

---

## Search for Relic neutralinos with Milagro

---

Lazar Fleysher<sup>1</sup> for the Milagro Collaboration  
(1) *New York University, New York, NY 10003, USA*

---

### Abstract

The neutralino, the lightest stable supersymmetric particle, is a strong theoretical candidate for the missing astronomical "dark matter". The Minimal Supersymmetric extension of the Standard Model predicts that the gamma rays emerging from one of the neutralino annihilation modes will give a distinct monochromatic signal in the energy range between 100GeV and 10TeV, depending on the neutralino mass. An additional "continuum" spectrum signal of photons will be produced by the decay of secondaries produced in the non-photonic annihilation modes.

Milagro is an air shower array which uses the water Cherenkov technique and is capable of detecting TeV gamma rays from the direction of the Sun with an angular resolution of less than a degree. In this report we present preliminary results of a search for near-solar neutralino to photon annihilation with the Milagro gamma-ray observatory.

### 1. Introduction

There is overwhelming evidence that the Universe, and the galaxies in particular, are full of the "dark matter". There is no reason to assume that the Milky Way is any different. In this work, it is supposed that the neutralino, a weakly interacting particle predicted by super-symmetric theories, is the solution of the "dark matter" problem. If this is indeed the case, the neutralinos form a halo around the Milky Way Galaxy and at the location of the Solar System the density of the halo neutralinos is often assumed to be  $\rho_0 = 0.3 \text{ (GeV/cm}^3\text{)}$ .

The neutralinos entering the Solar system may lose energy via elastic scattering with ordinary matter scatterers and become trapped in the Solar system. Due to the capture and repeated scatterings, there will be a near-solar enhancement in the neutralino density. The captured neutralinos may annihilate giving rise to an enhanced gamma-ray signal from the neighborhood of the Sun. The photon energy spectrum is expected to be continuum with two distinct lines corresponding to direct neutralino-photon annihilations in  $\chi\chi \rightarrow \gamma\gamma$  and  $\chi\chi \rightarrow Z\gamma$  processes.

