 95% CL limits on DM lifetime as a function of DM mass for generic decay channels. Bottom: 95% CL limits on DM lifetime as a function of DM mass for π+lepton decay channels.

4 Conclusions

From CALET all-electron and AMS-02 positron-only data, limits on DM lifetime (annihilation cross-section) have been calculated up to a DM mass of 100 TeV (50 TeV), which are comparable and complementing those from other messengers such as γ-rays and neutrinos.

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