PROCEEDINGS OF SCIENCE

Constraining Sub-GeV Dark Matter through Proton-Dark Matter Scatterings in Starburst Nuclei

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In this contribution, We investigate the possibility of constraining the properties of light Dark Matter (DM) particles exploiting the peculiar nature of Cosmic-Rays (CRs) transport inside Starburst Nuclei (SBNi). Indeed, since CRs are confined at length inside SBNi, the CR transport may be significantly affected by scattering with sub-GeV dark matter. Gamma-ray produced via hadronic collisions can indirectly probe the distortion of the cosmic-ray spectrum. Present gamma-ray data lead to stringent bounds on the cross section between protons and dark matter, showing no hint of distortion.These are competitive with current bounds, but have large room for improvement with the future gamma-ray measurements in the 0.1–10 TeV range from the Cherenkov Telescope Array, which can strengthen the limits by as much as two orders of magnitude

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)1386

1. Introduction

Starburst Galaxies are astrophysical sources known for their enhanced star-forming activity [2–6]. This activity should also impact the high-energy non thermal emissions of the sources. In fact, a dozen of local SBGs have been observed as GeV gamma-ray emitters [1]and a couple of them (M82 and NGC 253) as TeV gamma-ray emitters [10, 11]. They are usually considered as cosmic reservoirs, being able to (at least partially) confine high-energy protons expected to be powered by supernovae remnants (SNR). Furthermore, the gamma-ray spectrum of these sources is characterised by hard power-law spectra with spectral indexes $\gamma \simeq 2.3$, encompassing CR transport being dominated by energy-independent timescales (see for instance [2, 4]. In this contribution, we explore the possibility of probing exotic interactions between dark matter (DM) particles and protons, using high-energy emissions of SBGs (see [3] for more details). Indeed, collisions between DM particles (hereafter χ) and protons p, would change the CR transport inside SBGs, producing a dip in the gamma-ray spectrum, leading to significant bound on exotic $DM - p$ interactions. We show that current gamma-ray data are able to exclude $\sigma_{\chi p} \lesssim 10^{-34}\,\mathrm{cm}^2$ for $m_\chi \leq 10^{-6}\,\mathrm{GeV}$. The future Cherenkov Telescope Array (CTA) [16] will improve these limits by at least two orders of magnitudes. The proceeding is organized as follows: in Sec. 2, we describe the model we utilize in order to describe the non-thermal emission from SBGs. In Sec. 3, we describe DM-p interactions as well as the DM distribution inside Starburst Nuclei (SBNi). In Sec. 4, we show the phenomenological signature of DM-p interactions. In Sec. 5, we utilize M 82 and NGC 253 data, in order to pose strict constraints on the elastic DM-p cross section. Finally, we draw our conclusions in Sec. 6.

2. Cosmic-Ray Transport

In this section, we report how we describe the CR transport inside Starburst Nuclei (SBNi) (see [2–6] for more details). In particular, following Refs. [2–6], we utilize a leaky-box model in order to describe the steady-state CR distribution. Indeed, the proton distribution in the momentum phase space can be written as [2–6]

$$f(p) = Q(p)\left(\tau_{\mathrm{loss}}^{\mathrm{eff}}(p)^{-1} + \tau_{\mathrm{adv}}^{-1} + \tau_{\mathrm{diff}}(p)^{-1}\right)^{-1} \tag{1}$$

where $Q(p) \propto p^{-\alpha}e^{-p/p^{\max}}$ is the injection terms by SNRs, $\tau_{\mathrm{loss}}^{\mathrm{eff}}$ is the effective energy loss timescale (the energy loss timescale divided by $\alpha - 3$ [3]), τ_{adv} is the advection timescale (considered to be the radius R of the SBN divided by the wind velocity v_{wind}) and finally τ_{diff} is the diffusion timescale. The most important timescales are advection and inelastic proton-proton collision (τ_{pp}).

The gamma-ray emission is evaluate following the delta-function approximation following the approach of Ref. [12]. For instance, the pion production rate can be written as [2, 3]

$$q_{\pi}^{pp}(E_\pi) = \frac{n_{\mathrm{ISM}}}{k_\pi}\sigma_{pp}\left(m_p + \frac{E_\pi}{k_\pi}\right)n_p\left(m_p + \frac{E_\pi}{k_\pi}\right), \tag{2}$$

We also include the contribution of leptonic gamma-rays with bremsstrahlung and inverse compton scatterings. However, these processes are subdominant and so they do not have any major impact on our results.

