PROCEEDINGS OF SCIENCE

Light Dark Matter vs Starburst Nuclei

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Dark Matter (DM) existence is a milestone of the cosmological standard model and, yet its nature remains a complete mystery. In this contribution, we investigate an original way to probe the properties of sub-GeV DM particle candidates, by exploiting the cosmic-ray (CR) transport inside starburst nuclei (SBNi). Indeed, SBNi are considered CR reservoirs, thereby being able to trap CRs for $\sim 10^5$ yr years up to $\sim$ PeVs energies, leading to copious production of gamma-rays and neutrinos. As a result, interactions between DM and protons might indelibly change CR transport in these galaxies, perturbing the gamma-rays and neutrino production. We show that current gamma-ray observations from the M82 and the NGC 253, local starburst galaxies, pose strict limits on the elastic cross section down to $\sigma_{\chi p} \simeq 10^{-34}\,\mathrm{cm}^2$for DM masses $m_\chi \leq 10^{-3}$ MeV. Furthermore, the current bounds have considerable room for improvement with the future gamma-ray measurements in the 0.1-10 TeV range from the Cherenkov Telescope Array up to ~ 2 orders of magnitude.

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1. Introduction

Starburst galaxies (SBGs) are galaxies with a high star formation rate, which can be tens or even hundreds times higher than the one measured in the Milky-way [1–7]. In general, their stellar forming activity is concentrated in their nucleus and for this reason they are also referred to as starburst nuclei (SBNi) [2, 6]. M82 and NGC 253 are two nearby powerful SBGs, which are characterised by hard power-law spectra in the energy range between $0.1 - 3000\,\mathrm{GeV}$ [5, 8–11]. The main interpretation of these observations is given by diffuse gamma-rays emitted by CRs interacting with the interstellar gas inside the nuclei. On this regard, these sources are supposed to be characterised by a high degree of magnetic turbulence leading to a high diffusion timescale. Therefore, combined with a large density of the interstellar gas, they should be able to trap CRs for $\sim 10^5$ yr CRs inside their system. In this proceeding, we revisit the CR transport inside these sources and exploit it in order to pose strong constraints on potential light DM particle candidates (see [1, 7] for more details).

2. Conventional CR Transport and Gamma-rays

We study the CR transport inside SBNi in the context of a leaky-box model (please see [1] for more details). Hence, we obtain the CR density inside the nuclei as

$$f_{\mathrm{CR}}(p) = \left(\frac{1}{\tau_{\mathrm{adv}}} + \frac{1}{\tau_{\mathrm{diff}}} + \frac{1}{\tau_{\mathrm{loss}}^{\mathrm{eff}}}\right)^{-1} Q_{\mathrm{CR}}(p)\,, \tag{1}$$

where $f_{\mathrm{CR}}(p)$ is the momentum CR density, τ_{adv} is the advection timescale and τ_{diff} is the diffusion timescale. $Q_{\mathrm{CR}}(p)$ is the injected power-law flux with index α from supernovae remnants (SNRs) normalised assuming that 10% of the 10^{51} erg emitted by SNRs are going into CRs. Finally, $\tau_{\mathrm{loss}}^{\mathrm{eff}}$ is the energy loss timescale divided by $\alpha - 3$. In general, for powerful SBGs considered in this work, Eq. 1 can be simplified as $f_{\mathrm{CR}}(p) \simeq \left(\frac{1}{\tau_{\mathrm{adv}}} + \frac{1}{\tau_{\mathrm{loss}}^{\mathrm{eff}}}\right)^{-1} Q_{\mathrm{CR}}(p)$, because diffusion processes are negligible. The main channel for production of gamma-rays is given by hadronic collisions between high-energy protons and the interstellar gas. We semi-analytically evaluated the pion production rate q_π assuming the delta function approximation [12].

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

where n_{ISM} is the interstellar medium density and $n_p = 4\pi \frac{p}{E} f_{\mathrm{CR}}(p)$. The gamma-ray production rate is given by

$$Q_\pi(E, r) = 2\int_{E+m_\pi^2/4E}^{\infty} \frac{q_\pi^{pp}(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}}\,\mathrm{d}E_\pi\,. \tag{3}$$

The final flux at Earth is given by

$$\Phi_\gamma(E, z) = \frac{\mathrm{Abs}(E(1+z))\, e^{-\tau_{\gamma\gamma}(E,z)}}{4\pi\, d_c(z)^2} Q_{\mathrm{tot}}(E(1+z)) V_{\mathrm{SBN}} \tag{4}$$

where Q_{tot} accounts also for Bremsstrahlung and inverse compton processes and $\mathrm{Abs}(E(1+z))$ is the internal absorption coefficient (please see [1] for more details on these terms).

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3. Dark Matter Proton Interactions

If there is an interaction between a light DM particle and protons, it would generate a further energy loss process within Eq. 1. Therefore, this could indelibly change the CR transport inside the sources. The energy loss timescale for elastic DM-proton interaction is given by (see [1])

$$\tau_{\rm loss}^{\rm elastic\, DM-p}(E) = \left[\frac{\rho_\chi}{E \cdot m_\chi} \int_0^{T_\chi^{\max}} \mathrm{d}T_\chi \, T_\chi \frac{\mathrm{d}\sigma_{\rm el}}{\mathrm{d}T_\chi} \, , \right]^{-1} \tag{5}$$

where ρ_χ is the DM energy density profile which we consider as the NFW profile [7, 13]. We also have that

$$T_\chi^{\max}(E) = \frac{2T(E)^2 + 4m_p T(E)}{m_\chi} \left[\left(1 + \frac{m_p}{m_\chi}\right)^2 + \frac{2T(E)}{m_\chi} \right]^{-1} . \tag{6}$$

and

$$\frac{\mathrm{d}\sigma_{\rm el}}{\mathrm{d}T_\chi} = \frac{\sigma_{\chi p}}{T_\chi^{\max}} \frac{F_p^2(q^2)}{16\,\mu_{\chi p}^2\, s} (q^2 + 4m_p^2)(q^2 + 4m_\chi^2) \, , \tag{7}$$

