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Neutrinos Associated with Cosmic Rays

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Neutrinos Associated with Cosmic Rays

Francis Halzen
Department of Physics, University of Wisconsin, Madison, WI 53706,USA
and
DESY, Zeuthen, Germany

ABSTRACT

Construction of the first kilometer-scale neutrino observatory has been completed; IceCube has been fully commissioned and has been taking data since May 2011. Its present performance exceeds expectations in both the neutrino collection area (by a factor $2 \sim 3$ depending on energy) and angular resolution. It continues to improve with ongoing refinements in calibration, software tools and our understanding of the optics of the natural ice. IceCube was designed more than a decade ago with the goal of observing the sources of both Galactic and extragalactic cosmic rays with good statistical significance after 5 years. Because the origin of cosmic rays is still unresolved, the exercise is inevitably performed on models. We here revisit three illustrative examples chosen because they are predictive, although with relatively large errors associated with the astrophysics of the sources: Galactic supernova remnants, gamma-ray bursts and GZK neutrinos produced in interactions of cosmic rays with the microwave background. We conclude that the IceCube design, as well as the prospect for observing neutrinos from cosmic-ray sources, have survived the test of time.

1. The First Kilometer-Scale Neutrino Detector: IceCube

A series of first-generation experiments[1)] have demonstrated that high-energy neutrinos with $\sim$ 10 GeV energy and above can be detected by observing Cherenkov radiation from secondary particles produced in neutrino interactions inside large volumes of highly transparent ice or water instrumented with a lattice of photomultiplier tubes. Construction of the first second-generation detector, IceCube, at the geographic South Pole has been completed in December 2010[2)]; see Fig.1.

IceCube consists of 80 strings, each instrumented with 60 10-inch photomultipliers spaced by 17 m over a total length of 1 kilometer. The deepest module is located at a depth of 2.450 km so that the instrument is shielded from the large background of cosmic rays at the surface by approximately 1.5 km of ice. Strings are arranged at apexes of equilateral triangles that are 125 m on a side. The instrumented detector volume is a cubic kilometer of dark, highly transparent and sterile Antarctic ice. Radioactive background is dominated by the instrumentation deployed into this natural ice.

Each optical sensor consists of a glass sphere containing the photomultiplier and the electronics board that digitizes the signals locally using an on-board computer. The digitized signals are given a global time stamp with residuals accurate to less than 3 ns and are subsequently transmitted to the surface. Processors at the surface continuously collect these time-stamped signals from the optical modules; each functions independently. The digital messages are sent to a string processor and a global event trigger. They are subsequently sorted into the Cherenkov patterns emitted by secondary muon tracks, or electron and tau showers, that reveal the direction of the parent neutrino[3)].

Based on data taken during construction with 40 of the 59 strings, the anticipated effective area of the completed IceCube detector is shown in Fig.2. Notice the factor 2 to 3 increase in effective area over what had been anticipated[4)]. The neutrino collecting area will continue to increase with improved calibration and development of optimized software tools for the 86-string detector operating stably in its final configuration. Already reaching an angular resolution of better than 0.5 degree for high energies, reconstruction is also superior to what was anticipated.

Despite its discovery potential touching a wide range of scientific issues from the search of dark matter to the physics of neutrinos themselves, construction of IceCube has been largely motivated

