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SUPERSYMMETRIC COSMIC ACCELERATORS: FLUXES AT EARTH AND COMPANION STABILITY

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ABSTRACT

We perform a complete calculation of the flux of supersymmetric particles emitted by a binary star such as Cygnus X-3 taking into account production of particles in the interior as well as the atmosphere of the main sequence star. We calculate fluxes at Earth as well as their heating of the main sequence star inside the binary system. Although some supersymmetric models predict observable fluxes in future cosmic ray telescopes, supersymmetry cannot be the source of underground muons from point sources recently reported by some experiments.

1. Introduction

Many authors[1] have considered the emission of light stable supersymmetric particles, photinos or gluinos, by cosmic accelerators such as Cygnus X-3. Previous calculations were approximate and incomplete as only production in the atmosphere of the main sequence star was taken into account. The problem deserves a detailed investigation for several reasons:

- Supersymmetry is at present the leading candidate theory for solving the hierarchy problem. The very structure of the solution requires that masses of superparticles cannot exceed values of order TeV. They are therefore inevitably above threshold in cosmic accelerators with beam energies[2] up to $O(10^5$ TeV). If nature is supersymmetric, cosmic beams of such particles exist and it is an important question whether they can be detected by present experiments, or by the new generation[3] of cosmic ray telescopes now being planned or constructed.
- Independent of the question of observability the production of high energy light supersymmetric particles inside the binary system will contribute to the heating of the main sequence star in the same way conventional neutrinos[4] do. The stability of binary stars therefore can be a constraint on new high energy processes whether they are directly observed or not.
- Observations[5] of muons in the direction and with the characteristic time structure of Cygnus X-3, which motivated the original calculations, received further confirmation by the detection of muons during radio flares[6] in October 1983 and '85. Other sources[6] such as Hercules X-1 and 1E2259+586, have been tentatively identified. If muons keep time with the pulsar phase of these objects which is O(second) the mass of the neutral particle carrying

the radiation cannot exceed[3] a few MeV. This leaves us with photons, neutrinos or essentially massless light supersymmetric particles as candidate carriers of the radiation-producing muons and it has been established that the first two candidates cannot[3] accomodate the observations.

The results of our work are that

- observable fluxes and significant heating only result if both the photino and gluino are light. We here refer to the window of gluino masses of order a few GeV which has arguably not been closed by accelerator searches.[7] Stable light gluinos could conceivably produce muons at the 10% level of the flux parented by the photons.
- contrary to previous claims by some authors in Ref. 1, supersymmetric particles cannot be the source of the muon signal from point sources reported in Refs. 5 and 6.

The outline of our paper is as follows: we first describe the standard model of the cosmic accelerator.[2] We subsequently present calculation of the high energy processes (production and decay) of the supersymmetric particles. Using both ingredients we calculate the cascade of supersymmetric matter through the atmosphere and core of the main sequence star thus obtaining results for the emitted fluxes and heating of the system.

2. Input: Model of the Binary and High Energy Processes

Experience with calculations[2,8] of high energy photon and neutrino fluxes from binary stars shows that results are relatively insensitive to details of the model of the source. As the particle physics parameters are uncertain in the problem under consideration it is adequate to limit ourselves to the simplest model of a cosmic accelerator formulated by Hillas.[2] In this model of Cygnus X-3 a 10^5 TeV proton beam is accelerated by a pulsar. Its companion star acts as a beam-dump. Production and photon decay of neutral pions result in the emission of high energy photons leaving the target. The companion is taken to be a main-sequence star. Although the strong gravitational field of the pulsar must create important disturbances, we use the simple parametrization of Gaisser and Stanev[8] which describes a main sequence star with $M = 2.8$, $R = 2$ and a surface temperature of 10^4 K. We use solar units throughout. The orbital radius of the pulsar is taken to be 2.1. This model reproduces the observed photon flux at Earth provided the 10^5 TeV isotropic pulsar beam has a luminosity of 10^{39} ergs sec^{-1}. This assumes a source distance of 12 kpc.