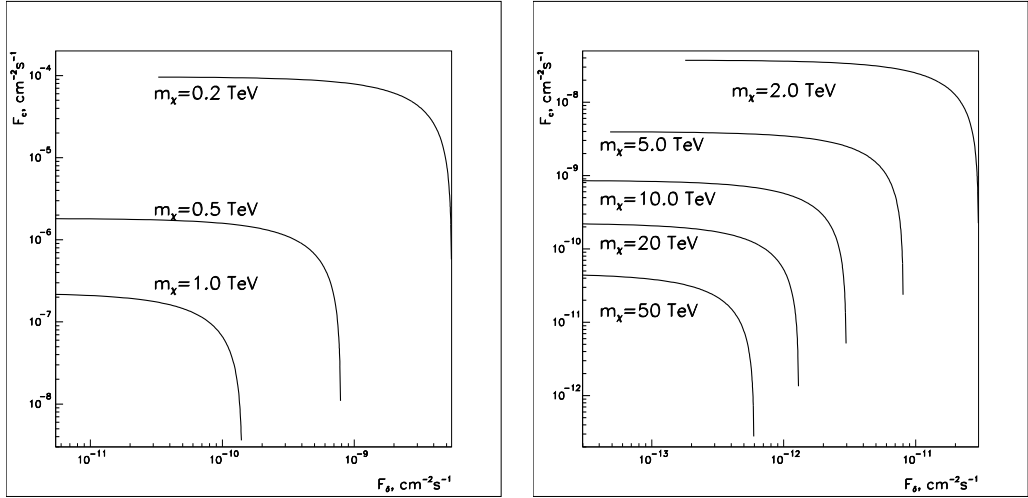
## 2. Data and analysis technique

The Milagro  $\gamma$ -ray observatory has been taking data since 1999, is sensitive to cosmic gamma rays at energies around 1 TeV, and is capable of continuously monitoring the overhead sky with angular resolution of less than 1 degree. The data to be used in this work was chosen to satisfy the following conditions: online reconstruction between July 19 2000 and September 10 2001, the number of photo-tubes required for a shower to trigger the detector greater than 60, the number of photo-tubes used in the angular reconstruction greater than 20, zenith angles smaller than 45 degrees, and passing the gamma/hadron separation cut [2]. The dates are motivated by introduction of the hadron separation parameter into the online reconstruction code on July 19, 2000 and detector turn-off for scheduled repairs on the 11th of September 2001. Several data runs were disregarded from the dataset which included calibration runs and the data when the online DAQ was in an unstable regime.

The gamma ray signal from neutralino annihilations near the Sun should appear as an excess number of events from the direction of the Sun over the expected cosmic-ray background. The interpretation of the observed signal, however, is not an easy problem. Largely, this is due to the fact that the cosmic-ray background is not expected to be uniform; the Sun absorbs the cosmic rays impinging on it and forms a cosmic-ray shadow. The situation is complicated by the magnetic fields of the Earth and the Sun. Due to bending of charged particles trajectories in magnetic fields, the Sun's shadow will be smeared and shifted from the geometrical position of the Sun in the TeV range of particle energies. On the other hand, in the presence of strong Solar magnetic fields, lower energy particles can not reach the surface of the Sun and are reflected from it. Such particles are not being removed from the interplanetary medium and may not even form a cosmic-ray shadow of the Sun. Therefore, it is difficult to ascertain the exact shape of the cosmic-ray shadow at the Sun's position and deduce excess above it.

The effect of the Earth's magnetic field and the Solar wind can be studied by observing the shadow of the Moon during the solar day. If the solar magnetic field is weak, the shadows of the Sun and the Moon should be very similar since the Sun and the Moon cover similar size regions on the celestial sphere and traverse similar paths on the local sky in one year of observation. In addition, the Earth's magnetic field at the Moon distance is already so small that any additional deflection by this field of particles originating from the Sun can be neglected.

The data analysis technique employed in this work uses the modified direct integration method [5] which allows combining the standard direct integration method [1] with the test statistic proposed in [6] by excluding the source events from the background estimation. The method is based on isotropy of the cosmic-ray background as well as on the short time scale detector stability assumptions. It also allows correct restoration of the number of excess events to be used for



**Fig. 1.** The values of  $(F_\delta, F_c)$  below the lines are allowed based the constructed upper limit for corresponding neutralino masses.

flux measurement.

For the solar region analysis,  $\pm 5^\circ$  regions around the Moon and the Crab nebula were vetoed from the data set as they present undesirable sources of anisotropy to the cosmic-ray background. For the lunar analysis, same size regions around the Sun and the Crab were vetoed. Overall, 1164.7 hours of exposure on the Sun and 423.5 hours of exposure on the Moon during the day time is obtained in this data set.

### 3. Limit on the photon flux due to neutralino annihilations

Because two close spectral lines can not be resolved by the Milagro detector, the differential photon flux due to neutralino annihilations will be assumed to have the form (see [3]):

$$\frac{dF(E)}{dE} = F_\delta \delta(E - m_\chi) + \frac{F_c(\frac{E}{m_\chi} > 0.01)}{m_\chi} \cdot \frac{(\frac{E}{m_\chi})^{-3/2} e^{-7.8E/m_\chi}}{\int_{0.01}^1 x^{-3/2} e^{-7.8x} dx} \quad (1)$$

where  $F_\delta$  is the integral flux due to a  $\delta$ -function-like photon annihilation channel and  $F_c(\frac{E}{m_\chi} > 0.01)$  is the integral flux of photons with energies greater than  $0.01 \cdot m_\chi$  due to continuum photon spectrum annihilation channel of neutralinos with mass  $m_\chi$ .

