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An analysis is carried out within mSUGRA of the estimated number of events originating from upward moving ultrahigh energy neutralinos passing through Earth's crust that could be detected by the Extreme Universe Space Observatory (EUSO). The analysis exploits a recently proposed technique that differentiates ultrahigh energy neutralinos from ultrahigh energy neutrinos using their different absorption lengths in the Earth's crust. It is shown that for the part of the parameter space, where the neutralino is mostly a *B*-ino and with squark mass ~ 1 TeV, EUSO could see ultrahigh energy neutralino events within mSUGRA models with essentially no background. In the energy range $10^9\ \mathrm{GeV} < E_{\tilde\chi} < 10^{11}$ GeV the unprecedented aperture of EUSO makes the telescope sensitive, after 3 yr of observation, to neutralino fluxes as low as $d\Phi/dE_{\tilde\chi} > 1.1 \times 10^{-6}\ (E_{\tilde\chi}/\mathrm{GeV})^{-1.3}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{yr}^{-1}\ \mathrm{sr}^{-1}$, at the 95% confidence limit (CL). Such a hard spectrum is characteristic of supermassive particles' *N*-body hadronic decay. The case in which the flux of ultrahigh energy neutralinos is produced via decay of metastable heavy ($m_X = 2\times 10^{12}$ GeV) particles with uniform distribution throughout the Universe, and primary decay mode into 5 quarks + 5 squarks, is analyzed in detail. The normalization of the ratio of the relics' density to their lifetime has been fixed so that the baryon flux produced in the supermassive particle decays contributes to about 1/3 of the events reported by the AGASA Collaboration below 10^{11} GeV, and hence the associated GeV γ-ray flux is in complete agreement with EGRET data. For this particular case, EUSO will collect between 4 and 5 neutralino events (with 0.3 of background) in ≈ 3 yr of running. NASA's planned mission, the Orbiting Wide-angle Light-collectors (OWL), is also briefly discussed in this context.

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I. INTRODUCTION

Minimal supergravity (mSUGRA) [1] and its extensions (generically called SUGRA models) are currently the leading candidates for physics beyond the standard model. These models contain a consistent mechanism for the breaking of supersymmetry softly by gravity mediation. An attractive feature of these models is that with *R* parity conservation the lightest neutralino is a possible candidate for cold dark matter [2] in a significant part of the mSUGRA parameter, space [3]. Further, over most of the parameter space the phenomenon of scaling occurs [3] so that the light neutralino is mostly the supersymmetric partner of the $U(1)_Y$ gauge boson B_μ, i.e., it is mostly a $U(1)_Y$ gaugino or a *B*-ino [3,4]. The parameter space of mSUGRA is characterized by the universal scalar mass, m_0, the universal gaugino mass, $m_{1/2}$, the universal trilinear coupling, A_0 (all taken at the grand unification scale $M_G \sim 2\times 10^{16}$ GeV), $\tan\beta = \langle H_2\rangle/\langle H_1\rangle$, where H_2 gives mass to the up quark, and H_1 gives mass to the down quark and the lepton. In addition the model contains the Higgs mixing parameter μ, which enters in the superpotential in the form $\mu H_1 H_2$. The magnitude of μ is determined by the constraint of radiative electroweak symmetry breaking in the theory while $\mathrm{sgn}\,\mu$ is arbitrary and must be constrained by experiment.

mSUGRA has been put to a stringent test by the recent precision data from the satellite experiment, the Wilkinson Microwave Anisotropy Probe (WMAP), which imposes a narrow range for cold dark matter (CDM) so that [5,6] $\Omega_{\mathrm{CDM}} h^2 = 0.1126^{+0.008}_{-0.009}$. The candidacy of neutralinos as the dark matter of the Universe is based on relic densities surviving annihilation processes of nonrelativistic particles. Detailed analyses show that mSUGRA allows for a small amount of the parameter space in agreement with WMAP observations [7]. As a consequence, the applicability of mSUGRA demands that the contribution of other sources of CDM to the dark matter mix is negligible. In this paper, we will be interested in a flux of ultrarelativistic neutralinos resulting from decays of a population of CDM metastable superheavy particles [8,9]. In concert with the previous statement, these particles should contribute negligibly to the dark matter density.

The weak couplings of neutralinos imply an interaction length in air that is greater than the atmospheric depth, even at horizontal incidence. The interaction probability is then roughly uniform throughout the atmosphere. As with neutrinos, showers initiated by neutralino primaries can be distinguished from hadronic events by restricting the zenith angle space to near horizontal—this maximizes the probability to detect showers of weakly interacting primaries, while screening out the electromagnetic component of hadronic showers that are initiated high in the atmosphere. However, deeply developing neutralino cascades cannot be isolated from neutrino-induced air showers.

In this paper we show that the part of the parameter space where the neutralino is mostly a *B*-ino and the mass $m_{\tilde q}$ of the first and second generation squarks is ~ 1 TeV can lead to ultrahigh energy neutralino signals that may be seen by the Extreme Universe Space Observatory (EUSO) [10,11].