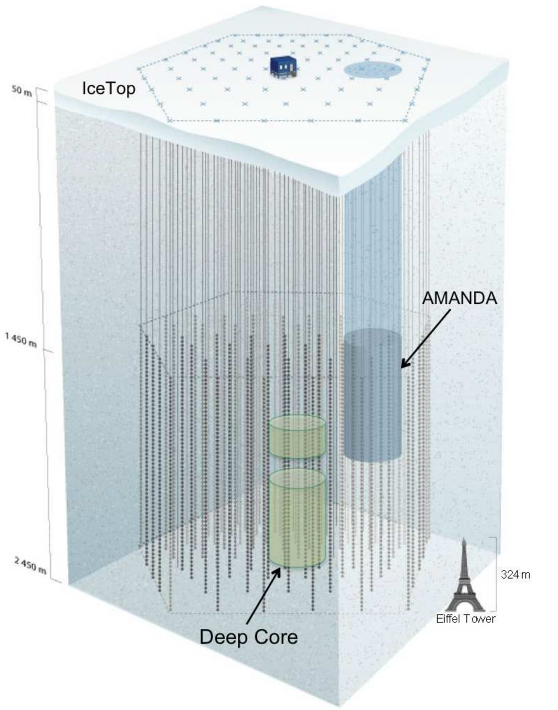

Figure 1: The IceCube detector, consisting of IceCube and IceTop and the low-energy sub-detector DeepCore. Also shown is the first-generation AMANDA detector.

by the possibility of opening a new window on the Universe using neutrinos as cosmic messengers. Specifically, we will revisit IceCube's prospects for detecting cosmic neutrinos associated with cosmic rays and for revealing their sources at a time when we are commemorating the 100th anniversary of their discovery by Victor Hess in 1912.

Cosmic accelerators produce particles with energies in excess of 10^8 TeV; we still do not know where or how[6)]. The flux of cosmic rays observed at Earth is shown in Fig.3. The energy spectrum follows a sequence of three power laws. The first two are separated by a feature dubbed the "knee" at an energy* of approximately 3 PeV. There is evidence that cosmic rays up to this energy are Galactic in origin. Any association with our Galaxy disappears in the vicinity of a second feature in the spectrum referred to as the "ankle"; see Fig.3. Above the ankle, the gyroradius of a proton in the Galactic magnetic field exceeds the size of the Galaxy, and we are witnessing the onset of an extragalactic component in the spectrum that extends to energies beyond 100 EeV. Direct support for this assumption now comes from two experiments [7)] that have observed the telltale structure in the cosmic-ray spectrum resulting from the absorption of the particle flux by the microwave background, the so-called Greissen-Zatsepin-Kuzmin (GZK) cutoff. Neutrinos are produced in GZK interactions; it was already recognized in the 1970s that their observation required kilometer-scale neutrino detectors. The origin of the cosmic-ray flux in the intermediate region covering PeV-to-EeV energies remains a mystery, although it is routinely assumed that it results from some high-energy extension of the reach of Galactic accelerators.

Acceleration of protons (or nuclei) to TeV energy and above requires massive bulk flows of relativistic charged particles. These are likely to originate from exceptional gravitational forces in the vicinity of black holes or neutron stars. The gravity of the collapsed objects powers large currents of charged particles that are the origin of high magnetic fields. These create the opportunity for

*We will use energy units TeV, PeV and EeV, increasing by factors of 1000 from GeV energy.

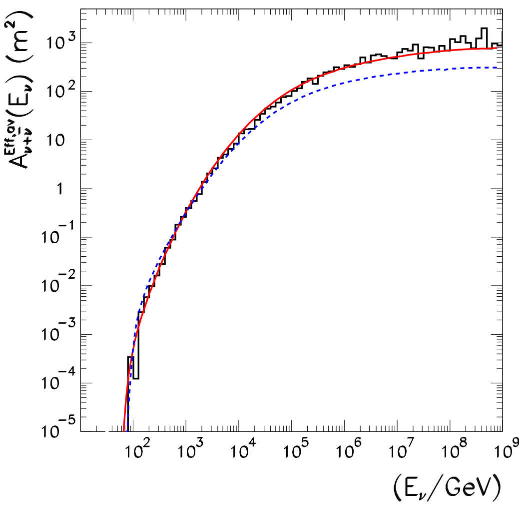

Figure 2: The neutrino effective area for point sources of cosmic neutrinos (averaged over the Northern Hemisphere) from IceCube simulation (black histogram) is compared to the convolution of the approximate muon effective area from reference[5] (solid red line) that we will use in the various estimates of event rates throughout this paper. The neutrino area exceeds the design area (shown as the dashed blue line) [4] at high energy.

particle acceleration by shocks. It is a fact that electrons are accelerated to high energy near black holes; astronomers detect them indirectly by their synchrotron radiation. Some must accelerate protons because we observe them as cosmic rays.

