Neutrinos from the Galactic Center in the Light of its Gamma-Ray Detection at TeV Energy

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ABSTRACT

We re-evaluate the event rate expected in km^3-scale detectors for neutrinos from the direction of the Galactic Center (GC) in light of recent spectral measurements obtained by the HESS instrument for ∼TeV γ-radiation from this direction. In the most plausible scenario the re-evaluated event rate is smaller than that previously calculated—and here re-calculated—on the basis of EGRET data. However, the GC TeV γ-ray detections by the Whipple, CANGAROO, and HESS instruments, together with the strong indications for an overabundance of cosmic rays coming from the GC at EeV energies, strengthen the expectation for a detectable, TeV-PeV GC neutrino signal from proton-proton interactions in that region. If the TeV gamma-ray–EeV cosmic ray anisotropy connection is correct, this signal will be detectable within a year and half for km^3-scale neutrino detectors in the Northern Hemisphere at super-TeV energies and, significantly, should also be detectable in 1.6 years by the South Polar IceCube detector at energies $\gtrsim 10^{14}$ eV. The GC neutrino signal should also produce a detectable signal from neutrino showering and resonant W^- production by $\overline{\nu}_e$'s in the volume of a km^3-scale detector.

Subject headings: cosmic-rays — elementary particles — Galaxy: center — neutrinos — radiation mechanisms: nonthermal — supernova remnants

1. Introduction

Several of us (Crocker et al. 2000; Crocker et al. 2002; Blasi and Melia 2004) have previously calculated the flux of neutrinos expected from the Galactic center (GC) based

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on the π^0-decay EGRET γ-ray signal (Fatuzzo and Melia 2003; Melia et al. 1998). However, a new calculation is now warranted in light of (i) new $\sim$TeV γ-ray observations of the GC with the Whipple and HESS air Čerenkov telescopes (Aharonian et al. 2004; Kosack and et al. 2004), (ii) analyses that indicate that the EGRET GeV source is offset from the actual GC (Hooper & Dingus 2002; Pohl 2004), and (iii) recent theoretical progress in understanding the totality of high-energy, GC astroparticle data (Crocker et al. 2004). In particular, both the extremely high-energy (EHE) GC cosmic ray anisotropy (Hayashida et al. 1999a; Bellido et al. 2001) and the GC γ-ray signals can be ascribed, respectively, to neutrons and neutral pions created by the collisions of protons from the same shock-accelerated, GC population with ambient protons.

In this picture, neutrinos too will be created as the result of the decay of the charged pions arising inevitably from the same *pp* interactions. In fact, we can normalize the expected neutrino flux to the γ-ray and (putative) neutron fluxes because of the common origin of all these particle species. On this basis, in this *Letter*, we re-calculate both the flux of high-energy neutrinos from the GC and the resulting event rates in the large scale neutrino telescopes[1]. Because of the EHE neutron connection, we expect the GC neutrino flux to extend to much higher energies than previously anticipated, meaning that it should now also be detectable through the resonant interactions of GC $\overline{\nu}_e$'s with electrons in the volume of a km^3-scale detector.

2. GC γ-ray Data: Evidence for Hadronic Acceleration

The GC has been detected in γ-rays by the EGRET instrument aboard the Compton Gamma-ray Observatory (Mayer-Hasselwander et al. 1998), CANGAROO (Tsuchiya et al. 2004), Whipple (Kosack and et al. 2004) and HESS (Aharonian et al. 2004). The latter three cover a similar energy range, $\sim 10^{-1} - 10$ TeV, while EGRET has lower energy data ($\sim 10^{-5} - 10^{-2}$ TeV). The Whipple result, while of limited statistical significance, shows a constant flux over a decade, and a flux consistent with the HESS result (K. Kosack 2005, private communication), extending to energies of at least 2-3 TeV. Because HESS has by far the best angular resolution and most detailed spectral results and these results are consistent with the 1995-2000 Whipple detections, we hereafter choose to employ the HESS spectrum, rather than that of CANGAROO in our analysis. We now review why these data point to a

[1]The implications of the putative GC neutron beam for the GC neutrino flux have also been examined by Anchordoqui et al. (2004a). These authors employ quite different particle physics to explain the neutrons, however, and their models do not address the GC γ-ray signal.

hadronic origin.