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These two conditions are fully compatible with the WMAP constraint and the neutralino as lightest supersymmetric particle. Further, with appropriate cuts the background events arising from ultrahigh energy neutrinos are essentially negligible. We discuss now the details of the analysis.

The problem of discriminating between neutralino and neutrino-induced showers with space-based experiments has been examined recently [12]. The method makes use of the Earth as a filter. Specifically, in the region of the mSUGRA parameter space under consideration the cross section for the neutralino-nucleon interaction is smaller than that for neutrino-nucleon scattering processes. Thus, by restricting the angular bin for arrival of upward going showers to a region where neutrinos are largely absorbed during traversal in the Earth, it may be possible to obtain a clean signal [13]. In Ref. [12], the discussion was presented in terms of neutralino-nucleon cross sections parametrized as a series of constant fractions of the neutrino-nucleon cross section. In this paper, we first calculate the neutralino cross section in the squark-resonance approximation. We then proceed to estimate the sensitivity of EUSO to neutralino-induced air showers. The sensitivity will be characterized by a lower bound on the neutralino flux, which is then related to some particular models of *X*-particle decay.

II. EUSO OUTLINE

In view of a mission starting in 2006–2007, the Extreme Universe Space Observatory [10,11] has been designed to observe the complex relativistic cascades induced by the incoming extraterrestrial radiation using sensors in the ultraviolet band (300–400 nm), a technique pioneered by the Fly's Eye experiment [14]. The telescope will operate for more than 3 yr on board of the International Space Station. The eye will be equipped with wide-angle Fresnel optics lens that provide a field of view of $\pm 30°$, at an orbit altitude of about 400 km. The monocular stand-alone configuration of the instrument will cover an area of $\approx 1.6\times 10^5$ km^2, imaging an air target mass that exceeds 10^{12} tons. This corresponds to a water equivalent (w.e.) effective volume of ≈ 2400 km^3. Observations can only be done on clear moonless nights. Limitations associated with the cloud system and ultraviolet background sources result in an average 10%–15% duty cycle [11]. Hence, the incredibly large geometric aperture, $A\approx 7500$ km^3 w.e. sr, is somewhat reduced.

The fluorescence eye consists of several large light collectors (or telescopes) that image regions of the sky onto clusters of light sensing and amplification devices. The basic elements of a telescope are the diaphragm, which defines the telescope aperture, the spherical mirror that must be dimensioned to collect all the light entering the diaphragm in the acceptance angular range, and the camera, which consists of an array of photomultiplier tubes (PMTs) positioned approximately on the mirror focal surface. The PMTs effectively pixelize the region of the sky covered by the telescope. The shower development is detected as a long, rather narrow sequence of hit PMTs. As the pointlike image of the shower proceeds through an individual PMT, the signal rises, levels off, and falls again.

The sensitivity of the detector depends primarily on the signal (S) to noise (N) ratio [14],

$$\frac{S}{N}=\frac{N_e N_\gamma}{8\pi}\left(\frac{c}{\langle B\rangle}\right)^{1/2}\frac{\kappa_1\kappa_2}{R_p^{3/2}}\left(\frac{\epsilon D^3}{d}\right)^{1/2} \tag{1}$$

where $\langle B\rangle\approx 400$ m^{-2} sr^{-1} ns^{-1} is the average photon night glow background in the ultraviolet band [15], $\epsilon\approx 20\%$ is the quantum efficiency of the detector, $\kappa_1\approx 1$ is the transmission coefficient in the ozone layer, $\kappa_2=e^{-r/\lambda_R}$ is the transmission coefficient in the atmosphere, $\lambda_{\rm R}\approx 23$ km (at 400 nm) is the Rayleigh scattering length at sea level, R_p is the distance of closest approach between the shower and the detector, $r\approx 15$ km is the effective slant depth of the lower atmosphere, $D=2.5$ m is the diameter of the mirror aperture, and $d=5$ mm is the diameter of the PMT. The fluorescence trail is emitted isotropically with an intensity that is proportional to the number of charged particles in the shower, N_e. The fluorescent signal is roughly $N_\gamma\sim 4$ photons/(electron m) and $N_e\approx 0.625\,(E/\mathrm{GeV})$. This translates into a 4σ energy threshold of

$$E=2.7\times 10^6 R_p^{3/2}\exp(r/\lambda_R)\ \ \mathrm{GeV}. \tag{2}$$

In addition to the fluorescence process, the electrons produce a large photon signal from Čerenkov radiation that is primarily beamed in the forward direction. The production of fluorescence light is less than 10^{-4} of that in the Čerenkov cone [16]. For Earth-penetrating showers emerging upward in the direction of the orbiting telescope, this Čerenkov signal extends the 4σ threshold of EUSO to the PeV energy band.