How many gamma rays and neutrinos are produced in association with the cosmic-ray beam? Generically, a cosmic-ray source should also be a beam dump. Cosmic rays accelerated in regions of high magnetic fields near black holes inevitably interact with radiation surrounding them, e.g., UV photons in active galaxies or MeV photons in gamma-ray-burst fireballs. In these interactions, neutral and charged pion secondaries are produced by the processes

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p \quad \text{and} \quad p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n.$$

While secondary protons may remain trapped in the high magnetic fields, neutrons and the decay products of neutral and charged pions escape. The energy escaping the source is therefore distributed among cosmic rays, gamma rays and neutrinos produced by the decay of neutrons, neutral pions and charged pions, respectively. In the case of Galactic supernova shocks, cosmic rays mostly interact with the hydrogen in the Galactic disk producing equal numbers of pions of all three charges in hadronic collisions $p + p \rightarrow n\,[\,\pi^0 + \pi^+ + \pi^-] + X$; n is the pion multiplicity. The flux should be enhanced in interaction of the cosmic rays with high-density molecular clouds that are ubiquitous in the star-forming regions where supernovae are more likely to explode.

Kilometer-scale neutrino detectors have the sensitivity to reveal generic cosmic-ray sources with an energy density in neutrinos comparable to their energy density in cosmic rays[8] and pionic TeV gamma rays[9].

2. Sources of Galactic Cosmic Rays

Supernova remnants were proposed as possible sources of Galactic cosmic rays as early as 1934 by Baade and Zwicky[10]; their proposal is still a matter of debate after more than 70 years[11]. Galactic

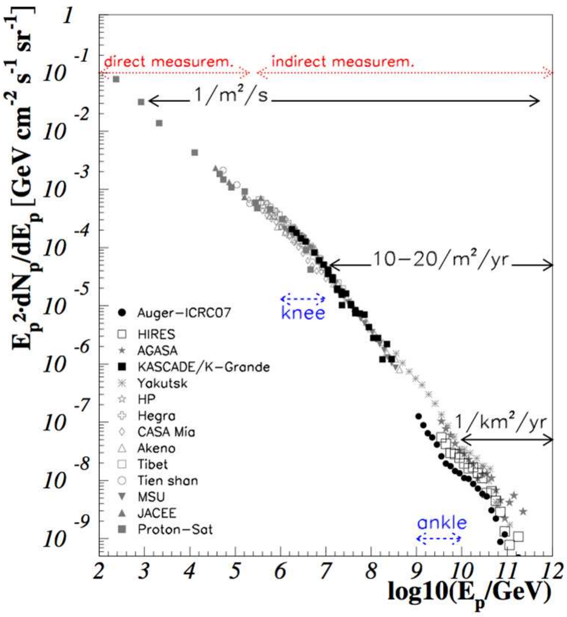

Figure 3: At the energies of interest here, the cosmic-ray spectrum follows a sequence of 3 power laws. The first 2 are separated by the "knee", the 2nd and 3rd by the "ankle". Cosmic rays beyond the ankle are a new population of particles produced in extragalactic sources.

cosmic rays reach energies of at least several PeV, the "knee" in the spectrum. Their interactions with Galactic hydrogen in the vicinity of the accelerator should generate gamma rays from the decay of secondary pions that reach energies of hundreds of TeV. Such sources should be identifiable by a relatively flat energy spectrum that extends to hundreds of TeV without attenuation, because the cosmic rays themselves reach at least several PeV near the knee; they have been dubbed PeVatrons. Straightforward energetics arguments are sufficient to conclude that present air Cherenkov telescopes should have the sensitivity necessary to detect TeV photons from PeVatrons[5,12)].

