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Towards Dark Matter Searches with the MAGIC Telescope

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MAGIC is a 17m diameter Imaging Air Cherenkov Telescope installed on the Canary Island La Palma. The telescope is designed for gamma-ray astronomy in the 30 GeV to 30 TeV energy range. Particle physics models predict candidate particles for Dark Matter, that might annihilate into gamma rays. Their predicted energy is in the accessible range of the MAGIC telescope. The expected gamma fluxes depend strongly on the density profiles in the innermost regions of the Dark Matter halos.
The prospects and strategies for indirect Dark Matter searches with the MAGIC Telescope are described. The observability and flux expectations from possible targets are discussed.

1. Introduction

The existence of Dark Matter is well established on scales from galaxies to the whole universe. Nevertheless, its nature is still unknown. Most of it cannot even be made of any of the known matter particles. A number of viable Weakly Interacting Massive Particle (WIMP) candidates have been proposed within different theoretical frameworks, mainly motivated by extensions of the standard model of particle physics (for a review see [1]). These include the widely studied models of supersymmetric (SUSY) Dark Matter [14]. Supersymmetric extensions of the standard model predict the existence of a good Dark Matter candidate, the neutralino χ. In most models its mass is below a few TeV. Also models involving extra dimensions are discussed like Kaluza-Klein Dark Matter [12, 13].

Any WIMP candidate (SUSY or not) may be detected directly via elastic scattering off nuclei in a detector on Earth. There are several dedicated experiments already exploiting this detection technique, but they have not yet claimed any strong and solid detection (for a review see [2]). Complementary, WIMPs and especially SUSY neutralinos might annihilate in high-density Dark Matter environments and may be detected by their annihilation products. In particular, annihilation channels that produce gamma-rays are interesting because these are not deflected by magnetic fields and preserve the information of the original annihilation region, i.e. they act as tracers of the Dark Matter density distribution.

The expected mass range of SUSY neutralinos lies between about 50 GeV and a few TeV. Thus the continuum gamma-ray spectra from potential SUSY neutralino annihilation coincides well with the MAGIC energy region.

2. The MAGIC Experiment

The Major Atmospheric Imaging Cherenkov telescope (MAGIC [3]) is the largest Imaging Air Cherenkov Telescope (IACT). Located on the Canary Island La Palma at 2200m a.s.l, the telescope has a 17m diameter high reflectivity tessellated parabolic mirror dish, mounted on a light weight carbon fiber frame. It is equipped with a high efficiency 576-pixel photomultiplier camera, whose analogue signals are transported via optical fibers to the trigger electronics and the 300 MHz FADC readout. Its physics program comprises, among other topics, pulsars, supernova remnants, active galactic nuclei, micro-quasars, gamma-ray bursts and Dark Matter.

MAGIC has started observations in summer 2004, during the last phase of commissioning. Several known gamma sources were observed and analyzed like the Crab nebula, Mrk-421 and 1ES1959+650. A further challenge is the analysis of events below 100 GeV. The analysis methods are presently being adapted to these low energies. A second telescope, MAGIC-II, is being constructed and expected to be ready for data taking in the end of 2006. This will improve the angular and spectral resolution and flux sensitivity of the system.

3. Gamma-rays from neutralino annihilations

Neutralino annihilation can generate continuum γ-ray emission, via the process $\chi\chi \rightarrow q\bar{q}$. The subsequent decay of π^0-mesons created in the resulting quark jets produces a continuum of γ-rays. The expected annihilation γ-ray flux above an energy threshold E_{thresh} arriving at Earth is given by:

$$\frac{dN_\gamma(E_\gamma > E_{\mathrm{thresh}})}{dt\; dA\; d\Omega} = N_\gamma(E_\gamma > E_{\mathrm{thresh}}) \cdot \frac{1}{2} \cdot \frac{\langle \sigma v \rangle}{4\pi m_\chi^2} \cdot \int_{\text{los}} \rho_\chi^2(\vec{r}(s,\Omega))ds \;, \tag{1}$$

where $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section, m_χ the mass and ρ_χ the spatial density distribution of the hypothetical Dark Matter particles. $N_\gamma(E_\gamma > E_{\mathrm{thresh}})$ is the gamma yield above the threshold energy per annihilation. The predicted flux depends on the SUSY parameters and on the spatial distribution of the Dark Matter. The energy spectrum of the produced gamma radiation has a very characteristic feature with a cut-off at the mass of the Dark Matter particle. Moreover, the flux should be absolutely stable in time.

As the expected flux is proportional to the Dark Matter density squared, high density Dark Matter regions are the most suitable places for indirect Dark Matter searches. Simulations and measurements of stellar dynamics indicate that the highest Dark Matter densities can be found in the central part of galaxies and Dark Matter dominated dwarf-spheroidal-satellite galaxies (with large mass-to-light ratio). Numerical simulations in a Cold Dark Matter framework predict a few universal DM halo profiles (for example see [4]). All of them differ mainly at low radii (pc scale), where simulation resolutions are at the very limit.

Combining the SUSY predictions with the models of the DM density profile for a specific object, the gamma flux from neutralino annihilations can be derived. The SUSY predictions are taken from a detailed scan of the parameter space assuming Minimal Supergravity (mSUGRA), a simple and widely studied scenario for supersymmetry breaking (for details see [5]). For a given choice of mSUGRA parameters the values of m_χ, $\langle \sigma v \rangle$ and N_γ are determined and the consistency with all observational constrains is checked. High DM density objects which are relatively nearby like the center of the Milky Way, its closest satellites and the nearby galaxies (M31,M87) are prime candidates for the indirect search for Dark Matter annihilation.