The EGRET spectrum exhibits a clear break at ~ 1 GeV which can be explained by neutral pion decays generated in collisions between relativistic and ambient protons. Such decays produce a broad γ-ray feature that mirrors all but the lowest energy EGRET datum which is, instead, explained self-consistently (in steady state) as resulting from the γ-ray emission via bremsstrahlung and Compton scattering of the charged leptons resulting from the decay of the charged pions also produced in these collisions. Further increasing our confidence in this picture, Fatuzzo and Melia (2004) have shown that when the same charged secondary lepton population is placed in a magnetic field sufficient to accelerate protons up to the required $\sim 10^{19}$ eV, it synchrotron radiates with an emissivity also in agreement with radio observations.

The TeV observations mentioned above all also lend crucial support to the notion that high-energy hadronic processes are taking place at the GC because, as argued by Crocker et al. (2004) these data then reliably *predict* the GC neutron flux apparently uncovered in the EHE cosmic ray observations. Non-hadronic origins of the HESS signal are possible, though, and have recently been discussed by Aharonian and Neronov (1).

Clouding these waters, however, the entirety of GC, astroparticle data can not be fit with a model involving proton shock acceleration and subsequent collision with ambient protons *at a single source* (Crocker et al. 2004): though a very good fit is possible to the EGRET+EHECR data, such a fit over-predicts the γ-ray flux from the GC at HESS energies by a factor of $\sim$20.

There are two reasonable resolutions of this: (i) the TeV flux is attenuated in propagation in which case the neutrino flux should be normalized to the combination of the unattenuated EGRET data and the EHECR data; (ii) there are two *effective* GC sources, in which case the EGRET source must cut-off well below a TeV in order not to pollute the HESS signal. In support of (ii) note that (a) the EGRET data themselves can, indeed, be interpretted as indicating just such a cut-off and (b) in analyses by Hooper and Dingus (2002) and Pohl (2004) an offset between the EGRET and TeV sources is evident. Finally, it is also possible that future observations will fail to confirm the existence of the GC cosmic-ray anisotropy. Alternatively, it might be established—despite all current contra-indications—that the GC γ-ray and EHECR signals are unrelated. Given these possibilities, we should also consider the implications for the GC neutrino flux of the HESS GC results *alone*. We shall compute the GC neutrino flux for all these three cases (labeled EGRET+EHECR, HESS+EHECR, and HESS ALONE) below.

3. Neutrino Fluxes

For the purposes of this study, we have generalized the standard technique based upon "spectrum weighted moments" (Gaisser 1990) to allow for (i) an exponential cut-off in the parent particle spectrum (which produces, to a good approximation, a mirroring exponential cut-off in the daughter particle population, though with a reduced cut-off energy), (ii) a scaling-violating growth of the total cross-section over the large energy ranges separating the different sorts of data, and (iii) various propagation effects.

With these generalizations in place, we can relate the fluxes of the various particle species (assuming that all the detected particles are created in the same interaction process). In particular, in (Crocker et al. 2004), we determined the theoretical relation between the γ-ray and neutron fluxes of the GC—at the vastly different energy scales of $\sim$MeV/GeV and $\sim 10^{18}$ eV—and were then able to perform simultaneous fits (in spectral index and γ-ray differential flux at some normalizing energy) to the EGRET+EHECR data and the HESS+EHECR data. This required that we account for the propagation effect of neutron decay-in-flight.

As mentioned above, the fit to the EGRET+EHECR data only makes sense given another propagation effect is operating: attenuation of the TeV gamma rays. A possible attenuation mechanism is $\gamma\gamma$ pair production on the background NIR photons emitted by the circumnuclear disk at the GC. It seems difficult, however, to arrange for a column density of NIR photons from the GC sufficient to produce the required attenuation. Further, were such attenuation to take place, the most natural expectation would then be that the resulting spectrum is distorted away from the initial (flat) power law. The lack of any such distortion in the observed spectrum and the relatively small column density of NIR photons together imply that this scenario seems unlikely (see Crocker et al. 2004 for more detail here). We examine this possibility in our analysis, then, only in the spirit that it provides something like an upper limit to the flux of neutrinos from the GC (due to conventional physics).

In the more compelling HESS+EHECR scenario, the neutrino fluxes are due, in principle, to two (effective) sources and should be normalized to the cut-off γ-ray flux measured by EGRET and the combination of the HESS and EHE CR data. In practice, however, because the cut-off energy for the EGRET source γ-rays must be in the 100 GeV energy range, the neutrino spectrum of this source will be similarly cut-off rendering it invisible to km^3-scale detectors against the atmospheric neutrino background (given reasonable values for detector angular resolution).