They may have been revealed by the highest-energy all-sky survey in ~ 10 TeV gamma rays with the Milagro detector[13)]. A subset of sources located within nearby star-forming regions in Cygnus and in the vicinity of Galactic latitude $l = 40$ degrees are identified; some cannot be readily associated with known supernova remnants or with non-thermal sources observed at other wavelengths. Subsequently, directional air Cherenkov telescopes were pointed at three of the sources, revealing them as PeVatron candidates with an approximate E^{-2} energy spectrum that extends to tens of TeV without evidence for a cutoff [14,15)], in contrast with the best studied supernova remnants RX J1713-3946 and RX J0852.0-4622 (Vela Junior).

Some Milagro sources may actually be molecular clouds illuminated by the cosmic-ray beam accelerated in young remnants located within ~ 100 pc. One expects indeed that multi-PeV cosmic rays are accelerated only over a short time period, when the remnant transitions from free expansion to the beginning of the Sedov phase and the shock velocity is high. The high-energy particles can produce photons and neutrinos over much longer periods when they diffuse through the interstellar medium to interact with nearby molecular clouds[16)]. An association of molecular clouds and supernova remnants is expected, of course, in star-forming regions.

Despite the rapid development of both ground-based and satellite-borne instruments with improved sensitivity, it has been impossible to conclusively pinpoint supernova remnants as the sources of cosmic-ray acceleration by identifying accompanying gamma rays of pion origin. In fact, recent data from Fermi LAT have challenged the hadronic interpretation of the GeV-TeV radiation from one of the best-studied candidates RX J1713-3946[17)]. In contrast, detecting the accompanying neutrinos provides incontrovertible evidence for cosmic-ray acceleration in cosmic- ray sources. Particle physics dictates the relation between pionic gamma rays and neutrinos and basically predicts the production of a $\nu_\mu + \bar{\nu}_\mu$ pair for every two gamma rays seen by Milagro. This calculation can be performed in a more sophisticated way with approximately the same outcome. We conclude that, within uncertainties in the source parameters, confirmation that Milagro mapped sources of Galactic cosmic rays should emerge after operating the complete IceCube detector for several years; see Fig.4.

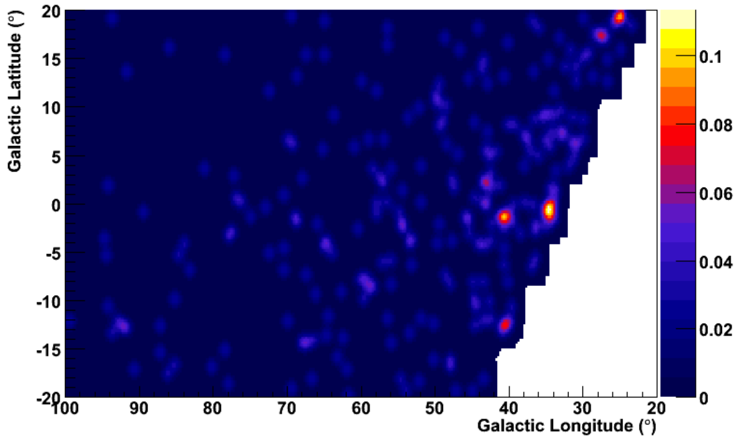

Figure 4: Simulated sky map of IceCube in Galactic coordinates after 5 years of operation of the completed detector. Two Milagro sources are visible "by eye" with 4 events for MGRO J1852+01 and 3 events for MGRO J1908+06 with energy in excess of 40 TeV. These, as well as the background events, have been randomly distributed according to the resolution of the detector and the size of the sources.

The quantitative statistics can be summarized as follows. For average values of the parameters describing the flux, we find that the completed IceCube detector could confirm sources in the Milagro sky map as sites of cosmic-ray acceleration at the 3σ level in less than one year and at the 5σ level in three years[5)]. We here assume that the source extends to 300 TeV, or 10% of the energy of the cosmic rays near the knee in the spectrum. These results agree with previous estimates[18)]. There are intrinsic ambiguities in this estimate of an astrophysical nature that may reduce or extend the time required for a 5σ observation[5)]. In the absence of observation of TeV-energy supernova neutrinos by IceCube in a period of 10 years, the nature of sources that produce cosmic rays near the knee of the spectrum will remain unresolved.