3.1 Galactic Center

The presence of a Dark Matter halo in the Milky Way Galaxy is well established by stellar dynamics [15]. In particular, stellar rotation curve data of the Milky Way can be fit with the universal DM profiles predicted by simulations [8, 7, 9]. In addition, the Dark Matter may be compressed due to the infall of baryons to the innermost region [5] of a galaxy creating a central spike of the Dark Matter density. This central Dark Matter spike would boost the expected gamma flux from neutralino annihilation in the center of the galaxy. Although

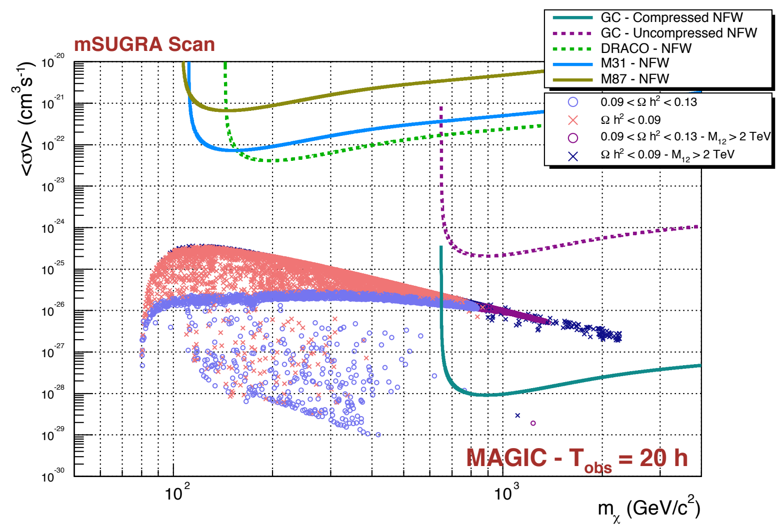

Figure 1. Expected exclusion limits for the four most promising sources of Dark Matter annihilation radiation for 20 hours of observation with MAGIC. The Galactic Center is expected to give the largest flux (lowest exclusion limits) amongst all sources.

this model of baryonic compression is based on observational data and in good agreement with cosmological simulations of the condensation of baryons [6], the existence of such a Dark Matter spike in the center of the Milky Way strongly depends on the Black Hole history during galaxy formation.

For a comparison between the expected gamma fluxes from neutralino annihilation and the MAGIC sensitivity both the uncompressed NFW DM halo model [7] and the adiabatic contracted NFW profile [5] are considered.

3.2 Draco dwarf spheroidal and nearby galaxies

The Milky Way is surrounded by a number of small and faint companion galaxies. These dwarf satellites are by far the most Dark Matter dominated known objects, with Mass-to-Light ratios up to 300. Draco is the most DM dominated dwarf satellite. DM density profiles derived from Draco stars cannot differentiate between cusped or cored profiles in the innermost region, as data are not available at small radial distances. Moreover, observational data disfavors tidal disruption effects, which may affect dramatically the DM distribution in Draco. We adopt the recent cusped DM model which includes new Draco rotation data [8].

Moreover, we adopted NFW models for the nearby galaxy M31 [9] and the Virgo Cluster [10]. These profiles do not take into account any enhancement effect, like adiabatic contraction or presence of DM substructures.

4. Summary

Comparing the expected gamma ray flux from neutralino annihilation in the considered candidate sources with the MAGIC sensitivity [17], expected exclusion limits can be derived. Figure 1 shows expected exclusion limits for 20 hours of MAGIC observations in the mSUGRA plane $N_\gamma(E_\gamma > E_{\rm thresh})\langle\sigma v\rangle$ vs. m_χ for the four most promising sources considered. The nominal energy threshold $E_{\rm thresh}$ has been conservatively assumed to be 100 GeV. The change in energy threshold and effective collection area of the telescope with the zenith angle of the observation have been taken into account.

The expected fluxes are rather low and depend strongly on the innermost density region of the DM halos considered. The detection of a DM γ-ray signal from the Galactic Center is possible in case of a very high density DM halo, like the one predicted by adiabatic contraction processes. Improvements on the E_{thresh} could allow to test a significant portion of the SUSY parameter space. The gamma flux from the Galactic Center as measured by the HESS experiment is far above the theoretical expectations and extends to energies above 10 TeV [16]. Thus only part of this flux may be due to the annihilation of SUSY-neutralino Dark Matter particles. Nevertheless, other models like Kaluza-Klein Dark Matter are not ruled out. It is interesting to investigate and characterize the observed gamma radiation to constrain the nature of the emission. Due to the large zenith angle for Galactic Center observations, MAGIC will have a large energy threshold but also a large collection area and good statistics at the highest energies. The Galactic Center was observed recently (May-July 2005) and data are being analyzed [11].

In the long term we consider Draco as a plausible candidate for Dark Matter inspired observations. Conservative scenarios give low fluxes which are not detectable by MAGIC in a reasonable observation time. However, there are several factors that might enhance the expected flux from neutralino annihilations in Draco. Other Dark Matter particles, like Kaluza-Klein particles, may produce higher gamma-rays fluxes. Draco is the most DM dominated dwarf (M/L up to 300) and an object where no other γ-ray emission is expected. Low zenith angle observations will preserve the nominal (low) E_{thresh} of the MAGIC telescope. Moreover, there are no known high energy γ-ray sources in the FOV which could compete with the predicted gamma flux from Dark Matter annihilation.

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