Finally, as presaged above, we examine for completeness the consequences of normalizing the GC neutrino flux to the HESS data by themselves. We include two cases here. The first is where the cut-off in the photon spectrum is taken to be at $\sim 10^{17}$ eV. This case is numerically identical to a pure power-law fit to the HESS data which, it should be noted, show no direct evidence for a cut-off. Second, *in order to arrive at a strict lower limit* to the GC flux we examine the case of $E_\gamma^{cut} = 10^{13}$ eV. This is the approximate *minimum* cut-off energy consistent with the HESS data.

Now, employing these fitted normalizations and spectral indices, we wish to calculate the muon and electron type neutrino fluxes coming from the GC direction. This calculation must account for a further propagation effect, viz. in-vacuum neutrino oscillations. Given the distance and energy scales involved these will be totally averaged out (unless sub-dominant, long-wavelength oscillation modes operate in nature; Crocker et al. 2002), implying flavor ratios close to $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at the Earth. With these inputs we find $\Phi_{\nu_e}[E_\nu] \simeq \Phi_{\nu_\mu}[E_\nu] = \Phi_{\nu_\tau}[E_\nu] \equiv \Phi_\nu[E_\nu]$ and the following neutrino fluxes:

$$\text{EGRET+EHECR:} \qquad \Phi_\nu[E_\nu] = 9.0 \times 10^{-11} \left(\frac{E_\nu}{\text{TeV}}\right)^{-2.22} \text{cm}^{-2}\ \text{s}^{-1}\ \text{TeV}^{-1} \tag{1}$$

$$\text{HESS+EHECR:} \qquad \Phi_\nu[E_\nu] = 1.3 \times 10^{-12} \left(\frac{E_\nu}{\text{TeV}}\right)^{-2.00} \text{cm}^{-2}\ \text{s}^{-1}\ \text{TeV}^{-1} \tag{2}$$

$$\text{HESS:} \qquad \Phi_\nu[E_\nu] = 1.2 \times 10^{-12} \left(\frac{E_\nu}{\text{TeV}}\right)^{-2.23} \exp\left[\frac{-E_\nu}{E_\nu^{\text{cut}}}\right] \text{cm}^{-2}\ \text{s}^{-1}\ \text{TeV}^{-1}\ , \tag{3}$$

where $E_\nu^{\text{cut}} \in \{10^{17}\ \text{eV}, 10^{13}\ \text{eV}\}$. The neutrino fluxes above are plotted in Figure 1 which also shows backgrounds to ν_μ CC events in a km^3 Mediterranean detector and to IceCube, labeled, "Atm ν_μ" and "Atm μ", respectively. Here the former corresponds to the atmospheric ν_μ flux inside a solid angle encircling the GC direction defined by the predicted angular resolution of the ANTARES neutrino telescope and the latter is the atmospheric muon flux, at a fiducial 1.6 km depth in the ice, inside the predicted IceCube angular resolution *weighted by the reciprocal of the (energy-dependent) neutrino detection probability.*

4. Event Rates

From these fluxes we now calculate the event rates in astrophysical neutrino detectors. In general, the yearly event rate in such devices will be given by

$$\text{N}_{year} = \int_{E_\nu^{min}} dE_\nu \int_0^{\text{year}} dt\ \text{Area}[E_\nu, \theta(t)]\ \Phi[E_\nu] \times P_{\text{detect}}[E_\nu]\ \text{Attn}\left[E_\nu, \theta(t)\right]\ . \tag{4}$$

Here Area$[E_\nu, \theta]$ is the energy- and nadir-angle-dependent effective (muon) area of the detector and $P_{\text{detect}}[E_\nu]$ is the probability that a neutrino will interact sufficiently close to the detector volume that a detectable signal (muon track, electromagnetic or hadronic shower, etc.) is created. The Attn $[E_\nu, \theta]$ function accounts for neutrino interactions in the Earth's volume before the detector is reached. For this function we employ a parameterization of the results in Naumov and Perrone (1999).

In Equation (4), both Area$[E_\nu, \theta]$ and $P_{\rm detect}[E_\nu]$ depend on the detector and the neutrino interaction process generating the signal. For CC interactions of ν_μ's leading to muon tracks through the volume of a H_2O-based neutrino telescope, we employ the detection probability presented by Halzen & Hooper (2002). Such detectors include, buried in the ice at the South Pole, (the currently-operating) AMANDA (Ahrens et al. 2004b) and (AMANDA's under-construction, km^3-scale replacement) IceCube (Ahrens et al. 2004a), and, in the deep Mediterranean, the prototype-stage, $\lesssim 0.1$ km^2 area ANTARES (Korolkova et al. 2004) or a future, km^3-scale upgrade of this device.