Since the shape of the solar shadow is not known, the null hypothesis is formulated as the cosmic-ray background is uniform and there is no  $\gamma$ -ray emission from the solar region. Based on the results of the measurement the formulated

null hypothesis can not be rejected with significance  $2.867 \cdot 10^{-7}$  and an upper limit on the possible  $\gamma$ -ray flux from the solar region should be obtained.

The deficit of events from the direction of the Sun can not be greater than that produced by the Moon because of Sun/Moon similarities. To be conservative in setting the upper limit, the strongest event deficit produced by the Moon in  $5^\circ$  radius from its position corrected for relative Sun/Moon exposure should be used as a correction for possible presence of the shadow of the Sun. The upper limit curve on the photon flux from the region of the Sun corresponding to the significance  $2.867 \cdot 10^{-7}$  and the power of the test of  $(1 - 2.275 \cdot 10^{-2})$  has a form of a straight line in the  $(F_\delta, F_c)$  plane and is shown in figure 1 for different neutralino masses. Once the cosmic-ray shadow of the Sun is understood quantitatively, it may be possible to improve upon the limit.

The interpretation of the constructed limit on the gamma-ray flux is highly model dependent. It is based, for instance, on assumptions regarding the shape of the velocity distribution of the dark matter in the halo and the assumed structure of the Solar System. The upper limit on the gamma-ray flux can be translated to a neutralino-mass dependent limit on the product of the neutralino-proton scattering crosssection  $\sigma_{p\chi}$ , the integrated photon yield per neutralino in neutralino-neutralino annihilation  $b_\gamma$  and the local galactic halo dark matter density  $\rho_0$  with the help of a computer simulation described in [4].

#### 4. Acknowledgements

This work is supported by the U. S. Department of Energy Office of High Energy Physics, the National Science Foundation, the LDRD program at Los Alamos National Laboratory, the University of California, the Institute of Geophysics and Planetary Physics, the Research Corporation, and the California Space Institute.

#### 5. References

1. Alexandreas D.E. et al. 1993, NIM A328, 570
2. Atkins R. et al. 2003, submitted to ApJ
3. Bergstrom L., Ullio P., Buckley J. H. 1998, ApP 9, 137
4. Fleysher L. 2003, New York University, Ph.D. thesis, astro-ph/0305056
5. Fleysher R. et al. 2003, Tests of Statistical Significance and Background Estimation in Gamma Ray Air Shower Experiments, in preparation, see also astro-ph/0301520
6. Li T., Ma Y. 1983, ApJ 272, 317

# Simulations

with G. Jungman

Steady state:  $N_{exp} = N_{in}$

Backward-in-time approach

Generate  $X_0$

Propagate to infinity  $X_0 \rightarrow X_\infty$

Given  $P(X_\infty)$  find weight  $w(X_0)$

Main approximations

Sun:

