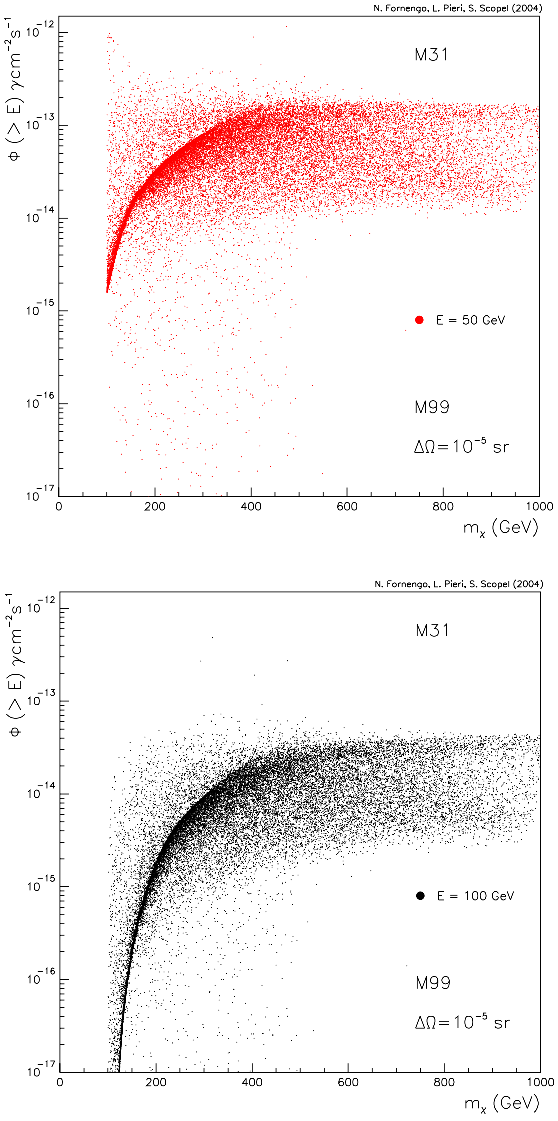

FIG. 10 (color online). Integrated gamma-ray fluxes from neutralino annihilation in M31, for an M99 density profile and inside a solid angle $\Delta\Omega = 10^{-5}$ sr. Two representative threshold energies have been assumed: 50 GeV (upper panel) and 100 GeV (lower panel).

the order of a few 10^{-13} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In the case of an M99 density profile toward the galactic center, the fluxes are increased by a factor of about 160, as can be deduced from Fig. 3. In this case the maximal fluxes can reach the level of 10^{-10} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. If the detector threshold energy is increased to 100 GeV the gamma-ray fluxes are 1 order of magnitude smaller. Finally, as a consequence of the previously discussed property of Φ^{SUSY}, we see that for neutralino masses heavier than about 500 GeV the supersymmetric models we are considering provide gamma-ray fluxes inside a band with a lower limit of a few 10^{-14} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, for an NFW97 profile. Obviously, if we enlarge the allowed intervals for the MSSM parameters (our definitions are given in Sec. IV), lower gamma-ray fluxes can be obtained also for heavy neutralinos. However, if we consider natural mass scales for the supersymmetric model, which means that we should not increase the scale of the mass parameters of the model much over the TeV scale, Fig. 9 shows the level of the lower limit on the gamma-ray flux for heavy neutralinos.

Also the Andromeda Galaxy can provide gamma-ray fluxes of the order of 10^{-12}–10^{-13} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ inside a solid angle of $\Delta\Omega = 10^{-5}$ sr, but only for an M99 density profile. These values therefore represent the maximal fluxes which can be produced by neutralino annihilation in M31. We remind that although the galactic center is much brighter for the same density profile, M31 can be resolved over the galactic gamma-ray signal due to its location at $\psi = 119°$, as is shown in Fig. 2.

In the following we will compare our expected fluxes with the sensitivity curves of foreseeable experiments.