For the showers created by the CC interactions of ν_e's or ν_τ's (the latter without visible τ track) and the neutral current interactions of all flavors we employ the event rate estimation set out by Beacom et al. (2003). For the event rate due to the Glashow (1960) process—i.e., the resonant, s-channel creation of W^-'s in $\overline{\nu}_e$ e^- interactions for $E_\nu \simeq 6.3 \times 10^{15}$ eV—we adopt the detection probability set out by Anchordoqui et al. (2004a) with their specification of an effective target volume of ~ 2 km^3 for the IceCube detector (which we also adopt for the hypothesized Mediterranean detector).

Note that we assume in this work that a detector can perfectly determine the energy of the primary neutrino. This is a good approximation for our purpose which is simply to determine the observability of the GC neutrino flux.

For Area$[E_\nu, \theta]$, in the case of IceCube we employ the results of the Monte Carlo modeling presented by Ahrens et al. (2004a) and for a future Mediterranean detector we assume an energy- and nadir-angle-dependent fiducial (muon) area of 1 km^2.

The background to the CC muon production process is generated by the atmospheric muon (for an above the horizon source) and neutrino fluxes (Chirkin 2004) within the solid angle defined by the detector angular resolution. The background to the showering and Glashow processes is due to the atmospheric neutrinos alone. In IceCube a 0.7° angular resolution for a muon track with $E_\mu \gtrsim 10^{12}$ eV is predicted (Ahrens et al. 2004, Anchordoqui et al. 2004a) allowing for a search window of $1^\circ \times 1^\circ$. Note that, as the GC is always overhead from the South Pole, its CC ν_μ signal (i) is invisible to AMANDA (Ahrens et al. 2004b) and (ii) can only be seen above $\sim 10^{14}$ eV in IceCube (given the atmospheric muon background at a fiducial depth of ~ 1.6 km depth in the ice). Further, Monte Carlo modeling by the IceCube collaboration shows that the detector effective (muon) area is significantly reduced for a down-going neutrino flux at energies $\lesssim 10^{15}$ eV(Ahrens et al. 2004a). At higher energies, the effective area recovers, however, and, further, the GC neutrino flux is not shadowed by the Earth in IceCube. Our analysis then indicates the GC should be detectable in ν_μ CC events by IceCube for both the EGRET+EHECR and HESS+EHECR cases (in the latter case, because of the hard spectrum, the IceCube event rate is actually comparable to that in a Mediterranean km^3 detector despite the necessarily higher energy threshold): see Figure 1.

Relative to IceCube, a Mediterranean km^3 detector would have—in the GC CC ν_μ signal context—the advantage of both a largely below-horizon source and a tighter angular resolution (due to the relatively longer scattering length of Čerenkov light in deep sea water in comparison with Antarctic ice). This would allow such a detector, according to our calculations[2], to detect the GC at energies ∼TeV (see Figure 1).

For showers the angular determination is much worse than for muons—we assume 25° as determined by Beacom et al. (2003). We also assume the same angular resolution for events due to the Glashow process. For shower processes, IceCube certainly has the advantage over a Mediterranean detector in the GC context: atmospheric muons do not significantly pollute the shower signal, so the imposition of the Earth between source and detector only serves to attenuate the signal.

Other potential signals in a km^3 detector from the GC neutrino flux are double-bang and lollipop events due to the CC interactions of higher-energy ν_τ's. Unfortunately, employing an event rate parameterization for these two processes that follows from the work of Beacom et al. (2003) we find an undetectably small GC ν_τ signal for all cases. (even in the EGRET+EHECR case the rate of either double-bang lollipop events is less than 0.03 per year). We have also checked whether the very high energy component of the signal from the GC neutrino source might be uncovered using "alternative" astrophysical neutrino detection techniques relying on, e.g., horizontal shower detection in the Auger cosmic ray air shower array (Bertou et al. 2002), or the RICE (Kravchenko et al. 2003) in-ice radio Čerenkov detector. Unfortunately, we find for every case investigated, a negligibly small signal.