Stationary protons

constant density

No planets

No "direct" annihilations

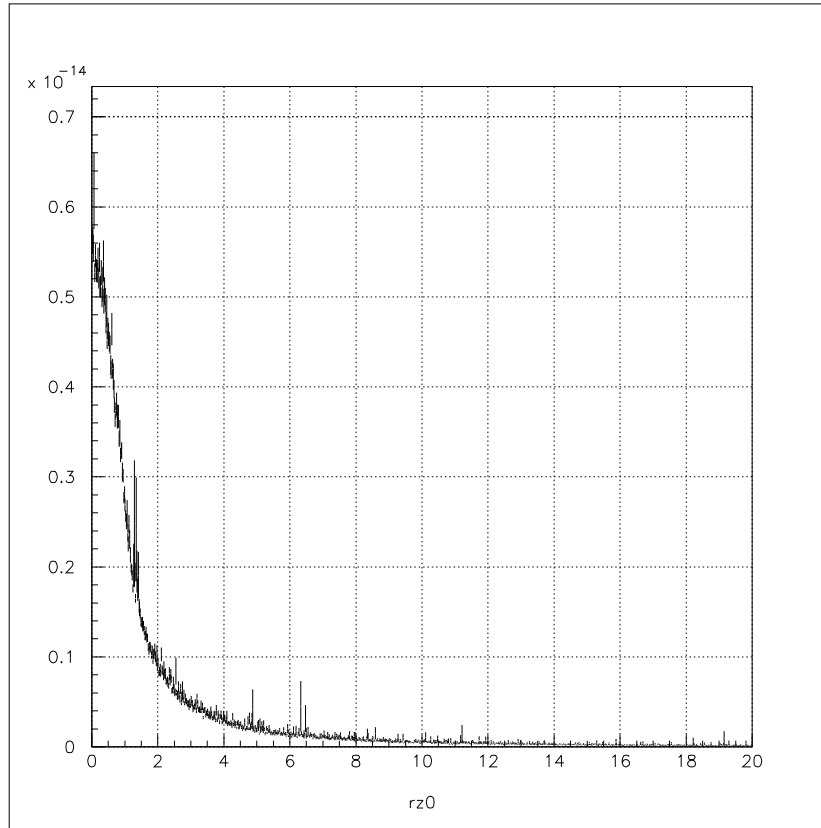


Figure 2: Radial distribution of the annihilation points for  $m_\chi = 200$  ( $GeV$ ) and  $\sigma_{p\chi} = 10^{-43}$  ( $cm^2$ ). Vertical scale is arbitrary, horizontal is in  $R_\odot$ , more than  $25 \cdot 10^6$  simulated particles.

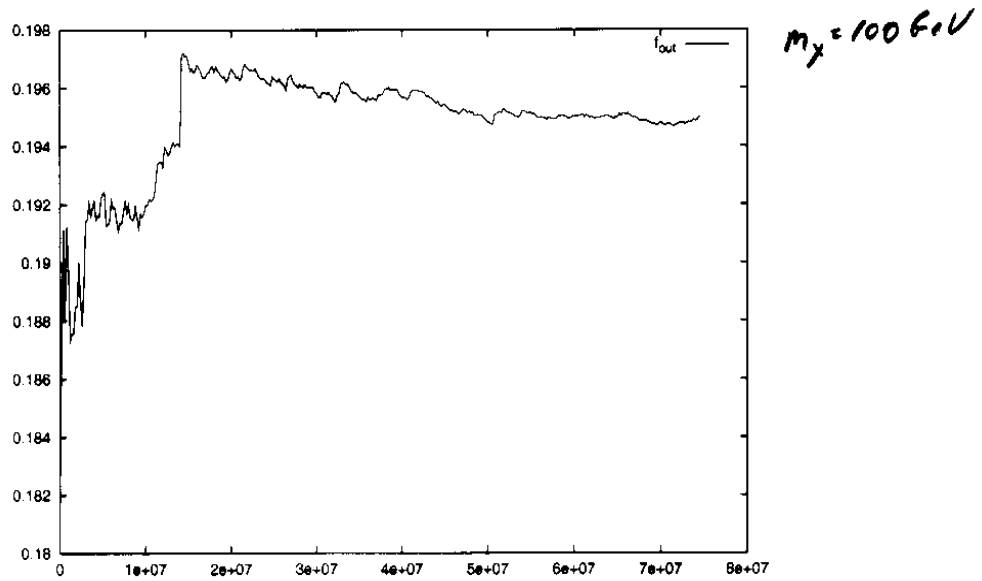


Figure 4: Fraction between  $R_{\odot}$  and  $2R_{\odot}$  as a function of number of particles in calculation.