3. Sources of the Extragalactic Cosmic Rays

Although there is no direct evidence that supernovae accelerate cosmic rays, the idea is generally accepted because of energetics: three supernovae per century converting a reasonable fraction of a solar mass into particle acceleration can accommodate the steady flux of cosmic rays in the Galaxy. Originally, energetics also drove speculations on the origin of extragalactic cosmic rays.

By integrating the cosmic-ray spectrum in Fig.3 above the ankle, we find that the energy density of the Universe in extragalactic cosmic rays is $\sim 3\times10^{-19}$ erg cm^{-3} [8)]. The power required for a population of sources to generate this energy density over the Hubble time of 10^{10} years is $\sim 3\times10^{37}$ erg s^{-1} per (Mpc)^3. (In the astroparticle community, this flux is also known as 5×10^{44} TeV Mpc^{-3} yr^{-1}). A gamma-ray-burst (GRB) fireball converts a fraction of a solar mass into the acceleration of electrons, seen as synchrotron photons. The energy in extragalactic cosmic rays can be accommodated with the reasonable assumption that shocks in the expanding GRB fireball convert roughly equal energy into the acceleration of electrons and cosmic rays[19)]. It so happens that $\sim 2\times10^{52}$ erg per GRB will yield the observed energy density in cosmic rays after 10^{10} years, given that the rate is of order 300 per Gpc^3 per year. Hundreds of bursts per year over Hubble time produce the observed cosmic-ray density, just like three supernovae per century accommodate the steady flux in the Galaxy.

Problem solved? Not really: it turns out that the same result can be achieved assuming that active galactic nuclei (AGN) convert $\sim 2 \times 10^{44}$ erg s^{-1} per AGN into particle acceleration. As is the case for GRB, this is an amount that matches their output in electromagnetic radiation. Whether GRB or AGN, the observation that these sources radiate similar energies in photons and cosmic rays is consistent with the beam-dump scenario previously discussed. In the interaction of cosmic rays with radiation and gases near the black hole, roughly equal energy goes into the secondary neutrons and neutral pions whose energy ends up in cosmic rays and gamma rays, respectively.

Unlike what is the case for Galactic cosmic rays, there is no straightforward γ-ray path to the neutrino flux expected from extragalactic cosmic-ray accelerators. Neutrino fluxes from AGN are difficult to estimate. For GRB, the situation is qualitatively better, because neutrinos of PeV energy should be produced when protons and photons coexist in the GRB fireball [21)]. As previously discussed, the model is credible because the observed cosmic-ray flux can be accommodated with the assumption that roughly equal energy is shared by electrons, observed as synchrotron photons, and protons. The GRB neutrino flux is related to the cosmic ray flux by

$$\begin{aligned} \frac{dN_\nu}{dE_\nu} &= \left[1 - \left(1 - e^{-n_{int}}\right)\right] \frac{1}{3} x_\nu \frac{dN_p}{dE_p}\left(\frac{E_p}{x_\nu}\right) f_{GZK} \\ &\simeq n_{int}\ x_\nu\ \frac{dN_p}{dE_p}\left(\frac{E_p}{x_\nu}\right), \end{aligned} \tag{1}$$

where $x_\nu \simeq 0.05$ is the average relative energy of the neutrino and the parent proton and n_{int} ($\simeq 1$) is the average number of interactions of the proton with fireball photons before it becomes optically transparent and the photons escape. Neutrinos reach us from sources distributed over all redshifts, while cosmic rays do so only from local sources inside the so-called GZK radius of less than 100 Mpc. The evolution of the sources will boost the neutrino flux by a factor $f_{GZK} \simeq 3$ that depends on the redshift distribution of GRB.