Yearly event rates and backgrounds are displayed in table 1. This also shows the expectation for the number of years required before a positive signal can be uncovered given the background (in the narrow sense of requiring that one achieves 95% confidence level assuming Poisson statistics – it should be emphasized here that, pragmatically, more than one neutrino detection and a higher level of statistical significance would be required before

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[2]These calculations employ a parameterization of the modeled angular resolution of ANTARES (Korolkova et al. 2004). A km^3-scale detector will at least match this.

a reasonable announcement of a detection could be made). We have presented the signal event rate above an energy which guarantees it is equal to or surpasses the background event rate. Detector-dependent modeling would be required to optimize this threshold energy. The CC ν_μ event rates for up and down-going neutrinos in a Mediterranean detector are given separately because a sea-water based detector might be restricted to purely up-coming events by design considerations. For the EGRET+EHECR case we present the CC ν_μ and shower event rates in IceCube above two threshold energies (design considerations may mean that IceCube only attains 4π sensitivity above 10^{14} eV). In the case of the HESS ALONE ν_μ (up) signal, we present the event rate for two different values of the cut-off energy in the HESS source spectrum as previously explained [though note that for both ν_μ CC in IceCube and ν_μ CC (down) in Med km^3 cases we set $E_\gamma^{cut} = 10^{17}$ eV, the lower-energy cut-off being undetectable in those cases].

5. Conclusion

We have calculated the expected flux of neutrinos from the GC given the high-energy, astroparticle signals that have been detected from this region. From these flux estimates we have predicted event rates in three neutrino telescopes: IceCube, ANTARES, and a km^3-scale successor to ANTARES. Recent data from HESS mean that earlier estimates for GC neutrino fluxes are likely to be over-optimistic, though the possibility that γ-γ attenuation is reducing the $\sim$TeV gamma-ray flux means that such high fluxes are not excluded. In this most optimistic case the GC would be seen within a year by ANTARES. Even if the γ-γ attenuation is not operating, the HESS data together with the EHE cosmic ray data on the GC now strongly suggest an interesting signal for *both* a Mediterranean km^3 detector and IceCube at the South Pole. This signal, in the most likely scenario, would be detected within about 1.5 years by either IceCube or a Mediterranean km^3 detector.

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	dtctr	prcss	rate	thrsh	bkgd	yrs
E	ICE	ν_μ	9.2	13.5	0.8	0.20
G			7.1	14.0	0.04	0.14
R		shwr	31	13.5	7	0.053
E			13	14.0	0.5	0.074
T		$\overline{\nu}_e$-rsnt	1.9		0.2	0.95
+	ANT	ν_μ	1.0	11.7	0.02	0.98
E		shwr	0.2	13.5	0.1	13
H	MED	ν_μ(up)	101.0	11.7	6.1	0.019
E		ν_μ(dn)	14.1	13.0	0.2	0.070
C		shwr	21.6	13.5	10.0	0.063
R		$\overline{\nu}_e$-rsnt	1.9		0.2	0.95
H	ICE	ν_μ	0.6	14.1	0.02	1.6
E +		shwr	0.8	14.0	0.5	3.9
S E		$\overline{\nu}_e$-rsnt	0.3		0.2	10
S H	MED	ν_μ(up)	2.0	12.0	1.3	1.5
E		ν_μ(dn)	0.7	13.0	0.2	3.3
C		shwr	0.3	14.0	0.2	10
R		$\overline{\nu}_e$-rsnt	0.3		0.2	10
H A	ICE	ν_μ	0.1	14	0.04	21
E L	MED	ν_μ(up)				
S O	(E_γ^{cut} =	10^{17} eV)	0.9	12.3	0.3	2.5
S N	(E_γ^{cut} =	10^{13} eV)	0.3	12.3	0.3	12
E		ν_μ(dn)	0.1	13.5	0.006	19

Table 1: Yearly event rates ("rate") and backgrounds ("bkgd") due to the various neutrino interaction processes ("prcss") and normalizations specified ('ICE', 'ANT', and 'MED' denote events in IceCube, ANTARES and a km^3 Mediterranean detector respectively). Backgrounds are over the same energy range as observations (above a threshold energy, "thrsh", which is specified by $\log[E_{th}/\text{eV}]$). Also displayed ("yrs") is the expectation for the number of years required before a real signal can be uncovered at the 95% confidence level.

