Ultrahigh-energy constraints on decaying superheavy dark matter

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Introduction

Cosmic rays from DM

UHECRs ($E \gtrsim 10^8$ GeV) are observed up to a few times 10^{11} GeV. Dark matter candidates of heavier mass has been proposed (D.J.H. Chung et al., PRD 1998; Kuzmin et al., JETP Lett. 2000.; A. Ibarra et al., PRL 2007; A. Esmaili et al., JCAP 2012).

Indirect detection

SHDM decay (Galactic + extragalactic) can lead to non-negligible contribution at higher energies extending upto Planck energy scale ($\approx 10^{19}$ GeV). [Ishiwata et al., PRD 2008, K. Murase et al., JCAP 2012, K. Murase et al., PRL 2015; O. Kalashev et al., PRD 2016]

Goal (This work)

- We constrain the timescale of SHDM decay in the mass range 10^9 GeV $\lesssim m_\chi \lesssim 10^{15}$ GeV from the observed cosmic ray and γ-ray fluxes.
- We use the latest PAO data which extends upto higher energies than earlier and hence an update to existing limits is required.

Modeling

Galactic

- We consider the NFW model for density distribution in our Galaxy with $r_h = 100$ kpc, $r_\odot = 8.34$ kpc and $\rho_\odot c^2 = 0.43$ GeV/cm^3

$$\Phi_{\rm G}(E, \leq \theta) = \frac{n_\odot r_\odot}{4\pi m_\chi \tau_\chi} \frac{dN_s}{dE} \frac{2\pi}{\Omega} \int_0^\theta \sin\theta d\theta \int_0^{s_{\rm max}(\theta)} n_\chi(r) ds \quad (1)$$

where, dN_s/dE is the flux of particle S from prompt dark matter decay.

Extragalactic

For the extragalactic case, we consider a uniform density distribution between $d_c = $ 1-5000 Mpc

$$\Phi_{\rm EG}(E) = \frac{c\Omega_\chi \rho_c}{4\pi m_\chi \tau_\chi} \int dz \left|\frac{dt}{dz}\right| \int dE' \frac{dN_s'}{dE'} \frac{d\eta}{dE}(E, E', z) \quad (2)$$

where, $d\eta/dE$ is the fraction of cosmic rays of energy E from parent particle of energy E'.

$p+\bar{p}$ fluxes

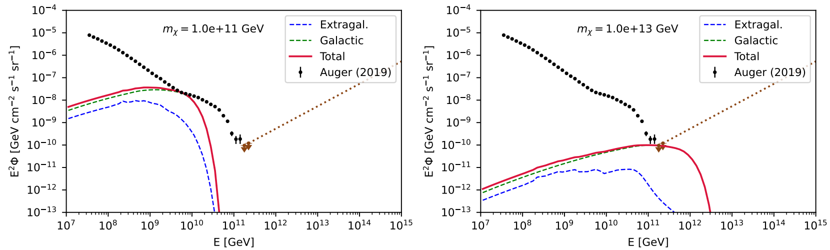

Figura 1: $p+\bar{p}$ fluxes at Earth from Galactic and extragalactic dark matter for discrete values of dark matter mass $m_\chi = 10^{11}$ and 10^{13} GeV; decaying through $b\bar{b}$ channel.

The PAO upper limits at the highest energy can be extrapolated to constrain the fluxes from DM decay.

DM + astrophysical fluxes

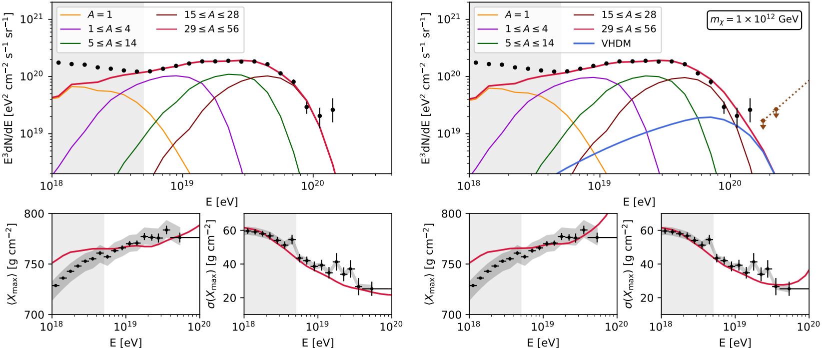

Figura 2: Simulated UHECR spectrum, $X_{\max}$, and $\sigma(X_{\max})$ for the best fit source parameters (left) and 2σ contribution from DM $m_\chi = 10^{12}$ GeV (right)