Per kebs/s

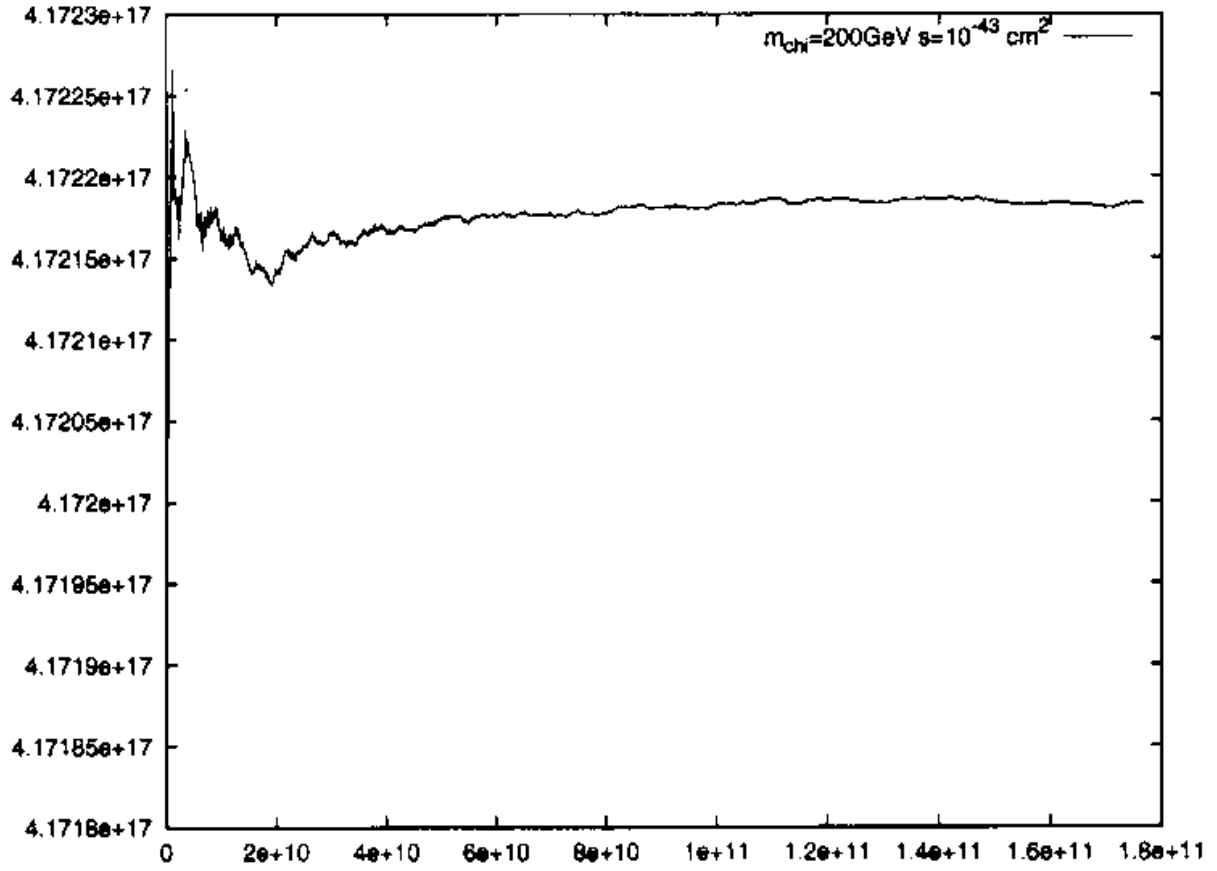


Figure 3: Capture rate (integral) as a function of number of particles in calculation

$m_\chi, (TeV)$	$f_{out}$	$I(m_\chi) \times \frac{\sigma_{\chi\chi}}{10^{-43}cm^2} \frac{\rho_0}{0.3GeV/cm^3}, (s^{-1})$
0.1	0.195	$1.65 \cdot 10^{18}$
0.2	0.196	$4.17 \cdot 10^{17}$
0.5	0.2	$6.72 \cdot 10^{16}$
1.0	0.199	$1.68 \cdot 10^{16}$
2.0	0.201	$4.22 \cdot 10^{15}$
5.0	0.2	$6.72 \cdot 10^{14}$
10.0	0.2	$1.69 \cdot 10^{14}$
20.0		$4.22 \cdot 10^{13}$
50.0		$6.75 \cdot 10^{12}$