We next need to specify the processes involving supersymmetric particles in the beam-dump. Supersymmetry predicts that a new multiplicative quantum number, R-parity, is conserved. This implies that superparticles are produced in pairs and that one of them is stable. Whereas the masses must be $O(\text{TeV})$ or less, the actual values are not predicted. Anticipating small effects in general, we concentrate on scenarios which maximize observable fluxes. We consider the simplest $N = 1$ supergravity where all scalar quarks have a common mass $m_{\tilde{q}}$ and the gauginos are not mixed.[7] If the masses originate from radiative corrections the photino is the most natural candidate for the lightest, stable superparticle.

Photino fluxes will result from the production and decay of gluinos and squarks in the dump. Gluino production cross sections exceed those of squarks of a similar mass. As furthermore present mass limits are less stringent for gluinos, we assume that they are the dominant source of photinos via the decay $\tilde{g} \to \tilde{\gamma} q \bar{q}$. Subsequently we will also discuss the possibility that the $\tilde{g}$ rather than the $\tilde{\gamma}$ is stable.

3. Cascade Calculation

As we are dealing with very high energy processes we will work with standard linear shower theory. A 10^5 TeV beam pointing at Earth hits the companion star and a shower develops along a chord of density ρ and column density z. The values of ρ, z depend on the position of the pulsar (phase angle ϕ) in the binary orbit. They are maximum at $\phi = 0$ (companion is centered on the line linking pulsar and Earth) and decrease when ϕ approaches 0.25, 0.75. They actually vanish when reaching phase angles $\phi = 0.22, 0.78$ assuming an orbital radius of 1.05 R. As the photinos are weakly interacting particles (they are similar to neutrinos) they can be produced throughout the body of the target star and not just in the star's atmosphere. This has not been considered in previous calculations.[1]

At each phase angle ϕ we perform a cascade calculation neglecting secondary interactions except for those of the protons and superparticles themselves. For the secondary protons we assume a constant number the energy of which is reduced by a factor of 2 for every interaction length λ_p, with

$$\lambda_p(\mathrm{g/cm^2}) = \frac{1.66\ 10^3}{\sigma_{\mathrm{tot}}(\mathrm{mb})} \tag{1}$$

and

$$\sigma_{\mathrm{tot}}(\mathrm{mb}) = 38.5 + 4.3 \ln^2 \left(\frac{s}{100\ \mathrm{GeV}^2} \right) . \tag{2}$$

Such a calculation correctly describes the emission of high energy photons by $p \to \pi^0 \to \gamma$ processes in the Hillas model. For each interaction length we subsequently calculate the number of produced gluinos[9] per incident proton, with

$$\frac{dN_{\tilde{g}}}{dE} \simeq \frac{2}{\sigma_{\mathrm{tot}}} \frac{d\sigma_{p \to \tilde{g}}}{dE} . \tag{3}$$

The gluinos decay into stable photinos or interact. The decay $\tilde{g} \to \tilde{\gamma} q \bar{q}$ is again calculated[10] in the collinear approximation. If they do not decay the gluinos are dressed into gluino-hadrons which reinteract in the target with hadronic-size cross sections

$$\sigma_{\tilde{g}p} \simeq 10 - 10^2\ \mathrm{mb} . \tag{4}$$

Explicit calculations are not very sensitive to the exact value. We will perform computations assuming a 10 mb cross section. The γ-flux after $(i-1)$ interaction lengths is given by

$$\left. \frac{dN_{\tilde{\gamma}}}{d \ln E} \right|_i = \int_{-\infty}^{0} d \ln x_{\tilde{g}} \, \frac{d\sigma_{p \to \tilde{g}}}{d \ln x_{\tilde{g}}} \, D_{\tilde{g} \to \tilde{\gamma}} \left(\frac{x_{\tilde{\gamma}}}{x_{\tilde{g}}} \right) \frac{x_{\tilde{\gamma}}}{x_{\tilde{g}}} \, f \, \theta \left(\frac{x_{\tilde{\gamma}}}{x_{\tilde{g}}} - \frac{m_{\tilde{\gamma}}^2}{m_{\tilde{g}}^2} \right) . \tag{5}$$