The critical quantity normalizing the GRB neutrino flux is n_{int}; its calculation is relatively straightforward. The phenomenology that successfully accommodates the astronomical observations is that of the creation of a hot fireball of electrons, photons and protons that is initially opaque to radiation. The hot plasma therefore expands by radiation pressure, and particles are accelerated to a Lorentz factor Γ that grows until the plasma becomes optically thin and produces the GRB display. From this point on, the fireball coasts with a Lorentz factor that is constant and depends on its baryonic load. The baryonic component carries the bulk of the fireball's kinetic energy. The energetics and rapid time structure of the burst can be successfully explained by shocks (shells) of width ΔR generated in the expanding fireball. The rapid temporal variation of the gamma-ray burst, t_v, is of the order of milliseconds, and can be interpreted as the collision of internal shocks with a varying baryonic load leading to differences in the bulk Lorentz factor. Electrons accelerated by first-order Fermi acceleration radiate synchrotron gamma rays in the strong internal magnetic field, and thus produce the spikes observed in the burst spectra.

The number of interactions is determined by the optical depth of the fireball shells to pγ interactions

$$n'_{int} = \frac{\Delta R'}{\lambda_{p\gamma}} = (\Gamma c t_v)\left(n'_\gamma \sigma_{p\gamma}\right). \tag{2}$$

The primes refer to the burst rest frame; unprimed quantities are in the observer frame. The density of fireball photons depends on the total energy in the burst $E_{GRB} \simeq 2 \times 10^{52}$ erg, the characteristic photon energy of $E_\gamma \simeq 1\,MeV$ and the volume V' of the shell

$$n'_\gamma = \frac{E_{GRB}/E_\gamma}{V'}, \tag{3}$$

with

$$V' = 4\pi R'^2 \Delta R' = 4\pi \left(\Gamma^2 c t_v\right)^2 (\Gamma c t_v)\,. \tag{4}$$

The only subtlety here is the Γ^2 dependence of the shell radius R'; for a simple derivation see ref. 21.

For typical choices of the parameters $\Gamma \sim 300$ and $t_v \sim 10^{-2}s$, about 100 events per year are predicted in IceCube, a flux that is already challenged[24)] by the limit on a diffuse flux of cosmic neutrinos obtained with one-half of IceCube in one year[25)]. Facing this negative conclusion, Ahlers *et al.* have investigated the dependence of the predicted neutrino flux on the cosmological evolution of the sources as well as on the parameters describing the fireball, most notably E_{GRB}, Γ and t_v. Although these are constrained by the electromagnetic observation and by the the requirement that the fireball must accommodate the observed cosmic-ray spectrum, the predictions can be stretched to the point that it will take 3 years of data with the now-completed instrument to conclusively rule out the GRB origin of the extragalactic cosmic rays; see Fig.5. Alternatively, detection of their neutrino emission may be imminent.