III. CROSS SECTIONS

The cross section for the resonant scattering $\tilde\chi+q(\overline{q})\to\tilde q(\bar{\tilde q})\to$all [17],

$$\sigma_{\tilde\chi N}=\sum_{q\bar q}2\pi\int dx\,q(x)\frac{1}{4p_q\cdot p_{\tilde\chi}}\frac{1}{4}\sum_{\rm spin}|\mathfrak{M}|^2 \times\delta(2(p_q\cdot p_{\tilde\chi})-m_{\tilde q}^2), \tag{3}$$

where p_q and $p_{\tilde\chi}$ are the four-momenta of the quark and neutralino in the interaction,

$$\frac{1}{4}\sum_{\rm spin}|\mathfrak{M}|^2=\frac{1}{4}[|a_{q_{\rm L}}|^2+|a_{q_{\rm R}}|^2]m_{\tilde q}^2, \tag{4}$$

where we have included the contributions from the left-handed and right-handed squarks assuming they are degenerate. In the above the first sum runs over all quark flavors with parton distribution functions (pdf's) indicated by $q(x)$. For small L-R mixing, and ignoring quark masses and small Higgsino mixings, one has [18]

$$\frac{a_{u_L}}{\sqrt{2}} = (X_2 \cos\theta_W - X_1 \sin\theta_W)\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\frac{g_2}{\cos\theta_W} + \frac{2}{3}e(X_1\cos\theta_W + X_2 \sin\theta_W), \quad (5)$$

$$\frac{a_{u_R}}{\sqrt{2}} = \frac{2}{3}\frac{g_2}{\cos\theta_W}\sin^2\theta_W(X_2\cos\theta_W - X_1\sin\theta_W) + \frac{2}{3}e(X_1\cos\theta_W + X_2\sin\theta_W), \quad (6)$$

$$\frac{a_{d_L}}{\sqrt{2}} = (X_2 \cos\theta_W - X_1 \sin\theta_W)\left(\frac{1}{3}\sin^2\theta_W - \frac{1}{2}\right)\frac{g_2}{\cos\theta_W} - \frac{1}{3}e(X_1\cos\theta_W + X_2 \sin\theta_W), \quad (7)$$

$$\frac{a_{d_R}}{\sqrt{2}} = \frac{1}{3}\frac{g_2}{\cos\theta_W}\sin^2\theta_W(X_2\cos\theta_W - X_1\sin\theta_W) - \frac{1}{3}e(X_1\cos\theta_W + X_2\sin\theta_W) \quad (8)$$

and similar relations hold for the charm and the strange squarks. In Eqs. (5)–(8) g_2 is the weak SU(2) gauge coupling constant, θ_W is the weak mixing angle, $e = g_2 \sin\theta_W$ is the $U(1)_{em}$ charge, and X_1 and X_2 are the projection of $\tilde{\chi}$ on the B-ino and W-ino superpartners, respectively, and we have ignored small Higgsino components X_3 and X_4 where $\Sigma_{i=1}^4 |X_i|^2 = 1$. In the analysis we use renormalization group evolution of the soft parameters from the grand unification scale M_G to low energy to compute the neutralino mass matrix. This matrix depends on the sign of μ. The recent experiment on the anomalous magnetic moment of the muon [19] indicates a positive sign for μ for the supersymmetric contribution [20] and thus in this analysis we have chosen a positive μ sign. The diagonalization of the neutralino mass matrix determines the projections X_1, X_2, which are computed in terms of the input mSUGRA parameters. In the parameter space of interest, i.e., where $m_{\tilde{q}} \sim 1$ TeV, and the WMAP constraint is obeyed, the neutralino is essentially a B-ino, and one has $X_1 \simeq 1$ while X_2, X_3, X_4 are relatively small.

Through use of the parton model relation $2p_q \cdot p_{\tilde{\chi}} = 2xP_N \cdot p_{\tilde{\chi}}$ (P_N is the nucleon momentum) and the δ function, one finds the compact expression

$$\sigma = \frac{\pi}{4}\sum_{q\bar{q}} [|a_{q_L}|^2 + |a_{q_R}|]^2 \frac{1}{m_{\tilde{q}}^2} xq(x), \quad (9)$$

where, using the laboratory relation $p_N \cdot p_\chi = M_N E_\chi$, we now have

$$x = \frac{m_{\tilde{q}}^2}{2M_N E_\chi}. \quad (10)$$

We use the CTEQ6D pdf's [21], which in the energy region of interest for up, down, strange, and charmed quarks and antiquarks can be parametrized as

$$xq(x) \approx 0.152 x^{-0.382}, \quad \text{with } 10^{-6} < x < 10^{-4.7}. \quad (11)$$