Here $x_{\tilde{g}} = E_{\tilde{g}}/E_p$, $x_{\tilde{\gamma}} = E_{\tilde{\gamma}}/E_p$ with $E_p = (10^5\ \mathrm{TeV})/2^{(i-1)}$. $D_{\tilde{g} \to \tilde{\gamma}}$ describes the gluino-decay in the collinear approximation[10] and the fraction f takes into account the competition between $\tilde{g}$-decay and interaction

$$f = \frac{\lambda_{\mathrm{int}}}{\lambda_{\mathrm{int}} + \lambda_d} \tag{6}$$

$$\lambda_{\rm int}({\rm cm}) = \frac{1.66 \times 10^3}{\sigma_{\tilde g p}({\rm mb})\rho({\rm g/cm^3})} \tag{7}$$

and

$$\lambda_d({\rm cm}) = 5.35\ 10^{-12}\ \frac{E_{\tilde g}({\rm GeV})}{\Gamma_{\tilde g}({\rm GeV}) m_{\tilde g}({\rm GeV})}\,. \tag{8}$$

As, unlike previous calculations, we take into account the full body of the star as well as its atmosphere, we also have to evaluate the photino's interaction after production. The cross section $\sigma_{\tilde\gamma p}$ is obtained from the dominant process $\tilde\gamma q \to \tilde g q$ which has been evaluated taking fully into account the width and propagator of the exchanged scalar quark. The final photino flux emitted by the binary is

$$\frac{dN_{\tilde\gamma}}{d\ln E} = \sum_i \frac{dN_{\tilde\gamma}}{d\ln E}\bigg|_i \exp\left(-\frac{z_i}{\lambda_{\tilde\gamma}}\right) \tag{9}$$

where

$$\lambda_{\tilde\gamma}({\rm g/cm^2}) = \frac{1.66\ 10^3}{\sigma_{\tilde\gamma p}({\rm mb})} \tag{10}$$

and

$$z_i = z - \sum_{j<i} \lambda_p \left(\frac{E_0}{2^{j-1}}\right). \tag{11}$$

One can also extract from (10) the $\tilde\gamma$-flux absorbed in the target-star by the substitution

$$\exp\left(-\frac{z_i}{\lambda_{\tilde\gamma}}\right) \longrightarrow 1 - \exp\left(-\frac{z_i}{\lambda_{\tilde\gamma}}\right). \tag{12}$$

4. Results and Conclusions

4.1 PHOTINO FLUX.

For reasons previously discussed we first investigate models with

$$m_{\tilde\gamma} < m_{\tilde g} < m_{\tilde q}\,. \tag{13}$$

Although we have done a rather exhaustive study we will illustrate the results with two examples

$$\begin{aligned} &({\rm I}) \quad m_{\tilde g} = 3\ {\rm GeV}\,, \qquad m_{\tilde q} = 300\ {\rm GeV} \\ &\phantom{({\rm I})} \quad m_{\tilde g} = 7\ {\rm GeV}\,, \qquad m_{\tilde q} = 100\ {\rm GeV} \\ &({\rm II}) \quad m_{\tilde g} = 60\ {\rm GeV}\,, \quad m_{\tilde q} = 600\ {\rm GeV} \end{aligned} \tag{14}$$

In each case the photino is light, we show calculations for $m_{\tilde\gamma} = \frac{1}{6} m_{\tilde g}$. The results are essentially the same as for a massless photino. Case (I) illustrates the "window of opportunity" for light supersymmetric particles, *i.e.* the low mass range not closed at present by accelerator limits. Notice that for a gluino mass as light as 3 GeV we have to increase the squark mass to be compatible with acceleration limits.[11] Example (II) illustrates a scenario of "realistic" masses not yet within reach of accelerator experiments.

Results for fluxes are shown in Fig. 1 and Fig. 2 as a function of energy and binary phase angle. As can be seen from Fig. 1, the photino fluxes at Earth are small compared to photon and neutrino fluxes obtained within the same framework. At the higher energies the fluxes of $\tilde\gamma$'s become a few percent of the photon flux for models of type (I). It is likely that we underestimated the $\tilde\gamma$ flux as in this case the cross section of the relatively light gluino parent particles could be underestimated by a leading order perturbative calculation. This is a familiar issue in connection with the hadronic production of charm. This class of models is within reach of the new generation of cosmic ray telescopes especially as the event signature for detecting the admixture of γ's in the photon flux are promising. This has been discussed elsewhere.[1] It is however also very clear from these illustrative calculations that supersymmetric particles are not the source of the underground muons from Cygnus X-3 reported by some experiments.[5,6] Whatever the details of the signature produced at Earth, the event rate in underground detectors will be relatively small and definitely unobservable with present detectors.