3. Dark Matter and Exotic Interactions

Any DM-p interactions would cause a change in Eq. 1 adding further terms in $\tau_{\rm loss}$ changing the gamma-ray spectrum. The energy loss term for elastic DM-p interactions can be written as [3]

$$\left(\frac{dE}{dt}\right)_{\chi p} = \frac{\rho_\chi}{m_\chi}\int_0^{T^{\rm max}} dT_\chi T_\chi \frac{d\sigma_{\rm el}}{dT_\chi} \tag{3}$$

where m_χ is the DM mass, ρ_χ is the DM energy density. $\frac{d\sigma_{\rm el}}{dT_\chi}$ is the elastic differential cross section between DM and proton interactions. For the cross section, following Ref. [7], we consider (see [3] for details)

$$\frac{d\sigma_{\rm el}}{dT_\chi} = \frac{\sigma_{\chi p}}{T^{\rm max}}\frac{F^2(q^2)}{16\,\mu^2_{\chi p}\,s}(q^2+4m_p^2)(q^2+4m_\chi^2) \tag{4}$$

For $T_\chi < T^{\rm max}$ and zero otherwise. $\sigma_{\chi p}$ is the DM-p at zero CM momentum [3]. $F(q)$ is the proton form factor which physically represent the probability for an elastic scattering to take place at high energies. In particular, the higher the energy, the less likely elastic collisions become. It is crucial to take inelastic DM-p interactions into account. We consider the inelastic DM-p cross section to follow the proton-neutrino cross section and rescale it to match the elastic DM-p cross section [3]. In this way, we can define the gamma-ray spectrum in terms of two actual parameters: $m_\chi, \sigma_{\chi p}$. The inelastic χp collision timescale is considered as

$$\tau_{\rm inel} = \left(k\sigma_{\rm inel}\cdot c\,\rho_\chi/m_\chi\right)^{-1} \tag{5}$$

where we consider $k = 0.5$ as for pp collisions. Finally, for the DM density, we consider a NFW profile [8]

$$\rho_{DM}(r) = \rho_s\frac{1}{r/r_s(1+r/r_s)^2} \tag{6}$$

taking the parameters from simulations of galaxies with similar properties of local SBGs such as M82 and NGC 253 [13–15]. For the pion production term, we still utilize Eq. 2, with the difference that now, it depends on the radial coordinate (see [3] for details).

4. Gamma-Ray Spectrum

In this section, focusing on M82, we report how DM-p interactions change the gamma-ray spectrum of the source. Fig. 1 shows, on the left, how the standard energy losses (black lines), compare with the three different cases for m_χ and $\sigma_{\chi p}$. In particular, the elastic DM-p timescale fastly decreases as a function of the proton energy and its minimum stands for $E_p = m_p^2/(2m_\chi)$ [3]. After this energy the elastic timescale start increasing due to the proton form factor. The inelastic DM-p timescale, on the contrary, start being dominant after the proton form factor takes over making the elastic DM-p interactions unlikely. In this regime, the SBG becomes totally calorimetric since 100% of the protons are transformed into gamma-rays. On the right, we show the corresponding features in the gamma-ray spectrum. The elastic DM-p interactions produce a dip in the gamma-ray spectrum peaking at energy $E_\gamma \sim 0.1 m_p^2/(2m_\chi)$, approximating a gamma-ray carrying 10% of the parent proton energy.

The dip makes the signature of DM-p interactions very clear to the SBG gamma-ray spectrum. Therefore, we can use this signature to pose strict bounds on DM- cross sections.

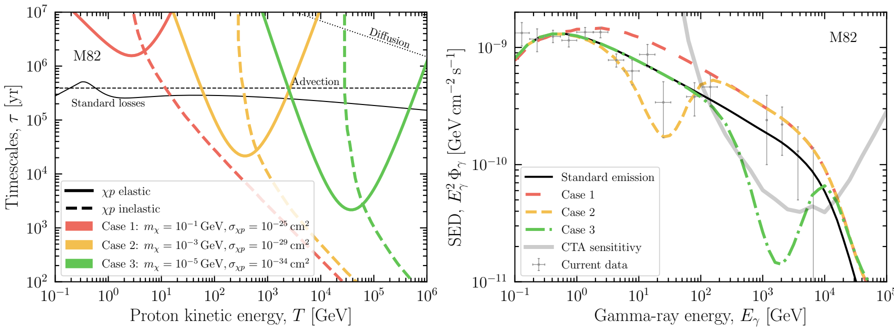

Figure 1: Left: Comparison between the *standard* timescales (effective losses, advection and diffusion) in black lines and the effective DM-p timescales for three different cases regarding m_χ and $\sigma_{\chi p}$. **Right**: The corresponding theoretical expected gamma-ray fluxes for the source compared with the experimental Fermi-LAT and VERITAS data [1, 10]. Image taken from Ref. [3] (see also [9]).

5. Bounds on DM-p Interactions

Since the gamma-ray data of M 82 and NGC 253 are consistent with unbroken power-laws, showing no sign of dip, we can derive strict bounds on DM-p interactions. We do it by means of a likelihood analysis following previous publications [3–5] . The likelihood defined as $\mathcal{L} = e^{-0.5\chi^2}$, where χ^2 is the chi-squared over the SED data

$$\chi^2 = \sum_i (SED_i - E_i^2 \phi(E_i, m_\chi, \sigma_{\chi p}|\theta))^2/\sigma_i^2) \tag{7}$$

where i runs over all the measurements [3–5] and θ represents all the astrophysical parameters treated as nuisance parameters (see [3]). We evaluate the bounds via the test statistic: $\Delta\chi^2 = \chi^2(m_\chi, \sigma_{\chi p}) - \chi^2(m_\chi, 0)$ [3], where the chi squared is marginalised over the astrophysical parameters. The bounds are set with $\Delta\chi^2 = 23.6$, namely at 5σ level [3].