$\sigma_{\chi p}$ is the DM-p cross section at zero momentum transferred, F_p is the proton form factor, $s = m_\chi^2 + m_p^2 + 2Em_\chi$ and $\mu_{\chi p}$ is the reduced mass between DM and p. For the inelastic DM-proton interaction, we simply assume that it follows the neutrino-proton cross section and rescale it for the elastic cross section value. This procedure allows us to estimate the inelastic cross section in terms of $\sigma_{\chi p}$. The inelastic DM-p timescale is estimated as

$$\tau_{\chi p}^{\rm inel} = \left(\kappa\, \sigma_{\rm inel} \frac{\rho_\chi}{m_\chi} \right)^{-1} \, , \tag{8}$$

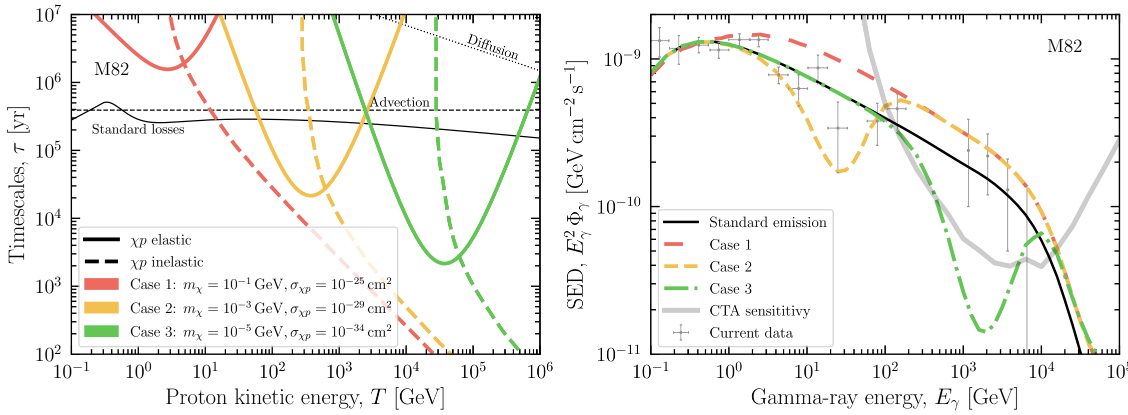

Figure 1: Left: Proton Timescales as a function of the kinetic energy. Black lines represent standard timescales such as energy losses, advection and diffusion. On the other hand, the colored lines represent the DM-proton timescales. The continued line refer to the elastic collisions while the dashed ones refer to the inelastic collisions. The three colors refer to different combination of m_χ and $\sigma_{\chi p}$. **Right**: The signature of the DM-protons interactions on the gamma-ray spectrum of M82 with the same color scheme shown on the left. The M82 data are taken from [8, 10]. Image taken from Ref. [1].

Fig. 1 shows, on the left, the the comparison between the standard proton timescales in the SBN of M82 with the elastic and inelastic DM-proton timescales. The elastic DM-proton interactions show a minimum at $E_p = m_p^2 c^2/(2m_{\chi^2})$, while the inelastic collisions strongly overtake the timescales above this energy. On the right, we show the corresponding signature on the gamma-ray spectrum of M82. In particular, the standard scenario is given by a simple power-law spectrum suppressed above $\sim 10\,\text{TeV}$ because of absorption phenomena. By contrast, The elastic DM-proton interactions cause a dip in the spectrum, while the inelastic timescale allows the source to become totally calorimetric, namely producing gamma-rays for each high-energy produced replenishing it. The overall signature of DM-proton interactions is given by a lack of photons in the range of $E_\gamma \sim 0.1 m_p^2 c^2/(2m_{\chi^2})$.

4. Bounds on DM-p and Conclusions

Given that the gamma-ray data of M82 and NGC 253 do not show any dip in the gamma-ray spectrum, we can use the gamma-ray spectrum to pose strong constraints on $\sigma_{\chi p}$. In particular, we can define the likelihood as

$$\mathcal{L} = e^{-\chi^2} \tag{9}$$

where

$$\chi^2 = \frac{1}{2}\sum_i \left(\frac{\text{SED}_i - E_i^2 \Phi_\gamma(E_i|m_\chi, \sigma_{\chi p}, \theta)}{\sigma_i}\right)^2 \tag{10}$$

where SED is the measured spectral energy distribution of the source. We set bounds according to $\Delta\chi^2 = \chi^2(m_\chi, \sigma_{\chi p}) - \chi^2(m_\chi, 0) = 23.6$, treating the SFR, the injection spectral index, interstellar gas density, wind velocity and SBN radius as nuisance parameters. Interestingly, we can constrain $\sigma_{\chi p}$ values up to $10^{-34}\,\text{cm}^2$ lor $m_\chi \lesssim 1\,\text{KeV}$. We notice that with the upcoming Cherenkov Telescope Array (CTA) [14] the bounds will improve of $\sim$ two orders of magnitude. We conclude that our methodology can strongly constrain the property of light DM particle using SBNi. In the future, also neutrino observations might be useful to constrain even further DM as well as combine gamma-ray measurements from other SBGs.

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