4.2 STABLE GLUINOS

In Fig. 3 we show the gluino flux from Cygnus X-3 assuming that the gluinos themselves are stable and reach Earth. Results are shown in Fig. 3 for $m_{\tilde{g}} = 3$ and 7 GeV. They qualitatively agree with a calculation from Ref. 12, which was done for a E^{-2} spectrum of the pulsar beam and did not take into account the details of the companion's atmosphere. Notice however that an E^{-2} flux predicts enhanced gluino production as one more readily samples low energy processes where the cross section is enhanced. Even here the fluxes are in general small. The gluinos will interact with the atmosphere very much the way regular hadrons do. They will therefore produce roughly 10^2 times more underground muons than photons do.[13] As the flux in Fig. 3 is however suppressed by a factor $10^3 \sim 10^5$ we expect a muon rate of 10% or less of the rate generated by photons. Again, such rates might be observable in future experiment but exclude stable gluinos as a source of the muons reported in Ref. 5.

4.3 COMPANION HEATING

The previous calculation illustrates how results can be insensitive to the details of the beam. This is however not the case for the stable $\tilde{\gamma}$ calculations where the main contribution to the flux comes from the core of the target star. The reason for this is clear as protons interact until they are below threshold for producing supersymmetric particles. This takes about 20 interaction lengths and is realized throughout the star but not the atmosphere. Results are only sensitive to the total luminosity of the beam. This discussion brings us naturally to the issue of heating of the companion by photinos deposited in the core. The discussion is completely parallel to that of neutrino-heating.[4] Results are obtained from Eqs. (9)-(12) and shown in Table I. From the particle physics point of view the crucial ingredients into the calculation are the $\tilde{\gamma}$ interaction cross sections with matter. They are shown in Fig. 4 where they are compared with the corresponding cross section for conventional neutrinos. We conclude that the heating is at most $O(2\%)$ of that due to neutrinos.[4]

As previously pointed out these results should be rather independent of the details of the binary system. The crucial astronomical input is the luminosity of the beam. It is important to remember at this point that the "measured" luminosity of 10^{39} ergs/sec represents a lower limit. A case for boosting it has been made in connection with the puzzling observation of underground muons. A corresponding boost in flux will result for neutrinos and supersymmetric particles, but not necessarily for photons. The latter could be reabsorbed by adjusting the beam-dump density. One does not have total freedom as the increased flux eventually destabilizes the companion star by heating.[4] The fact that binaries are stable represents a constraint on high energy particle physics processes, independent from any direct observations.

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Table I. Heating of the companion star.

$m_{\tilde{g}}$, $m_{\tilde{q}}$ (GeV)	Heating (10^{33} GeV s^{-1})
3, 300	1.7 10^{2}
7, 100	1.2 10^{5}
60, 600	3.3 10^{2}

FIGURE CAPTIONS

Fig. 1. Energy dependence of the photino flux at Earth for models I and II described by Eq. (14), compared with neutrino and photon fluxes.

Fig. 2. Phase dependence of the photino fluxes at Earth for cases I and II described by Eq. (14). The flux vanishes between $\phi = 0.22$ and 0.78 and is the mirror image of Fig. 2 in the interval $\phi = 0.78 - 1$.

Fig. 3. Stable gluino fluxes at Earth compared with the results from Ref. 12.

Fig. 4. Photino interaction cross sections with protons are compared with neutrino and antineutrino cross-sections. These cross sections determine the absorption of flux by the companion star.