B. Detectability of photon fluxes from neutralino annihilation

We have considered two platforms of observations of γ rays from neutralino annihilation, corresponding to a Čerenkov apparatus with the characteristics of VERITAS [1] and to a satellite-borne experiment similar to GLAST [4]. The detectability of the diffuse flux from DM annihilation is computed by comparing the number n_γ of expected γ events with the fluctuations of background events n_{bkg}. To this purpose we define the following ratio σ given by:

$$\begin{aligned}\sigma &\equiv \frac{n_\gamma}{\sqrt{n_{\mathrm{bkg}}}}\\ &= \frac{\sqrt{T_\delta}\,\epsilon_{\Delta\Omega}}{\sqrt{\Delta\Omega}}\,\frac{\int A_\gamma^{\mathrm{eff}}(E,\theta)[d\phi_\gamma^{\mathrm{DM}}/dEd\Omega]dEd\Omega}{\sqrt{\int\sum_{\mathrm{bkg}} A_{\mathrm{bkg}}^{\mathrm{eff}}(E,\theta)[d\phi_{\mathrm{bkg}}/dEd\Omega]dEd\Omega}}\end{aligned} \tag{12}$$

where T_δ defines the effective observation time and ϕ_{bkg} is the background flux. For a Čerenkov apparatus, for instance, it is defined as the time during which the source is seen with zenith angle $\theta \leq 60°$. The quantity $\epsilon_{\Delta\Omega} = 0.7$ is the fraction of signal events within the optimal solid angle $\Delta\Omega$ corresponding to the angular resolution of the instrument. The effective detection areas A^{eff} for electromagnetic and hadronic induced showers are defined as the detection efficiency times the geometrical detection area. For the case of a Čerenkov apparatus we have assumed a conservative effective area $A^{\mathrm{eff}} = 4 \times 10^8$ cm^2, while for a satellite experiment we have considered $A^{\mathrm{eff}} = 10^4$ cm^2. Both values have been assumed independent from E and θ. Note that while the former can be increased by adding together more Čerenkov telescopes, the latter is intrinsically limited by the size of the satellite and cannot be much greater than the fiducial value quoted here. Finally we have assumed an angular resolution of 0.1°

for both instruments, and a total effective pointing time of 20 days for the Čerenkov telescope and 30 days for the experiment on satellite. An identification efficiency ϵ must be taken into account, which is one of the most important factors which have to be studied in order to reduce the physical background level. A Čerenkov apparatus has a typical identification efficiency for electromagnetic induced (primary γ or electron) showers $\epsilon_{\mathrm{e.m.}} \sim 99\%$ and for hadronic showers $\epsilon_{\mathrm{had}} \sim 99\%$. This means that only one hadronic shower out of 100 is misidentified as an electromagnetic shower. Unfortunately, this method cannot distinguish between primary photons and electrons, which therefore represent an irreducible background for ground-based detectors. As far as a satellite-borne experiment is concerned, an identification efficiency for charged particles of $\epsilon_{\mathrm{charged}} \sim 99.997\%$ can be assumed, while for photons it lowers to $\epsilon_{\mathrm{neutral}} \sim 90\%$ due to the backsplash of high energy photons [62].

We have considered the following values for the background levels. For the proton background we use [63]:

$$\frac{d\phi^h}{d\Omega dE} = 1.49 E^{-2.74} \frac{p}{\mathrm{cm^2\,s\,sr\,GeV}}, \tag{13}$$

while for the electron background [64]:

$$\frac{d\phi^e}{d\Omega dE} = 6.9 \times 10^{-2} E^{-3.3} \frac{e}{\mathrm{cm^2\,s\,sr\,GeV}} \tag{14}$$

and finally for the Galactic photon emission, as extrapolated by EGRET data at lower energies, we employ [13]:

$$\frac{d\phi^{\mathrm{gal}-\gamma}_{\mathrm{diffuse}}}{d\Omega dE} = N_0(l, b) 10^{-6} E_\gamma^\alpha \frac{\gamma}{\mathrm{cm^2\,s\,sr\,GeV}}, \tag{15}$$

with α set to -2.7 in the considered energy range, with lack of data for energies higher than tens of GeV. The normalization factor N_0 depends only on the interstellar matter distribution, and is modeled as [13]:

$$N_0(l, b) = \frac{85.5}{\sqrt{1 + (l/35)^2}\sqrt{1 + [b/(1.1 + |l| 0.022)]^2}} + 0.5 \tag{16}$$

for $|l| \geq 30°$ and

$$N_0(l, b) = \frac{85.5}{\sqrt{1 + (l/35)^2}\sqrt{1 + (b/1.8)^2}} + 0.5 \tag{17}$$

for $|l| \leq 30°$, where the longitude l and the latitude b are assumed to vary in the intervals $-180° \leq l \leq 180°$ and $-90° \leq b \leq 90°$, respectively. Finally, for the diffuse extragalactic γ emission, as extrapolated from EGRET data at lower energies [65], we use:

$$\frac{d\phi^{\mathrm{extra}-\gamma}_{\mathrm{diffuse}}}{d\Omega dE} = 1.38 \times 10^{-6} E^{-2.1} \frac{\gamma}{\mathrm{cm^2\,s\,sr\,GeV}}. \tag{18}$$

If a galactic origin of high galactic latitude γ emission is considered, then this last estimate should be increased by about 60% [66].

