Search for Supersymmetric Dark Matter in M31 with CELESTE

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Abstract

Under the assumption that the dark matter is composed of the lightest stable supersymmetric particle, assumed to be the neutralino, the feasibility of its indirect detection by the CELESTE experiment via the observation of a continuous gamma-ray signal due to neutralino annihilation within M31 is examined. The dark matter halo modelling in M31 is addressed and predictions are made in the framework of mSUGRA models.

1. Introduction

The question of the nature of dark matter (DM) is one of the most outstanding problems confronting cosmology and astrophysics. A multitude of observations suggest the existence of DM and furthermore, supersymmetric extensions of the standard model of particle physics provide a natural candidate for non-baryonic/cold DM. This particle, the neutralino, is a stable uncharged Majorana fermion. Hereafter, we briefly report on the potential for indirect detection of neutralinos through their annihilation in the halo of M31 by CELESTE, a high-energy γ-ray ($E_\gamma \geq 50$ GeV) ground-based detector (for the detailed study see [3]). CELESTE is a sampling and timing Cherenkov detector located in southern France. It uses 53 heliostats (54 m^2 each) of the former solar power plant Thémis to collect the Cherenkov light from atmospheric showers. The detector has been described elsewhere, as well as the analysis method used to extract the signal [6,4]. The analysis uses the homogeneity and the time distribution of the Cherenkov wavefront to discriminate between γ and hadronic cosmic-ray showers.

2. Dark matter halo around M31 and neutralino annihilation

The late-type Sb spiral galaxy M31, lying at a distance of 700 kpc, has a visible part consisting mostly of a bulge and a disk. As described in [3], we have reconsidered the two mass components fit to the rotation curve of M31 performed by Braun [2] and we have shown that a DM halo around M31 is a viable possibility depending on the mass-to-light ratio for the disk (Υ_{disk}) and the bulge

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(Υ_{bulge}). Therefore, we have assumed the presence of an additional mass component in terms of a spherical halo whose mass density profile is generically given by $\rho_\chi(r) = \rho_0 \, (r_0/r)^\gamma \, [(r_0^\alpha + a^\alpha)/(r^\alpha + a^\alpha)]^\epsilon$ where γ, α and ϵ define the various profiles. While a fit to the observations constrains weakly the ratio $\Upsilon_{disk}/\Upsilon_{bulge}$, it leads to more stringent constraints on the structure of the neutralino halo, actually favouring a NFW profile with $\gamma = 1, \alpha = 1, \epsilon = 2$ [5]. The results are presented in Fig. 1.

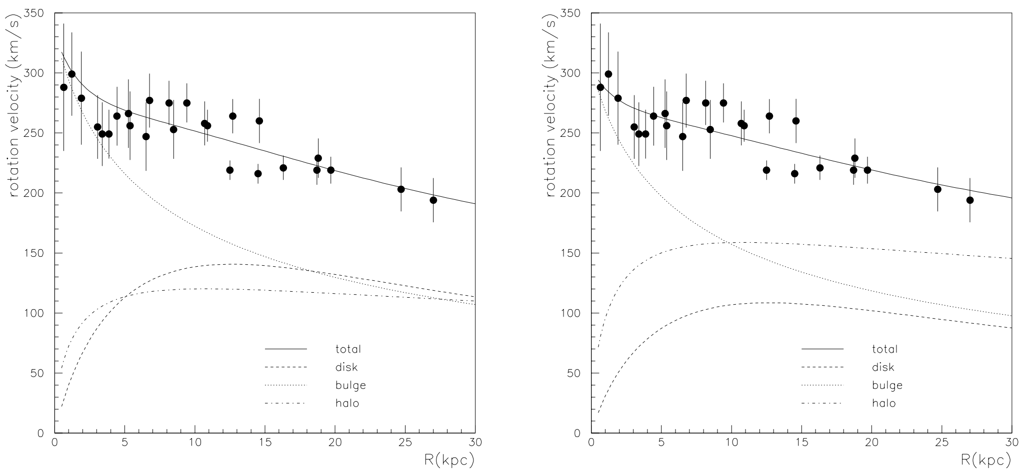

Fig. 1. A $\gamma = 1$ neutralino halo is added to the bulge and to the disk of M31. *Left:* an intermediate case with $\Upsilon_{bulge} = 4.2\ \Upsilon_{B,\odot}$ and $\Upsilon_{disk} = 4.2\ \Upsilon_{B,\odot}$ (where $\Upsilon_{B,\odot}$ is the mass-to-light ratio for the Sun). *Right:* a maximal halo with $\Upsilon_{bulge} = 3.5\ \Upsilon_{B,\odot}$, $\Upsilon_{disk} = 2.5\ \Upsilon_{B,\odot}$. The global solid rotation curve is in good agreement with the data of Braun [2].

In case of a substantial neutralino component of the DM halo around M31, the annihilation processes could produce photon fluxes $I_\gamma = \langle \sigma v \rangle \, N_\gamma / (4\pi m_\chi^2) \times \Sigma$ (in $cm^{-2}s^{-1}$). Here m_χ is the neutralino mass and $\langle \sigma v \rangle \, N_\gamma$ denotes the thermally averaged annihilation rate with N_γ gamma-rays in the final state. This includes the dependence on elementary annihilation cross sections whereas Σ represents the integral of ρ_χ^2 over the line of sight (in $GeV^2 cm^{-5}$). In Table 1 of Fig. 2 we illustrate some typical fluxes for $m_\chi = 500$ GeV, and $\langle \sigma v \rangle \, N_\gamma = 10^{-25} cm^3 s^{-1}$.