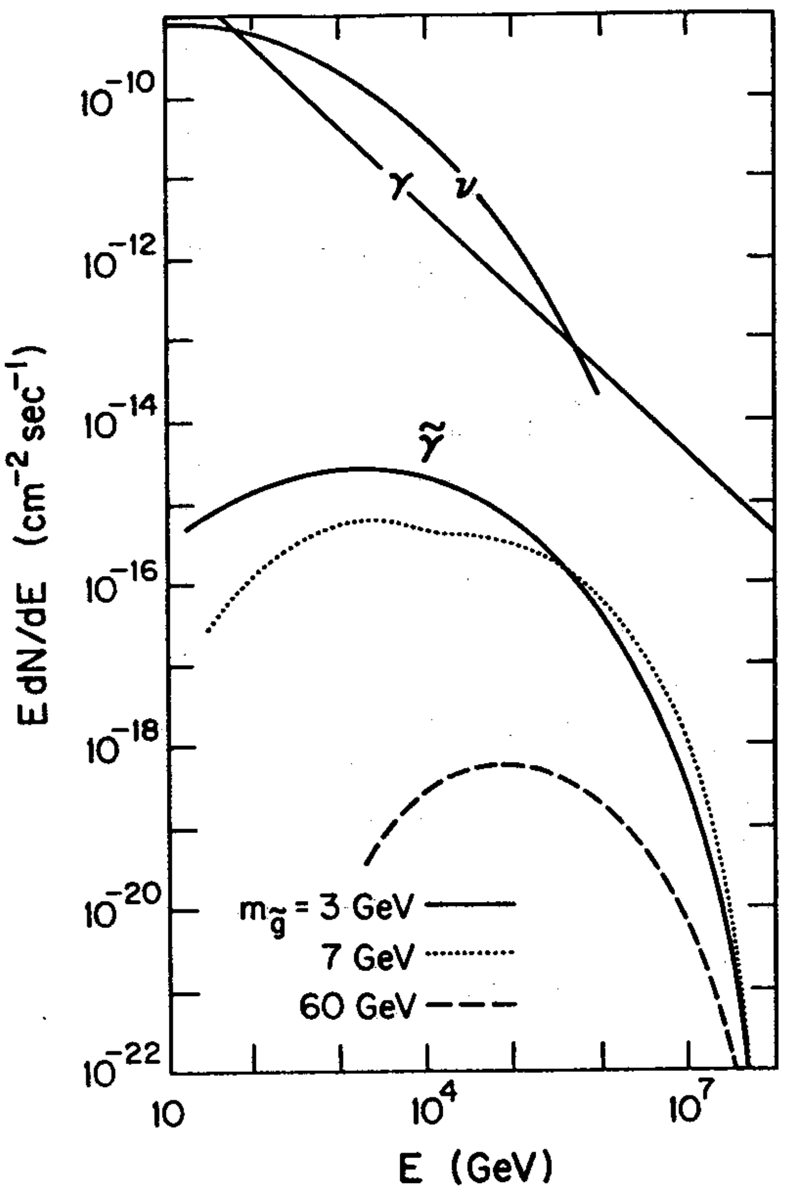

10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
E dN/dE (cm^{-2} sec^{-1})
10
10^4
10^7
E (GeV)
γ
ν
$\tilde{\gamma}$
$m_{\tilde{g}}$ = 3 GeV
7 GeV
60 GeV