Figure 11 shows the five σ sensitivity curves for the experimental apparata discussed above. Because of the different γ backgrounds, the curves are slightly different in the direction of the galactic center or toward the M31

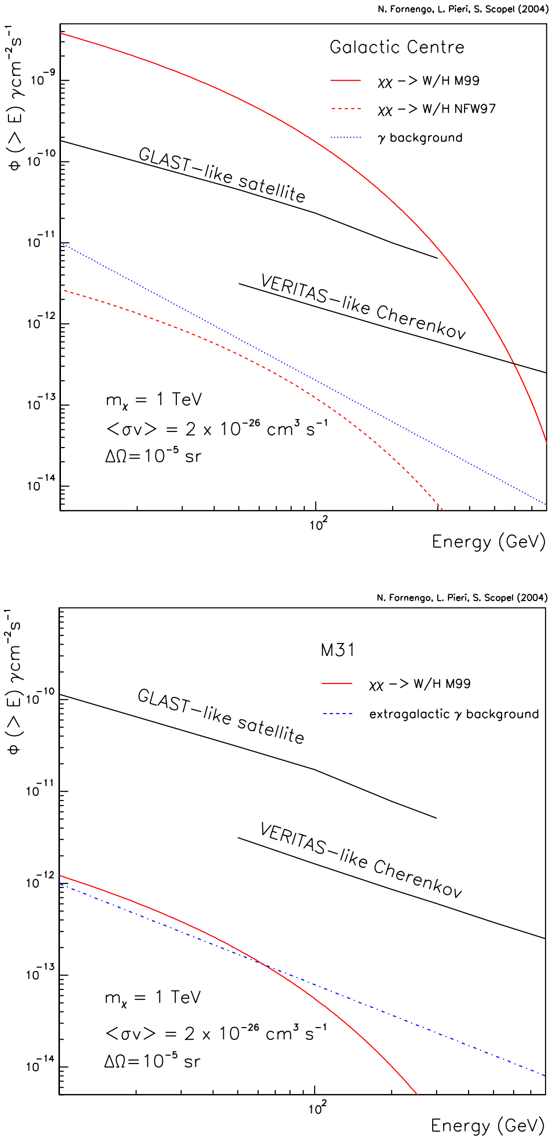

FIG. 11 (color online). Study of the sensitivity of an ACT detector and a satellite-borne experiment to photon fluxes from a TeV neutralino annihilation. Solid lines denote the 5σ sensitivity curves for satellite and Čerenkov detectors. These curves have been calculated according to the prescriptions given in the text. The flux expected from the galactic center with an NFW97 and an M99 profile are shown in the upper panel. The flux from M31 with an M99 profile is shown in the lower panel. Photon fluxes are given for $\Delta\Omega = 10^{-5}$ sr, which is the typical detector acceptance.

galaxy. Also plotted for reference is the expected integrated γ-ray flux for a SUSY model with $m_\chi = 1$ TeV, 50% branching ratio of annihilation into W bosons and 50% into Higgs bosons (following the results of Fig. 6 for the branching ratios of high mass neutralinos), and an annihilation cross section of 2×10^{-26} cm^3 s^{-1} which refers to the most optimistic values of Figs. 9 and 10. Because of our discussion in the previous section on the properties of $\Phi^{\rm SUSY}$, one could then consider the curve of γ-ray flux from neutralino annihilation which we show in Fig. 11 as the highest spectrum of a range of curves given by the spread of points in Figs. 9 and 10.