We also perform a forecast analysis for the CTA telescope, making use of only CTA public information [3, 4]. In particular, we produce 50 mock data sets for M 82 and NGC 253 and perform the same statistical analysis. Fig. 2 shows our findings, on the left for M 82, and on the right for NGC 253. The continous lines show current data bounds, red for M 82 and yellow for NGC 253. The limits constrain $\sigma_{\chi p}$ up to 10^{-34} cm^2 for $m_\chi \leq 10^{-3}$ MeV. The bands correspond to the forecast performed for the CTA telescope. This will increase the bounds over two orders of magnitude making the bounds from both sources at the same $\sigma_{\chi p}$ level. Finally, we show the minimal theoretical bounds obtained as [3]

$$\min_{E<E_{\rm cut}} \left[\tau_{\chi p}^{\rm el,eff} \left(\frac{1}{\tau_{\rm esc}} + \frac{1}{\tau_{\rm loss}^{\rm eff}} \right) \right] = 1\,. \tag{8}$$

where E simulates the maximal energy reachable by different gamma-ray experiments. Eq. 8 physically tells us that at lest the gamma-ray spectrum should vary of the 50% in order to probe DM-interactions. Our result demonstrates that not-only current-data bounds provide significant constraints, but there will be big room for future improvements.

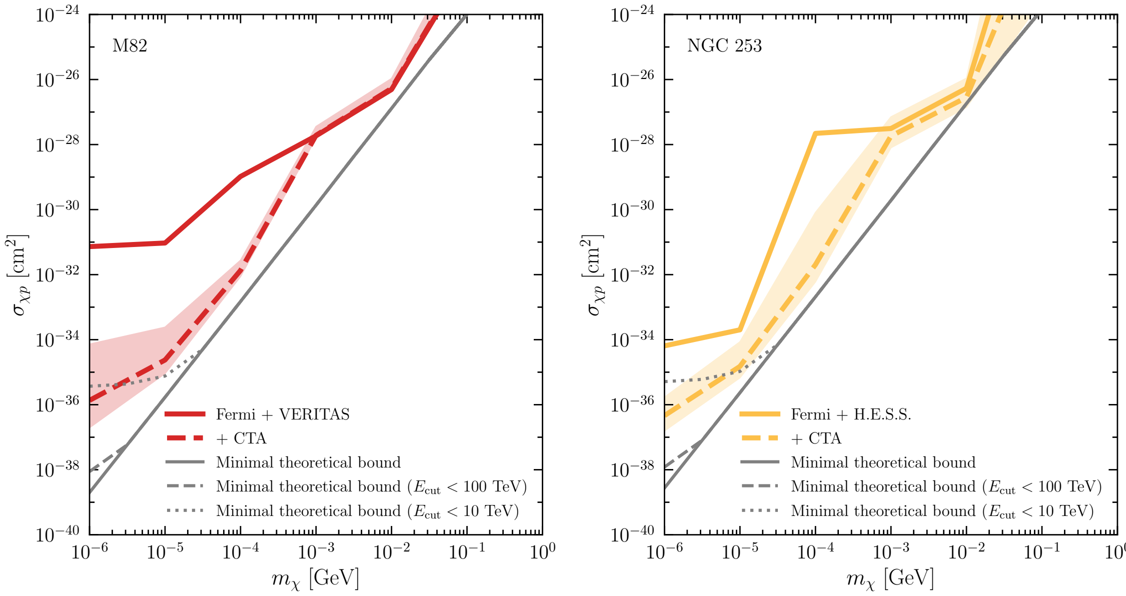

Figure 2: Left: Current data bounds on $\sigma_{\chi p}$ as a function of m_χ (continous red line) for M 82. The red band corresponds to the forecast for the CTA telescope. The black lines show the theoretical minimal bounds. **Right**: Current data bounds on $\sigma_{\chi p}$ as a function of m_χ (continuous yellow line) for NGC 253. The yellow band corresponds to the forecast for the CTA telescope. The black lines show the theoretical minimal bounds. Image taken from Ref. [3]

6. Conclusions

In this proceeding, we have shown how SBNi can be used as a probe of DM-p interactions. We have used current gamma-ray data of M 82 and NGC 253 to constrain $\sigma_{\chi p}$ up to 10^{-34} cm^2. We have also shown a forecast for the CTA telescope and shown that the future telescope will improve current bounds up to two order of magnitudes. Overall, SBGs have proven to be significant astrophysical laboratories.

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