Then, for

$$10^9\left(\frac{m_{\tilde{q}}}{1\ \text{TeV}}\right)^2 < \frac{E_{\tilde{\chi}}}{1\ \text{GeV}} < 10^{11.7}\left(\frac{m_{\tilde{q}}}{1\ \text{TeV}}\right)^2, \quad (12)$$

the neutralino-nucleon interaction cross section becomes

$$\sigma_{\tilde{\chi}N} = 1.73 \times 10^{-37}\left(\frac{1\ \text{TeV}}{m_{\tilde{q}}}\right)^{2.784}\left(\frac{E_{\tilde{\chi}}}{1\ \text{GeV}}\right)^{0.382} \times \sum_{q\bar{q}} [|a_{q_L}|^2 + |a_{q_R}|^2]\ \text{cm}^2. \quad (13)$$

We comment briefly on the relation of our calculation to a previous estimate [22]. In contrast to that work, we do not characterize the SUSY parameter space according to the decay branching ratio $\Gamma(\tilde{q} \to q\tilde{g})/\Gamma(\tilde{q} \to q\tilde{\chi})$. The total cross section, as given above, is independent of any branching to gluinos. Comparison of Eq. (13) with the cross section for the competing process $\tilde{\chi}g \to \tilde{q}q$ estimated in Ref. [22] shows that the resonant cross section is about an order of magnitude greater.

IV. EVENT RATES

The most popular mechanism to date to produce ultrahigh energy neutralinos is annihilation or decay of supermassive (10^{12} GeV $\lesssim m_X \lesssim 10^{16}$ GeV) X particles. To maintain an appreciable decay rate today, one has to tune the X lifetime to be longer (but not too much longer) than the age of the Universe [8,9], or else "store" short-lived X particles in topological vestiges of early Universe phase transitions [23]. The cascade decay to cosmic ray particles is driven by the ratio of the volume density of the X particle ($n_X = \rho_c \Omega_X / m_X$) to its decay time ($\tau_X$). This is very model dependent, as neither the cosmic average mass density contributed by the relics (Ω_X) nor τ_X is known with any degree of confidence ($\rho_c \approx 1.05 \times 10^{-4}$ h^2 GeV cm^{-3}, with $h \equiv$ Hubble constant in units of 100 km sec^{-1} Mpc^{-1}). Moreover, the internal mechanisms of the decay and the detailed dynamics of the first secondaries do depend on the exact nature of the particles. Consequently, no firm prediction on the expected flux of neutralinos can be made. However, if there are no new mass scales between $M_{SUSY} \sim 1$ TeV and m_X, the squark and sleptons would behave like their corresponding supersymmetric partners, enabling one to infer from the "known" evolution of quarks and leptons the gross features of the X-particle cascade: the quarks hadronize, producing jets of hadrons containing mainly pions together with

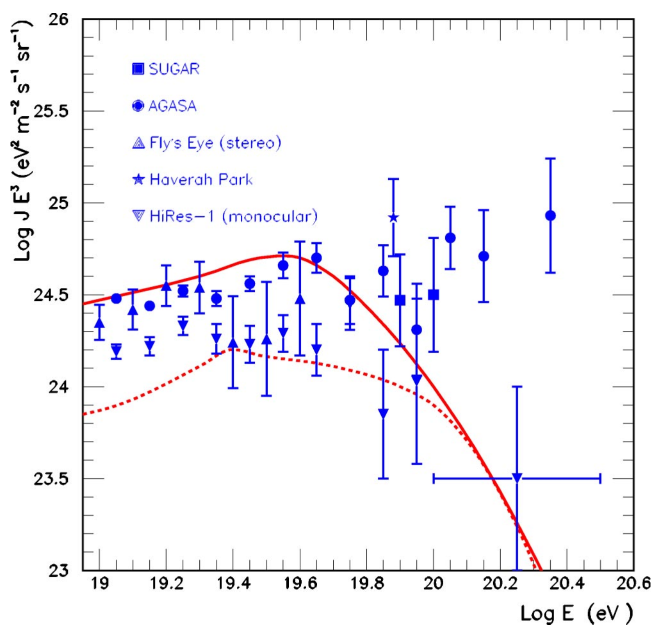

FIG. 1. The solid line is a 2-component prediction of the ultrahigh energy proton flux, consisting of emission from ultrahigh energy ''stars'' plus decay of super heavy relics, both sources distributed uniformly throughout the universe [30]. The dashed line indicates the contribution from the X decay, with initial state of 5 quarks + 5 squarks and $m_X = 2\times10^{12}$ GeV. The upper end of the spectrum as seen by different experiments (AGASA [29], HiRes [31], Fly's Eye [32] SUGAR [33], and Haverah Park [34]) is also shown for comparison.