In some cases, addition of the DM component improves χ^2 value of the combined fit (cf. earlier suggestions in- M.S. Muzio et al., PRD 2019)

Integral γ-ray fluxes

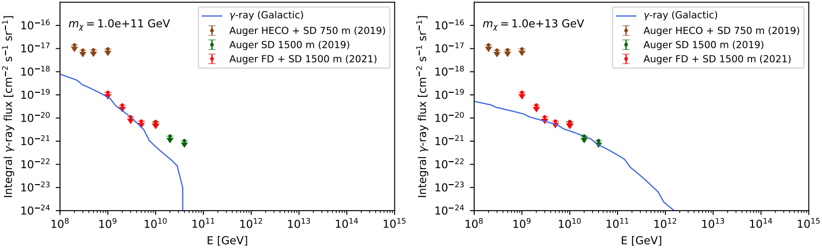

Figura 3: Integrated γ-ray fluxes at Earth from the Galactic dark matter component

M.F.P. of γ-rays from the prompt dark matter decay is larger than the Galactic length scales and hence the cascades can be neglected.

Constraints on decay rate

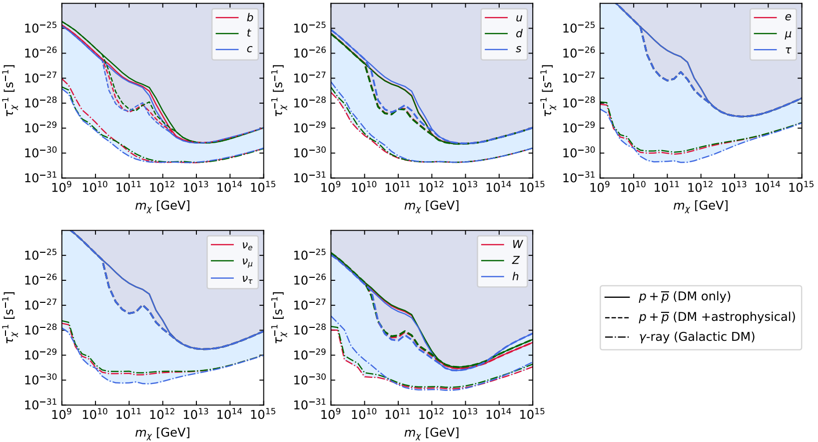

Figura 4: Dark matter decay rate (Galactic + Extragalactic) constrained by the observed UHECR flux

Earlier works

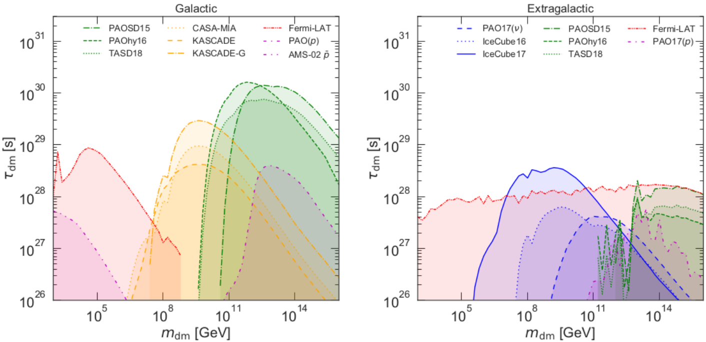

Figura 5: K. Ishiwata et al (JCAP, 2020)

- The γ-ray constraints are a factor of few weaker than obtained in our work for the leptonic decay channels.
- ν- constraints are important in the range 10^6 GeV $\lesssim m_\chi \lesssim 10^8$ GeV, not considered in our work.

Summary & Future Prospects

I We place lower limits to the timescale of dark matter decay at energies larger than 1 EeV and extending up to $\approx 10^{15}$ GeV.

II The constraints from the extragalactic components are weaker than the Galactic components.

III The cosmic ray flux constrains τ_χ to $\gtrsim 4 \times 10^{29}$ s at 10^{13} GeV for the quark decay channel.

IV For the leptonic decay channels, the γ-ray constraints limit the timescales to $\tau_\chi \gtrsim 2.25 \times 10^{30}$ s at 10^{13} GeV (factor of few stronger than O. Kalashev et al., PRD 2016)

V The systematics due to various DM density profiles can be calculated (NFW, Einasto, ...).