From Fig. 11 and our previous discussion on the cosmological and supersymmetric factor it therefore arises that signals from extragalactic objects could hardly be detected. The gamma-ray spectrum calculated for an M99 profile is 2 orders of magnitude smaller than the expected sensitivities we estimate for detectors like GLAST and about 1 order of magnitude smaller than the estimated sensitivity of VERITAS. We also notice that the most optimistic prediction for the flux we are showing in Fig. 11 is at the level of the extrapolated background, a fact which by itself would make problematic the observation of a signal from M31. Only in the very optimistic case of a clumpy M99 matter density, would the expected signal exceed the extrapolated background, but it would nevertheless remain inaccessible.

In the case of a signal from the galactic center, a density profile as cuspy as M99 (or the adiab-NFW) could be resolved by both a satellite detector like GLAST and a Čerenkov telescope with the characteristics of VERITAS. In the case of an NFW97 profile, a potential signal would not be accessible. Therefore, in the case of the signal from the galactic center a density profile harder than NFW97 is required in order to have a signal accessible to GLAST-like and VERITAS-like detectors.

C. Comparison with recent data

Recent experimental data taken from CANGAROO-II [6] in the direction of the galactic center show that the spectral shape of photons from the galactic center is in excess of the extrapolated background from standard processes. Figure 12 shows the CANGAROO-II data in the right panel, and the EGRET data [5] at lower energies in the left panel. We have superimposed on the data the γ-ray background used in our previous analysis, as well as the predicted γ-ray spectra from high mass neutralino annihilation, for the NFW97 and the M99 profiles. These spectra have been normalized within a solid angle coherent with the observations. We can see that not even an M99 profile can reproduce the observed data, as already observed in Ref. [67]. Figure 13 reproduces the same information of Fig. 12, but the cosmological factor has been enhanced by a factor 2.5 (equivalently, one could think to an enhancement in the supersymmetric factor, but this is not possible in the effective MSSM, neither in more constrained minimal SUGRA models which usually provide annihilation cross sections smaller than the effective MSSM). However, in the case of a DM pull-in induced by the presence of baryons, an M99 profile could easily account for the CANGAROO-II data. We can also see that, when appropriately boosted, the signals from annihilation of neutralinos with mass higher than 1 TeV have the property of matching the observed CANGAROO-II data and not being in conflict with the EGRET data.

On the other hand, Fig. 12 shows that it is not possible to explain at the same time both the EGRET excess in the 1–20 GeV energy range and the CANGAROO-II flux at energies above 250 GeV with the spectral shape of a gamma-ray flux from neutralino annihilation. While the EGRET spectrum can be well explained by a light neutralino in a nonuniversal gaugino model [7], with $m_\chi \sim$ 30–40 GeV, or by a neutralino of about 50–60 GeV [68]

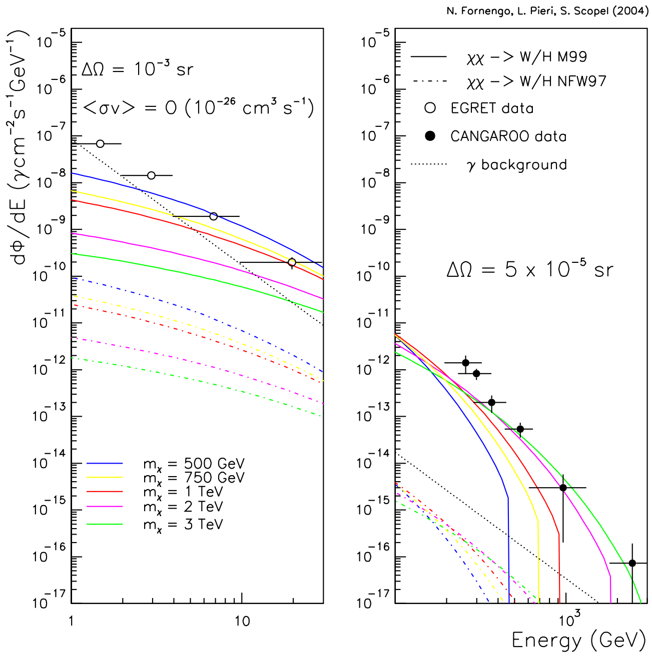

FIG. 12 (color online). Differential spectrum of the photon flux expected from neutralino annihilation in the galactic center. A 50% branching ratio into W pairs and 50% into b quarks has been assumed. Solid lines represent the calculation for an M99 profile for different neutralino masses, while dash-dotted lines show the same spectra assuming an NFW97 profile. Dotted lines show the extrapolated γ-ray "conventional" background. Open circles (left panel) show the EGRET results on photon flux from the galactic center, while filled circles (right panel) show the recent data at higher energies from CANGAROO-II. Photon fluxes are given for the corresponding typical detector acceptance, that is for $\Delta\Omega = 10^{-3}$ sr in the left panel and for $\Delta\Omega = 5 \times 10^{-5}$ sr in the right panel.