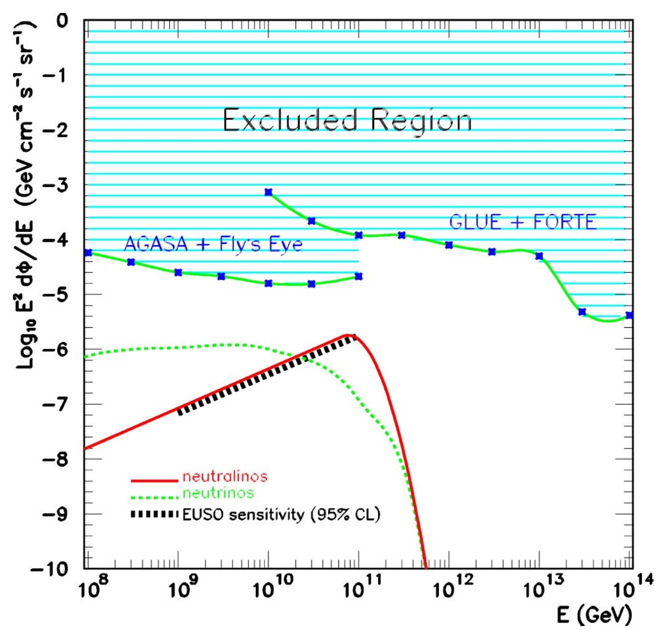

FIG. 2. The solid (dashed) line indicates the neutralino [12] (neutrino plus antineutrino [30]) energy spectrum corresponding to the proton flux from X-particle decay given in Fig. 1. The horizontally hatched region at the top of the figure has been already excluded from null results at AGASA+Fly's Eye (95% CL) [35] and GLUE+FORTE (90% CL) [36]. The thick dashed line indicates the 95% CL sensitivity of the EUSO mission.

a 3% admixture of nucleons [24]. The final spectrum is then dominated by γ rays and neutrinos produced via pion decay.

In light of the mounting evidence that ultrahigh energy cosmic rays are not γ rays [25], proton dominance at ultrahigh energies is achieved by efficient absorption of the dominant ultrahigh energy photon flux on the universal and/or Galactic radio background. This results in a recycling of the photon energy down to the MeV-GeV region. Thus, since the baryon and photon components of the X-particle decay are correlated by the dynamics, the measurement of the GeV diffuse γ ray flux can significantly constrain the cosmic ray production by X particles, integrated over the redshift [26]. In this direction, the new EGRET limits [27] on the photon flux in the GeV region have severely limited [28] the contribution of X-particle decay to the high energy end of the cosmic ray spectrum reported by the AGASA Collaboration [29].

In our analysis we adopt the recent estimates of neutralino fluxes from decay of superheavy relics derived in Ref. [12]. The normalization is determined by matching the X-particle baryon flux to the difference between the observed spectrum at $E\approx10^{11}$ GeV and contributions from a homogeneous population of astrophysical sources. Among the homogeneous models discussed in Ref. [12], the only one to accommodate both the ultrahigh energy cosmic ray intensity and the GeV photon flux is a distribution of X particles with $m_X\approx2\times10^{12}$ GeV and primary 10-body decay $X\rightarrow5q\ 5\tilde{q}$. As can be seen in Fig. 1, this model is constrained to fit only the AGASA data below 10^{11} GeV, with the baryonic flux from X decay contributing less than 1/3 of the total [30]. It is noteworthy that the associated flux of neutrinos from $\pi^\pm$ decay produced in this scenario is also consistent with existing data. This is shown in Fig. 2.

As mentioned in the Introduction, in order to comply with existing fits of mSUGRA to the WMAP dark matter density, the contribution to this density from superheavy relics must be much less than that of the relic neutralinos. We recall that the cosmic ray flux resulting from X-particle decays depends on the dimensionless parameter $r_X\equiv\xi_X t_0/\tau_X$, where $\xi_X=\Omega_X/\Omega_{\rm CDM}$, and t_0 is the age of the universe. Scenarios which include in the rate normalization photon flux from X particles clustered in the halo lead to a value $r_X\sim5\times10^{-11}$ [8]. Omission of the photon channel in the normalization increases r_X by a factor of about 10, and the extension from halo dominance to the homogeneous population used in this work further increases r_X by a factor of 15. Since models of X production and decay typically lead to exponential dependence of both ξ_X and τ_X on a reheating temperature T_R and a quantum mechanical tunneling action, respectively, there is no impediment on accommodating this change in r_X while maintaining $\Omega_X\ll\Omega_{\rm CDM}$. (For example, for the model provided in Ref. [8], $\xi_X\propto e^{-2m_X/T_R}\sim10^{-4}-10^{-8}$.)

Establishing a neutralino signal in upward going showers will require suppression of neutrino events that create a background. This occurs naturally because the difference in neutrino and neutralino cross sections leads to differing absorption lengths in the Earth's crust. The neutrino flux is greatly attenuated by selecting events entering the Earth at

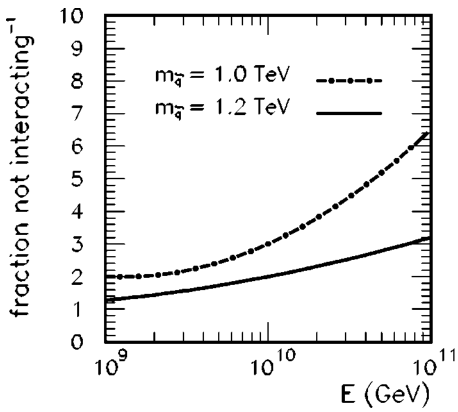

FIG. 3. Fraction of neutralinos that traverse the Earth, for all zenith angles less than 85°, as a function of energy.

angles $>5°$ below the horizon. For the EUSO effective aperture (duty cycle of 10%), the neutrino background from a homogeneous population of X's decaying into $5q\ 5\tilde{q}$ (during the 3-yr mission lifetime) is about 0.3 events [37]. The use of Poisson statistics implies the observation of $\geqslant 3.09$ events establishes a signal significance at 95% CL [38].