Table 4: Simulation/computation results



Predicted photon flux  
 due to neutrino annihilations

$$\frac{dF}{dE} = \rho_0 \sigma_{py} b(E, m_x) t_{\text{out}}(m_x) t_e \frac{I(m_x)}{4\pi L^2}$$

$$b(E, m_x) = b^\delta(m_x) \delta(E - m_x) +$$

$$+ b^c(m_x) P_c(E, m_x)$$

$$P_c(E, m_x) = P\left(\frac{E}{m_x}\right) \sim$$

$$\sim \frac{1}{m_x} \left(\frac{E}{m_x}\right)^{-3/2} e^{-7.8 E/m_x}$$

## Background

$$dN(x,t) = G(x) R(t) dx dt - \text{direct integration}$$

$$N_0 = \int [1 - \psi(x,t)] G(x) R(t) dx dt \quad \psi = \begin{cases} 0 & x \in \Omega(t) \\ 1 & x \notin \Omega(t) \end{cases}$$

$$dN_{\text{out}}(x,t) = \psi(x,t) G(x) R(t) dx dt$$

$x$  - local coordinate

$$\psi = \begin{cases} 0, & x \in \bar{\Omega} \\ 1, & x \notin \bar{\Omega} \end{cases}$$

$$\Omega(t) \subset \bar{\Omega} \quad \forall t$$

$$\left\{ \begin{aligned} N_{\text{out}}(x) &= G(x) \int \psi(x,t') R(t') dt' \\ R_{\text{out}}(t) &= R(t) \int \psi(x',t) G(x') dx' \end{aligned} \right.$$

$$d(x) = \frac{N_0(x)}{N_{\text{out}}(x)} = \frac{\int [1 - \psi(x,t)] R(t) dt}{\int \psi(x,t) R(t) dt}$$

Li Ma statistic:

$$\bar{U} = \frac{\sum_x N_S(x) - \sum_x N_0(x)}{\sqrt{\sum_x d(x) N_S(x) + \sum_x N_0(x)}} =$$