3. Supersymmetric model predictions and resulting fluxes

In this study we will focus mainly on the minimal supergravity scenario (mSUGRA) where the gaugino mass $m_{1/2}$, the scalar mass m_0 and trilinear supersymmetry breaking parameters A_0 are constrained to be universal at an input GUT scale $\sim 2 \times 10^{16}$GeV. All results have been obtained using an interfaced version of the two public codes DarkSUSY and SUSPECT as described in [3]. We take into account various physical limits from elementary particle experiments and require the corresponding neutralino relic density to be within the range $0.025 \leq \Omega_\chi h^2 \leq 0.3$. We then make specific predictions for the γ fluxes in terms of mSUGRA parameters. The scan within the mSUGRA allowed parameter space is shown in Fig. 2, where the γ fluxes were multiplied by a possible enhancement factor of 500 due to clumpiness and black hole accretion effects [3]. As shown in Fig. 2, only such very optimistic astrophysical assumptions and a CELESTE observation time of at least 10 hours may lead to exclusion/discovery in the mSUGRA domain.

Υ_{bulge}	Υ_{disk}	Σ_{19}(3.5 kpc)	Σ_{19}(28 kpc)	I_γ(3.5 kpc)	I_γ(28 kpc)
6.5	6.4	0	0	0	0
4.2	4.2	1	1.2	3.2×10^{-13}	3.8×10^{-13}
3.5	2.5	3	3.7	10.2×10^{-13}	11.8×10^{-13}

Table 1:

Clump distribution	Dynamics	SBH environment	Σ	Σ^{10}
compact	no evaporation	SIS spike	165	100
extended	no evaporation	SIS spike	140	90
compact	no evaporation	$\rho \propto r^{-1.5}$	80	20
extended	no evaporation	$\rho \propto r^{-1.5}$	55	6
compact	evaporation	$\rho \propto r^{-1.5}$	25	6
extended	evaporation	$\rho \propto r^{-1.5}$	40	5

Table 2:

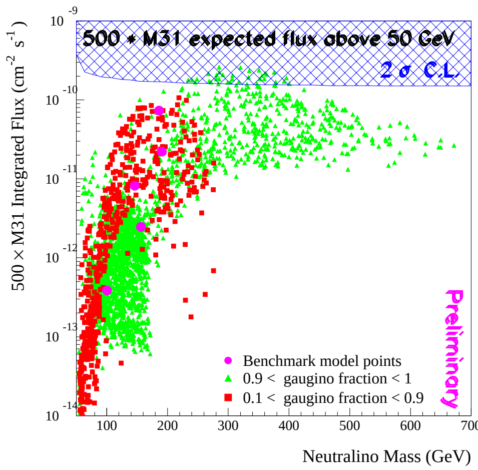

Fig. 2. Table 1: Three different models for M31 are featured. The first corresponds to the case where no halo is needed. $\Sigma_{19}(R)$ is in units of $10^{19} GeV^2 cm^{-5}$ and the integral flux I_γ(R) is given for a circular region encompassing the inner 3.5 kpc (corresponding to the CELESTE field of view of 10 mrad) and 28 kpc. Table 2: Impact on flux predictions of astrophysical parameters such as clumpiness of the M31 halo and supermassive black hole (SBH) in its centre, smooth and clump contributions added ($\Sigma^{10} = \Sigma_{19}$(3.5 kpc) and $\Sigma = \Sigma_{19}$(28 kpc)). *Right*: 500 × the integrated γ flux above 50 GeV from M31 with standard NFW profile as a function of m_χ. Each point corresponds to a model in our "wild scan" (where two different ranges of gaugino fraction are considered) and must be compared to the 2σ C.L. expected for CELESTE in 10 hours of observations.

4. CELESTE sensitivity estimation

As shown in [1], the differential γ distribution as a function of the $x = E/m_\chi$ variable presents a scaling behaviour which depends only on the annihilation channels. Thus, the differential flux dependence on m_χ can be expressed as

$f(E, m_\chi) \propto \sqrt{m_\chi} E^{-\frac{3}{2}} exp(-\alpha E/m_\chi)$ where E is the photon energy and α is fixed using a fitting procedure. This leads to :

$$\frac{d\phi(E, m_\chi)}{dE} = \phi_{int}(E > E_{th}, m_\chi) \times \frac{f(E, m_\chi)}{\int_{E_{th}}^{\infty} f(E, m_\chi) dE} ,$$

and then, the detected flux above E_{th} is

$$\phi_{\gamma,cuts}(E > E_{th}) = \phi_{int}(E > E_{th}, m_\chi) \times \frac{\int_{E_{th}}^{\infty} \mathcal{A}(E) f(E, m_\chi) dE}{\int_{E_{th}}^{\infty} f(E, m_\chi) dE} ,$$

where $\mathcal{A}(E)$ is the acceptance in energy. The chosen energy threshold E_{th} depends on m_χ and its value is optimised to get the best signal-to-noise ratio.

Assuming no detected signal from M31, we will derive an upper limit for the expected fluxes induced by neutralino annihilation within the M31 halo. For a given "on-source" observation time T, any signal would then be excluded up to $\tilde{N}_\sigma$ of background fluctuations according to $\phi_{\gamma,cuts}(E > E_{th}) < \tilde{N}_\sigma \sqrt{2\phi_{bg}/T}$. The background signal after event selection has been extracted from the "off-source" data and the 2σ C.L. ($\tilde{N}_\sigma = 2$) is shown in Fig. 2.

5. Conclusion

In conclusion, we show that under very optimistic astrophysical conditions such as rapid accretion of the neutralinos on the central black hole in M31 and excessive halo clumpiness, a neutralino annihilation γ-ray signal is within the reach of ongoing observations of M31 with CELESTE.

6. References

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