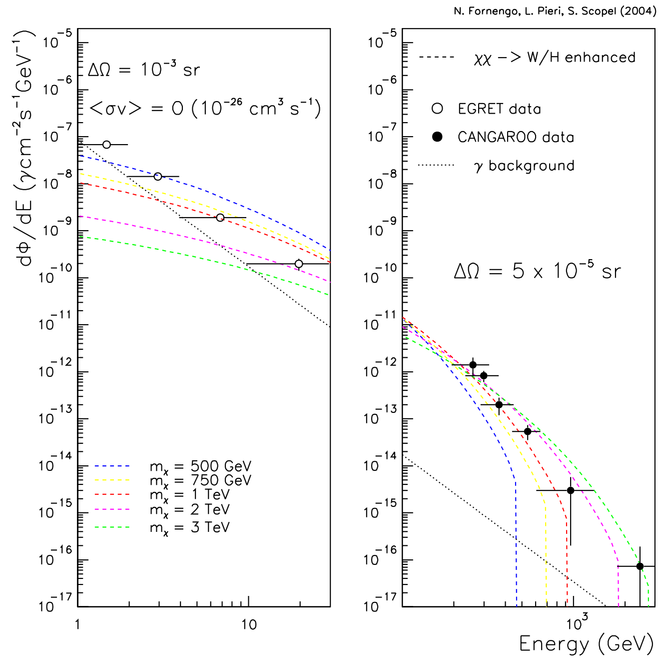

FIG. 13 (color online). The same as in Fig. 12 for an M99 profile multiplied by a factor 2.5 (dashed lines).

in the effective MSSM, the CANGAROO-II data require much heavier neutralinos in order to produce photons in the hundreds of GeV range: in this case, however, the ensuing gamma-ray spectra are too low in the 1–10 GeV range and cannot reproduce the EGRET data together with the CANGAROO-II ones.

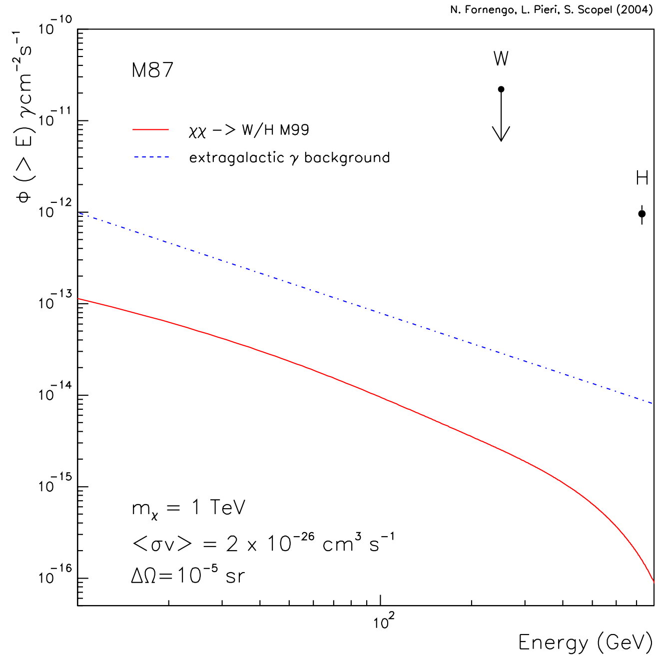

FIG. 14 (color online). Integrated photon flux as expected from a TeV neutralino annihilation in the M87 galaxy. Photon fluxes are given for $\Delta\Omega = 10^{-5}$ sr, which is the typical detector acceptance. Also shown in the figure is the upper limit determined by WHIPPLE [70] and the measurement from HEGRA [69].

We complete this section by applying our method to M87 and comparing our results with the measurements available for that galaxy, which show a possible indication of a γ-ray excess. This is shown in Fig. 14, where one can see that our predictions are well below the flux measured by HEGRA [69], even if an M99 profile is assumed. Not even a clumpy distribution, which could enhance the predicted fluxes by at most a factor of 5, would allow us to explain the HEGRA excess by means of neutralino annihilations in the effective MSSM.