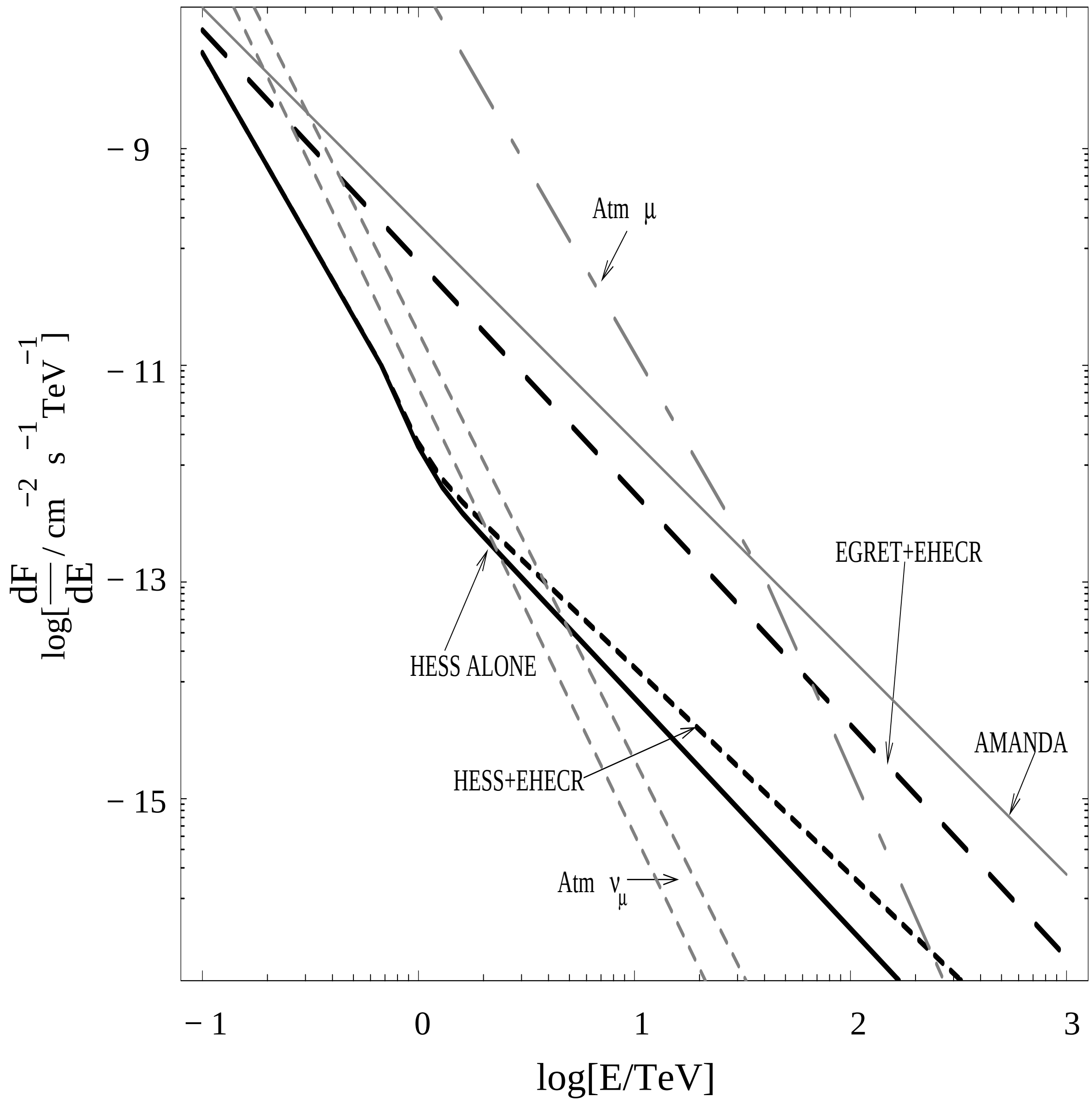

Fig. 1.— GC neutrino fluxes. Signals (black curves) with normalizations: (i) EGRET+EHECR—long dashed, (ii) EGRET with cut-off (at 200 GeV) combined with HESS+EHECR—short dashed, and (iii) EGRET with cut-off (at 200 GeV) combined with HESS ALONE (with 10^{17} eV cut-off)—unbroken. The two dashed gray curves give the upper and lower limiting values of the atmospheric neutrino background in a km^3 Mediterranean detector and the single gray dot-dashed curve gives the atmospheric muon background in IceCube. For reference, the solid gray curve gives the present AMANDA limit on a neutrino source in the *northern* sky (Ahrens et al. 2004b) with E^{-2} spectrum.