The determination of a neutralino event rate will depend strongly on the neutralino-nucleon cross section, and hence, through Eq. (13), on the squark mass. Let us define P as the probability that the neutralino does not interact while traversing the Earth's crust. A large cross section will reduce P and lead to a lowering of emerging flux. In Fig. 3 we illustrate the behavior of P with energy, for two different values of $m_{\tilde{q}}$. On the other hand, it will enhance the event rate in the atmosphere for the neutralinos that do emerge without interacting. (Conservatively, we omit regeneration effects in the Earth when estimating a signal.) Apart from the direct effect on the size of the cross section, the squark mass will also influence the event rate through the position of the resonant peak: A larger squark mass will probe higher value of $E_{\tilde{\chi}}$, and hence lead to a decrease in event rate because of the sharply falling flux. After considering these effects, we have found that a value of $m_{\tilde{q}} \simeq 1$ TeV leads to an optimal signal. The degree of tolerance is fairly narrow: Values lower than 800 GeV or larger than 1200 GeV will vitiate a signal at 95% CL We note once more that this coincides with the region of B-ino dominance for the parameter space compatible with WMAP data [7].

For a given flux of neutralinos $d\Phi/dE_{\tilde{\chi}}$ and observation time t, the event rate at EUSO is found to be

$$\mathcal{N} = \int_{E_{\tilde{\chi}}^{\min}}^{E_{\tilde{\chi}}^{\max}} dE_{\tilde{\chi}} N_A P \frac{d\Phi}{dE_{\tilde{\chi}}} \sigma_{\tilde{\chi}N} A \epsilon_{\rm DC} t, \quad (14)$$

where N_A is Avogadro's number and $\epsilon_{\rm DC} \approx 10\%$ is the duty cycle. The fraction of unscathed neutralinos, integrated over zenith angle $<85°$, emerging upward in the direction of the orbiting telescope, is found to be $P \approx 107\ (E_{\tilde{\chi}}/\text{GeV})^{-0.256}$. Now, by setting $E_{\tilde{\chi}}^{\min} = 10^9$ GeV and $E_{\tilde{\chi}}^{\max} = 10^{11}$ GeV, one finds that for the full mission lifetime EUSO will typically collect between 4 and 5 events, and hence provide sensitivity to the neutralino flux given in Fig. 2 at more than 95% CL.

V. CONCLUSIONS

Using a technique that exploits the different absorption lengths of neutrinos and neutralinos in the Earth's crust, we have estimated the sensitivity of EUSO to isolate upward coming showers of ultrahigh energy $\tilde{\chi}$. The neutralino-nucleon interaction has been approximated by resonant squark production, with the neutralino being largely B-ino in composition, and $m_{\tilde{q}} \simeq 1$ TeV. We have shown that, during the complete mission lifetime, the telescope will be sensitive to $E_{\tilde{\chi}}^2\ d\Phi/dE_{\tilde{\chi}} > 1.1 \times 10^{-6}\ (E_{\tilde{\chi}}/\text{GeV})^{0.7}$ GeV cm^{-2} yr^{-1} sr^{-1} at the 95% CL, for 10^9 GeV$<E_{\tilde{\chi}}<10^{11}$ GeV, and for the region $m_{\tilde{q}} = 1.0 \pm 0.2$ TeV. A hard spectrum $\propto E_{\tilde{\chi}}^{-1.3}$ is typical of superheavy relic N-body decays that are purely hadronic. This is a conservative estimate, since regeneration effects have been only considered in computing the neutrino background. We have explicitly analyzed the case in which the flux of ultrahigh energy neutralinos is produced via decay of metastable heavy ($m_X = 2 \times 10^{12}$ GeV) particles with uniform distribution throughout the Universe, and primary decay mode into 5 quarks + 5 squarks. The normalization of n_X/τ_X has been fixed to contribute about 1/3 of the events reported by the AGASA Collaboration below 10^{11} GeV [29]. For this particular case, EUSO will collect between 4 and 5 neutralino events (with 0.3 of background) in ≈ 3 yr of running.