VI. CONCLUSIONS

We have discussed the gamma-ray signal from dark matter annihilation in our Galaxy and in external objects, namely, the Large Magellanic Cloud, the Andromeda Galaxy (M31), and M87. The aim of our paper was to derive consistent predictions for the fluxes in a specific realization of supersymmetry, the effective MSSM, and to compare the predictions with the capabilities of new-generation satellite-borne experiments, like GLAST, and ground-based Čerenkov telescopes, for which we have used, for definiteness, the characteristics of the VERITAS telescope.

Our results show that only the signal from neutralino annihilation at the galactic center could be accessible to

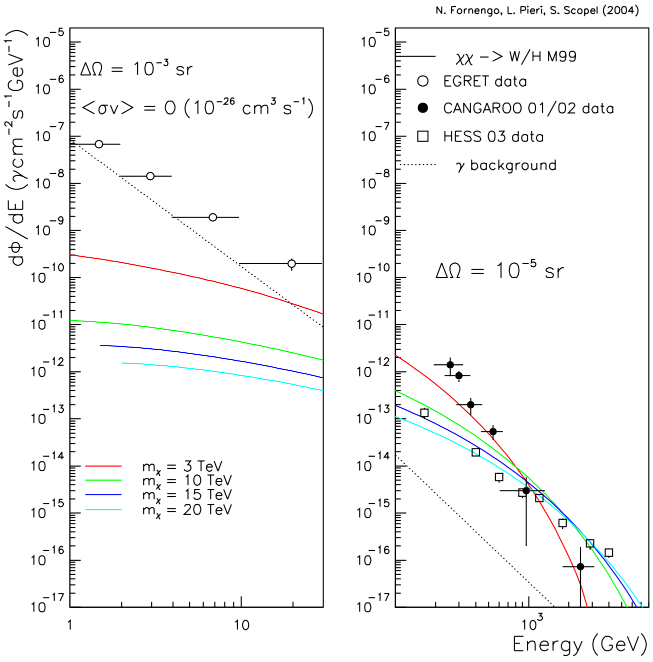

FIG. 15 (color online). The same as in Fig. 12, including the data from HESS [71] (see *Note Added* at the end of the paper). Photon fluxes are shown for neutralino masses up to 20 TeV and for an M99 density profile.

both satellite-borne experiments and to ACTs, even though this requires very steep dark matter density profiles toward the galactic center. A profile steeper than NFW97 is required in order to provide signals which can reach detectable levels. In the case of signals coming from external galaxies, even though the extragalactic signal is larger than the galactic contribution from neutralino annihilation, the absolute level of the flux is too low to allow detection with the experimental techniques currently under development.

We have also compared our theoretical predictions with the recent CANGAROO-II data from the galactic center and with the HEGRA data from M87. In both cases an indication of a gamma-ray excess is present. In the case of the CANGAROO-II data, the spectral shape is well reproduced by a gamma-ray flux from annihilation of neutralinos somewhat heavier than about 1 TeV, in agreement with Ref. [67]. However the overall normalization of the flux requires a boost factor of about 2.5 over the flux obtained with a Moore *et al.* profile: this seems hard to obtain even in the presence of clumps. On the other hand, we notice that in the case of a DM pull-in induced by the presence of baryons, as discussed in Sec. III A 2, the data could be easily explained by a Moore *et al.* profile, without the necessity to invoke strong clumpiness. We also showed that the agreement with the CANGAROO-II data which is obtained with these boosted fluxes is not in contrast with the lower-energy EGRET data from the galactic center. In addition we showed that the spectral features of such fluxes cannot explain at the same time both the CANGAROO-II and EGRET excess by invoking a very heavy neutralino. Finally, we compared our predictions for the signal from M87 with the HEGRA data and found that the predicted fluxes from neutralino annihilation are too low to explain the HEGRA result.

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Note added.—The HESS Čerenkov telescope [71] has recently published new data on gamma rays from the galactic center. The measured flux and spectrum differ substantially from previous results, in particular those reported by the CANGAROO Collaboration, exhibiting a much harder power-law energy spectrum, with spectral index of about -2.2. According to our analysis, these data, if interpreted in terms of neutralino annihilation, would require a neutralino mass in the range 10 TeV $\lesssim m_\chi \lesssim$ 20 TeV and an M99 profile for the DM distribution, as shown in Fig. 15.

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