$$= \frac{N_S - N_0}{\sqrt{\sum_x d(x) N_S(x) + N_0}}$$

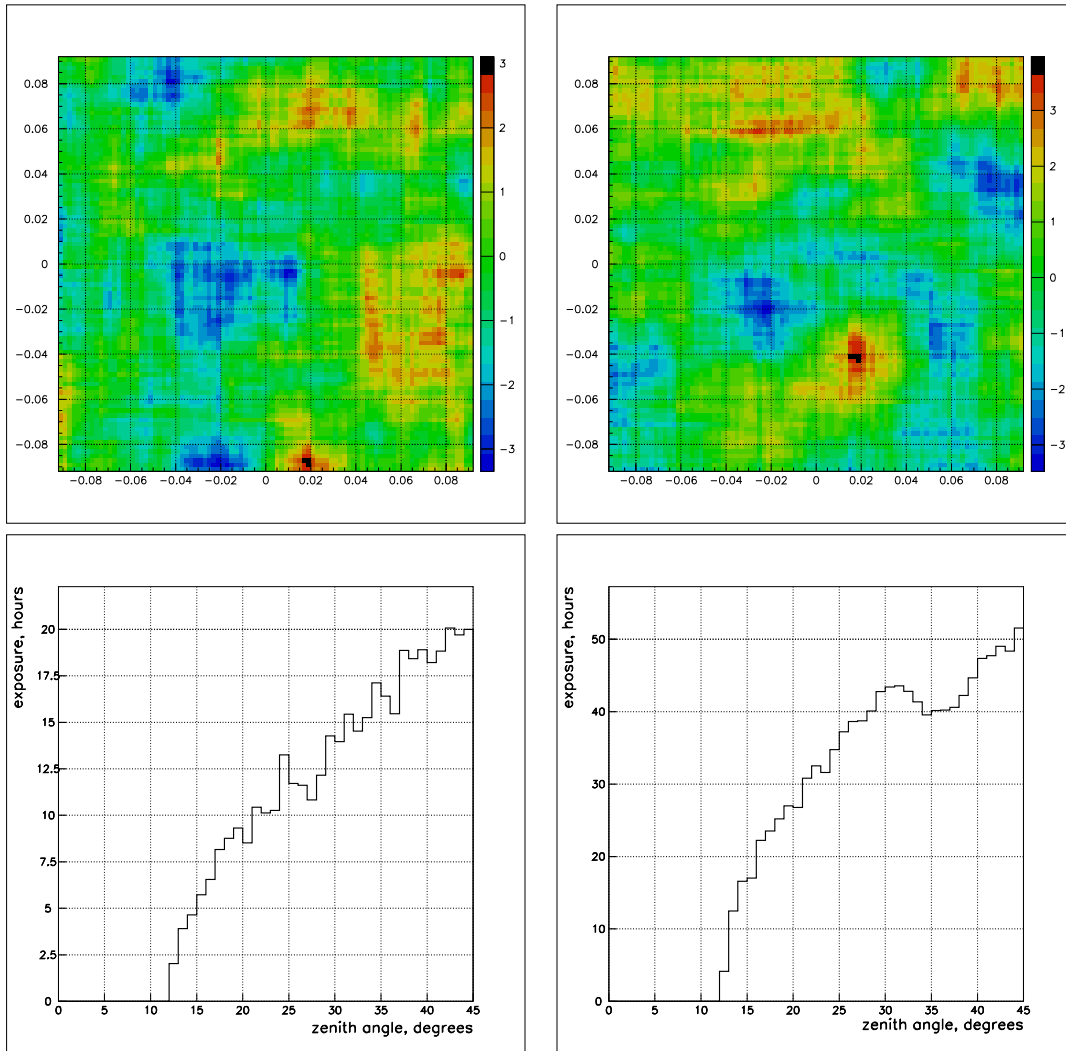


Figure 1: Significance maps of the regions of the sky around the daytime Moon(left) and the Sun(right) and the corresponding source exposure as function of zenith angle in hours per degree. The color code is the number of sigmas.