Existing limits on the diffuse photon flux in the GeV region strongly limit the sensitivity of EUSO for primary 2-body decays of hadronic nature. This is because, for the normalization of the baryonic contribution to the ultrahigh energy cosmic ray flux assumed in Ref. [12], which is marginally consistent with new EGRET bounds, the accompanying neutralino flux produced for $q\overline{q}$ and $q\tilde{q}$ is about an order of magnitude below the flux generated in the primary 10-body decay discussed above. On the other hand, the telescope can still be sensitive to the leptonic mode $X \to l\tilde{l}$. In this case, by reducing n_X/τ_X by a factor of ~ 2, one lessens the problem with EGRET data and still leaves a window open for neutralino detection at EUSO.

We note that for a B-ino-like neutralino, the primary decay mode (90% branching fraction) of the squark is $\tilde{q} \to q\tilde{g}$, with a subsequent decay $\tilde{g} \to q\overline{q}\tilde{\chi}$. Thus, the neutralino energy of the decay is about 1/6 of the primary energy. In the remaining 10% of the decays, $\tilde{q} \to q\tilde{\chi}$. In either case, the shower energies are far above the ~ 1 PeV threshold for the detector. If more detailed considerations are warranted in the future, regeneration effects during passage through Earth can be assessed, taking into account the energy losses of the decay modes. These effects will lead to some enhancement of P, and consequently of the event rate.

We turn now to a brief discussion on the potential of the planned NASA mission Orbiting Wide-angle Light-collectors

(OWL) [39]. This mission will involve photodetectors mounted on two satellites in low equatorial orbit (600–1200 km). The eyes of the OWL will stereoscopically image a geometric area of $\sim 9\times 10^5$ km^2, yielding $A\sim 3\times 10^6$ km^2 sr. With its superior effective aperture ($\epsilon_{DC}\approx 10\%$), a 10 yr mission lifetime will allow one to discern the contributions of metastable relics to the upper end of the cosmic ray spectrum at the level of 1 part in 10^2. Consequently, the data from this mission will allow one to probe more deeply the parameter space of mSUGRA and its extensions.

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[1] A.H. Chamseddine, R. Arnowitt, and P. Nath, Phys. Rev. Lett. **49**, 970 (1982); R. Barbieri, S. Ferrara, and C.A. Savoy, Phys. Lett. **119B**, 343 (1982); L. Hall, J. Lykken, and S. Weinberg, Phys. Rev. D **27**, 2359 (1983); P. Nath, R. Arnowitt, and A.H. Chamseddine, Nucl. Phys. **B227**, 121 (1983). For a recent review see P. Nath, hep-ph/0307123.

[2] H. Goldberg, Phys. Rev. Lett. **50**, 1419 (1983); J.R. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive, and M. Srednicki, Nucl. Phys. **B238**, 453 (1984).

[3] R. Arnowitt and P. Nath, Phys. Rev. Lett. **69**, 725 (1992); Phys. Lett. B **289**, 368 (1992).

[4] R.G. Roberts and L. Roszkowski, Phys. Lett. B **309**, 329 (1993).

[5] C.L. Bennett *et al.*, Astrophys. J., Suppl. Ser. **148**, 1 (2003).

[6] D.N. Spergel *et al.*, Astrophys. J., Suppl. Ser. **148**, 175 (2003).

[7] J.R. Ellis, K.A. Olive, Y. Santoso, and V.C. Spanos, Phys. Lett. B **565**, 176 (2003); H. Baer and C. Balazs, J. Cosmol. Astropart. Phys. **05**, 006 (2003); U. Chattopadhyay, A. Corsetti, and P. Nath, Phys. Rev. D **68**, 035005 (2003); A.B. Lahanas and D.V. Nanopoulos, Phys. Lett. B **568**, 55 (2003); H. Baer, T. Krupovnickas, and X. Tata, J. High Energy Phys. **07**, 020 (2003).

[8] V. Berezinsky, M. Kachelriess, and A. Vilenkin, Phys. Rev. Lett. **79**, 4302 (1997).

[9] V.A. Kuzmin and V.A. Rubakov, Yad. Fiz. **61**, 1122 (1998) [Phys. At. Nucl. **61**, 1028 (1998)]; Z. Fodor and S.D. Katz, Phys. Rev. Lett. **86**, 3224 (2001); C. Coriano, A.E. Faraggi, and M. Plumacher, Nucl. Phys. **B614**, 233 (2001); S. Sarkar and R. Toldra, *ibid.* **B621**, 495 (2002); P. Blasi, R. Dick, and E.W. Kolb, Astropart. Phys. **18**, 57 (2002); C. Barbot and M. Drees, Phys. Lett. B **533**, 107 (2002); P. Jaikumar and A. Mazumdar, Phys. Rev. Lett. **90**, 191301 (2003).

[10] O. Catalano, Nuovo Cimento Soc. Ital. Fis., C **24C**, 445 (2001).

[11] L. Scarsi, Nuovo Cimento Soc. Ital. Fis., C **24C**, 471 (2001).

[12] C. Barbot, M. Drees, F. Halzen, and D. Hooper, Phys. Lett. B **563**, 132 (2003).