Fig. 1

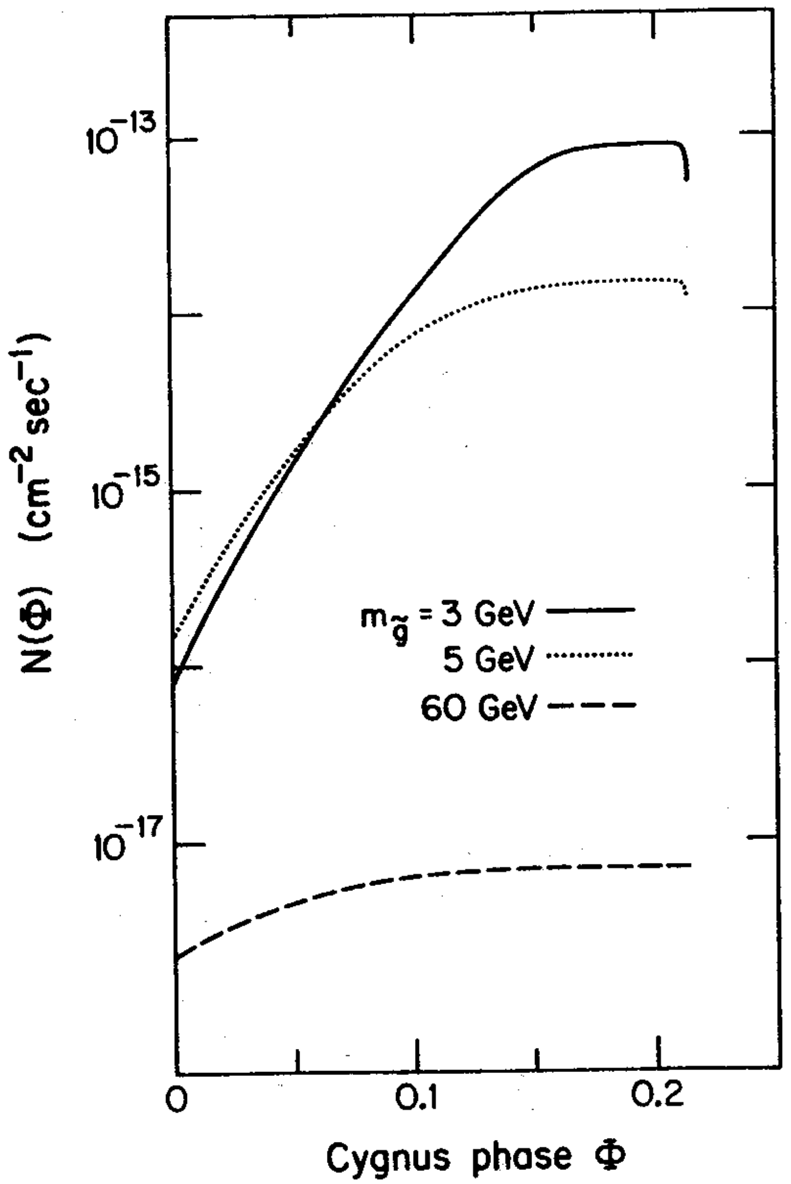
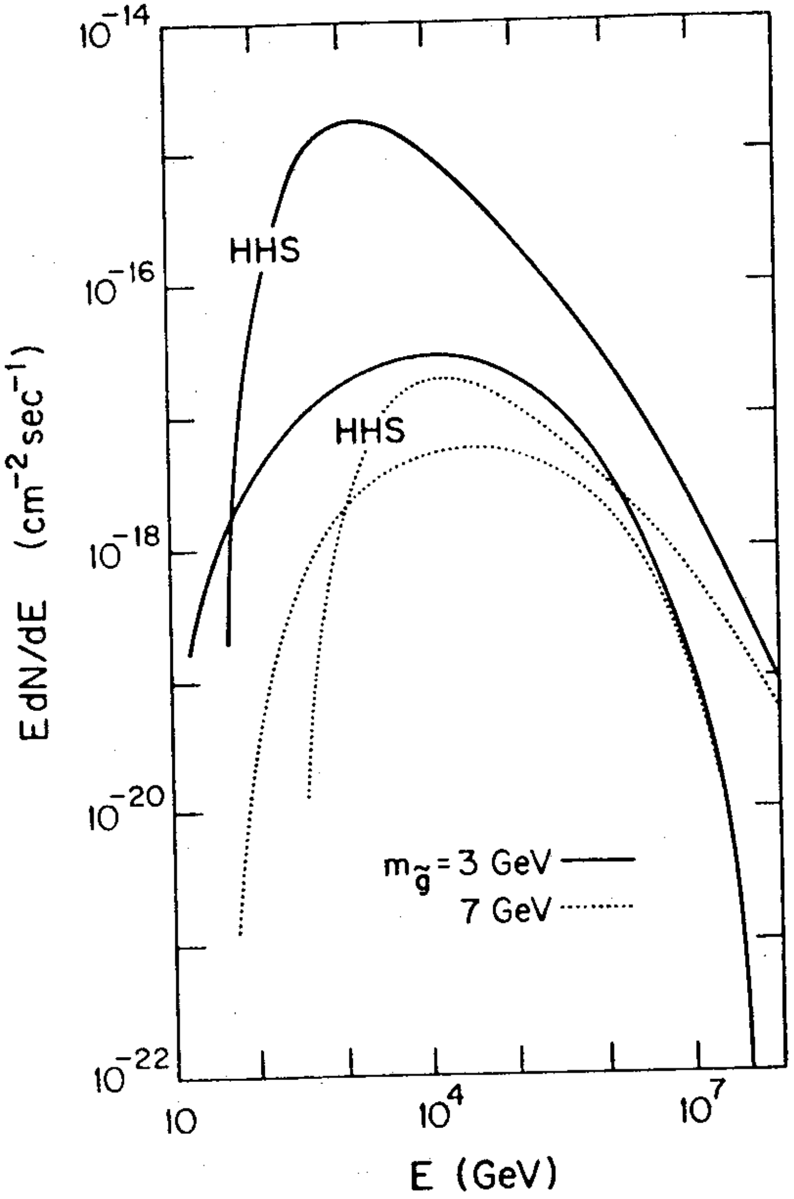
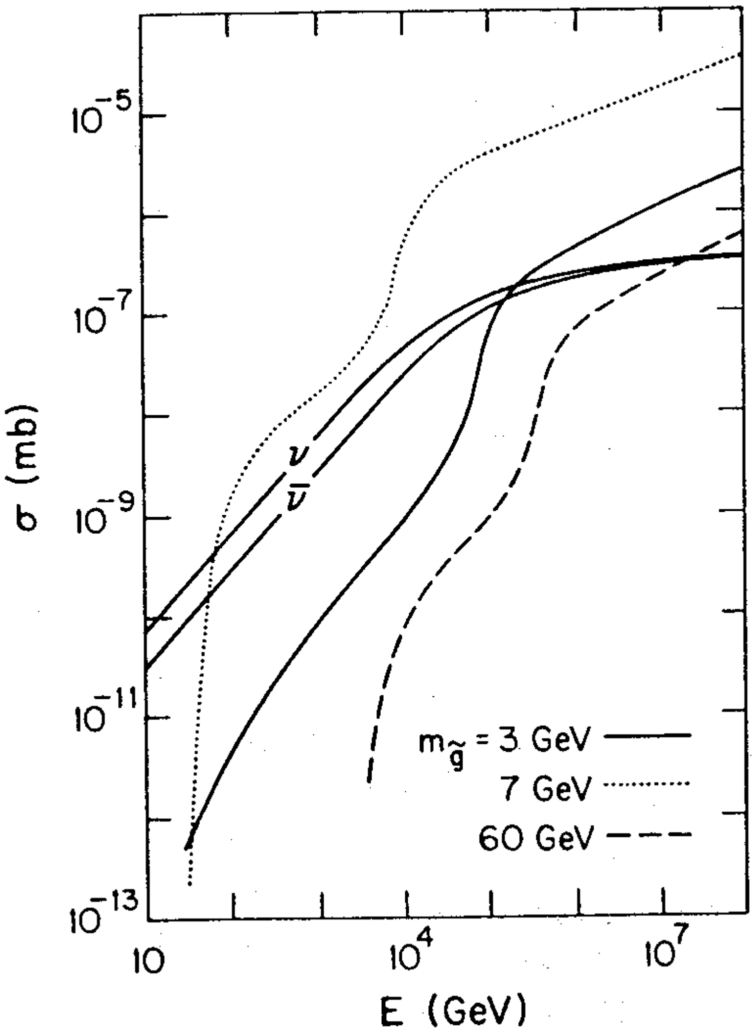

10^{-13}
10^{-15}
10^{-17}
N(Φ) (cm^{-2} sec^{-1})
0
0.1
0.2
Cygnus phase Φ
$m_{\tilde{g}}$ = 3 GeV
5 GeV
60 GeV

Fig. 2



10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
E dN/dE $(cm^{-2}sec^{-1})$
HHS
HHS
$m_{\tilde{g}}$ = 3 GeV
7 GeV
10
10^4
10^7
E (GeV)

Fig. 3



10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
σ (mb)
ν
$\bar{\nu}$
$m_{\tilde{g}}$ = 3 GeV
7 GeV
60 GeV
10
10^4
10^7
E (GeV)

Fig. 4