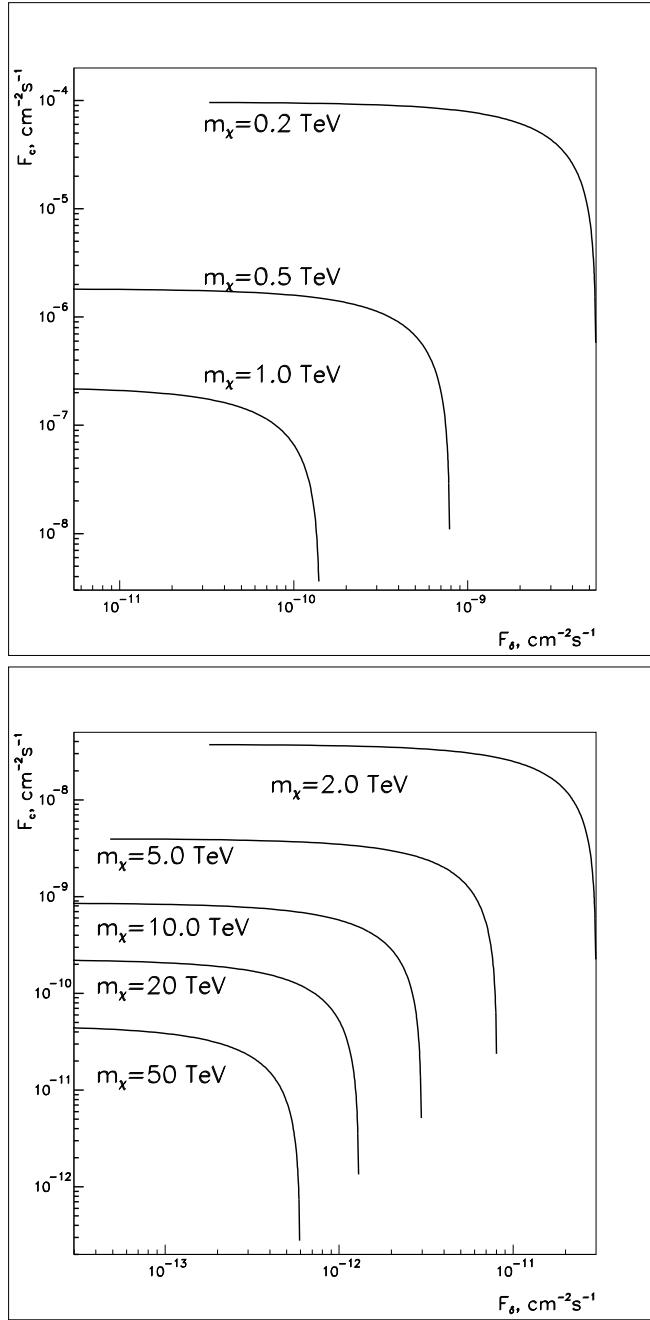


Figure 2: The values of  $(F_\delta, F_c)$  below the lines are allowed based the constructed limit for corresponding neutralino masses.

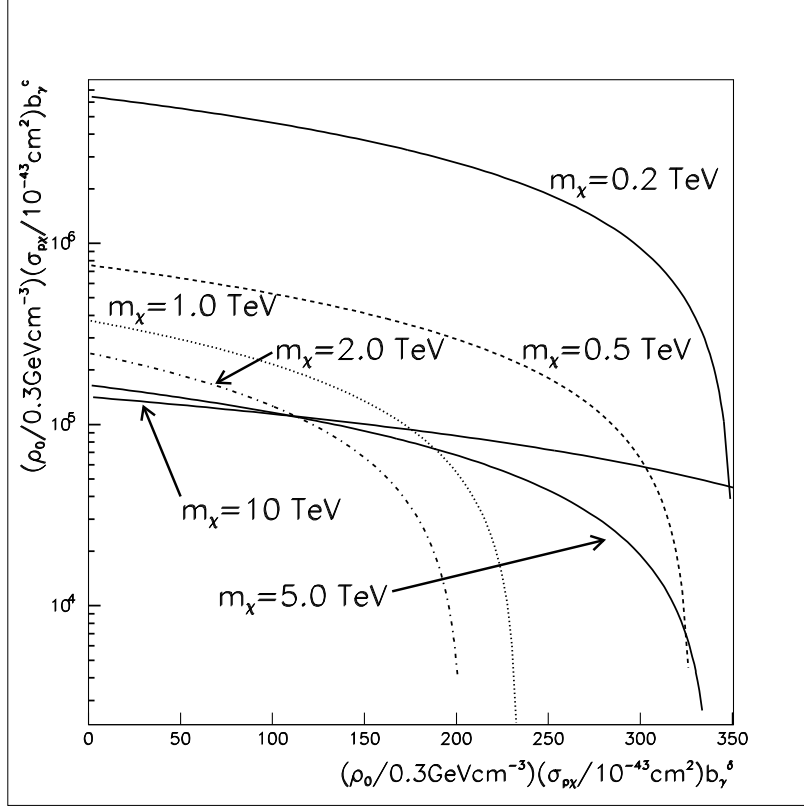


Figure 3: The values of  $(\rho_0 \sigma_{p\chi} b_\gamma^\delta, \rho_0 \sigma_{p\chi} b_\gamma^\epsilon)$  below the lines are allowed based the constructed limit for corresponding neutralino masses.