[13] The binning of events according to the arrival direction, with the Earth as a filter, has already provided an important tool to probe physics beyond the standard model. L.A. Anchordoqui, J.L. Feng, H. Goldberg, and A.D. Shapere, Phys. Rev. D **65**, 124027 (2002).

[14] R.M. Baltrusaitis *et al.*, Nucl. Instrum. Methods Phys. Res. A **240**, 410 (1985).

[15] O. Catalano *et al.*, Nucl. Instrum. Methods Phys. Res. A **480**, 547 (2002).

[16] F.I. Boley, Rev. Mod. Phys. **36**, 792 (1964).

[17] There will be also resonant selectron scattering of neutralinos from electrons. This process probes a narrow region of the neutralino flux spectrum, and contributes negligibly to the event rate.

[18] J.F. Gunion and H.E. Haber, Nucl. Phys. **B272**, 1 (1986); **B402**, 567(E) (1993).

[19] Muon g−2 Collaboration, G.W. Bennett *et al.*, Phys. Rev. Lett. **89**, 101804 (2002); **89**, 129903(E) (2002); Muon g−2 Collaboration, G.W. Bennett *et al.*, *ibid.* **92**, 161802 (2004).

[20] U. Chattopadhyay and P. Nath, Phys. Rev. Lett. **86**, 5854 (2001); Phys. Rev. D **66**, 093001 (2002), and the references therein.

[21] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P. Nadolsky, and W.K. Tung, J. High Energy Phys. **07**, 012 (2002).

[22] V. Berezinsky and M. Kachelriess, Phys. Lett. B **422**, 163 (1998).

[23] See, e.g., C.T. Hill, D.N. Schramm, and T.P. Walker, Phys. Rev. D **36**, 1007 (1987); P. Bhattacharjee, C.T. Hill, and D.N. Schramm, Phys. Rev. Lett. **69**, 567 (1992); V. Berezinsky, X. Martin, and A. Vilenkin, Phys. Rev. D **56**, 2024 (1997); P. Bhattacharjee and G. Sigl, Phys. Rep. **327**, 109 (2000).

[24] C. Coriano and A.E. Faraggi, Phys. Rev. D **65**, 075001 (2002); C. Barbot and M. Drees, Astropart. Phys. **20**, 5 (2003).

[25] See, e.g., L. Anchordoqui, T. Paul, S. Reucroft, and J. Swain, Int. J. Mod. Phys. A **18**, 2229 (2003).

[26] R.J. Protheroe and T. Stanev, Phys. Rev. Lett. **77**, 3708 (1996); **78**, 3420(E) (1997).

[27] A.W. Strong, I.V. Moskalenko, and O. Reimer, astro-ph/0306345; U. Keshet, E. Waxman, and A. Loeb, J. Cosmol. Astropart. Phys. **04**, 006 (2004).

[28] D.V. Semikoz and G. Sigl, J. Cosmol. Astropart. Phys. **04**, 003 (2004).

[29] M. Takeda *et al.*, Astropart. Phys. **19**, 447 (2003).

[30] C. Barbot, M. Drees, F. Halzen, and D. Hooper, Phys. Lett. B **555**, 22 (2003).

[31] High Resolution Fly's Eye Collaboration, T. Abu-Zayyad *et al.*, astro-ph/0208301.

[32] HIRES Collaboration, D.J. Bird *et al.*, Astrophys. J. **424**, 491 (1994).

[33] L. Anchordoqui and H. Goldberg, Phys. Lett. B **583**, 213 (2004).

[34] M. Ave, J. Knapp, J. Lloyd-Evans, M. Marchesini, and A.A. Watson, Astropart. Phys. **19**, 47 (2003).

[35] L.A. Anchordoqui, J.L. Feng, H. Goldberg, and A.D. Shapere, Phys. Rev. D **66**, 103002 (2002).

[36] P.W. Gorham, K.M. Liewer, C.J. Naudet, D.P. Saltzberg, and D.R. Williams, astro-ph/0102435; N.G. Lehtinen, P.W. Gorham, A.R. Jacobson, and R.A. Roussel-Dupre, Phys. Rev. D **69**, 013008 (2004); P.W. Gorham, C.L. Hebert, K.M. Liewer, C.J. Naudet, D. Saltzberg, and D. Williams, Phys. Rev. Lett. (to be published), astro-ph/0310232.
[37] This number is arrived at by scaling the 0.1-event background obtained in Ref. [12] (for X overdensity of 10^5 in the Galactic Halo and neutrino flux calculated with $q\bar{q}$ model of X decay), with a factor of 5 to account for the flux enhancement of a homogeneous population over a halolike distribution, a factor of 2 to take into account the difference in the X-particle primary decay mode, and a factor of 0.32 for the difference in w.e. effective volumes. This background includes effects of regeneration on Earth.
[38] G.J. Feldman and R.D. Cousins, Phys. Rev. D **57**, 3873 (1998).
[39] F.W. Stecker, astro-ph/0101072.