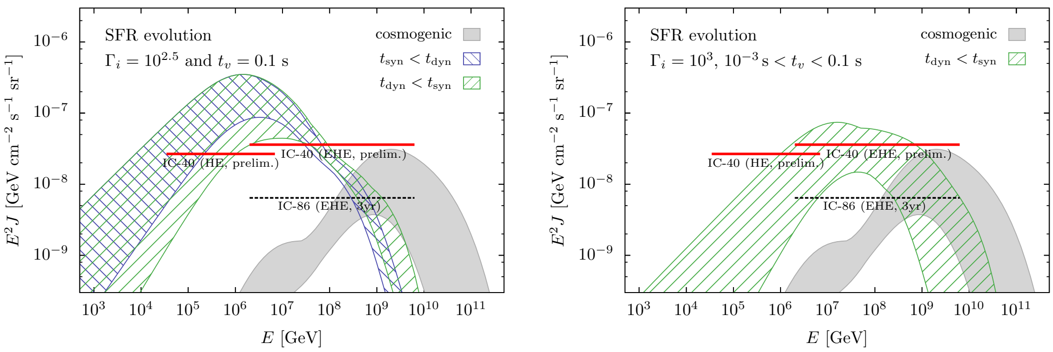

Figure 5: GRB neutrino spectra (the prompt spectrum emitted by the sources and neutrino spectrum generated in GZK interactions are shown separately), assuming the luminosity range $0.1 < (\epsilon_B/\epsilon_e)\, L_{\gamma,52} < 10$ and star-forming redshift evolution of the sources. Here $\epsilon_{e,B}$ are the fractional energies in the fireball carried by the electrons and the magnetic field; the two are equal in the case of equipartition. $L_{\gamma,52}$ is the photon energy in units of 10^{52} erg. We show the prompt spectra separately for models where the fireball's dynamical timescale t_{dyn} is smaller(larger) than the synchrotron loss time scale t_{syn} (green right-hatched and blue left-hatched respectively). Here the dynamical time scale is just the variability scale $t_{dyn} = t_v$ and $t'_{dyn} = t_v\Gamma$. The IceCube limits[25)] on the total neutrino flux from the analysis of high-energy and ultrahigh-energy muon neutrinos with the 40 string sub-array assume 1:1:1 flavor composition after oscillation. We also show the sensitivity of the full IceCube detector (IC-86) to muon neutrinos after 3 years of observation. The gray solid area shows the range of GZK neutrinos expected at the 99% C.L.

Although it is well known that GRBs satisfy the necessary conditions for accelerating protons to UHE, it is problematic how these protons may eventually be ejected as cosmic rays: protons are magnetically connected to the expanding fireball, and its adiabatic cooling will reduce the maximum proton energy significantly. However, this does not apply to neutrons that are produced in pγ-interactions of accelerated protons with fireball photons. Cosmic-ray protons could thus be identified as neutrons that can escape from the magnetic environment and decay back to protons at a safe distance. As was already discussed, a smoking-gun test of this scenario is the production of PeV neutrinos from decay of the charged pions inevitably produced along with the neutrons. Identifying the observed cosmic rays with secondary neutrons rather than fireball protons significantly raises the contributions of individual GRB to the energy budget in the Universe of $\sim 3 \times 10^{-19}$ erg cm^{-3}.

Is the GRB origin of sources of the highest-energy cosmic rays challenged? Recall that calculation of the GRB neutrino flux is normalized to the observed total energy in extragalactic cosmic rays of $\sim 3\times10^{-19}$ erg cm^{-3}, a value that is highly uncertain because it critically depends on the assumption that no cosmic rays above the ankle are Galactic in origin. Although direct fits to the spectrum support this assumption[24)], by shifting this transition to higher energies one can reduce the energy budget by as much as an order of magnitude. The lower value of 0.5×10^{44} TeV Mpc^{-3} yr^{-1} can be accommodated with a more modest fraction of $\sim 2 \times 10^{51}$ erg (or $\sim 1\,\%$ of a solar mass) going into particle acceleration in individual bursts. We will revisit this issue in the context of GZK neutrinos.

While this temporarily remedies the direct conflict with the present diffuse limit, IceCube has the alternative possibility to perform a direct search for neutrinos in spatial and time coincidence with GRB observed by the Swift and Fermi satellites. In this essentially background-free search, 14 events are expected when IceCube operated with 40 and 59 strings during 2 years of construction, even for the lowest value of the cosmic-ray energy budget of 0.5×10^{44} TeV Mpc^{-3} yr^{-1}. Two different and independent searches failed to observe this flux at the 90% confidence level[26)]. Also, the reliability of calculating the neutrino flux is an issue here and, as already discussed, IceCube has the potential to confirm or rule out GRB as the sources of the highest-energy cosmic rays within 3 years of operation.

If, on the contrary, AGN were indeed the sources, the proximity of the Fanaroff-Riley I active galaxies Cen A and M87 singles them out as potential accelerators[27,28)]. As we did for the Milagro sources, we have attempted to translate their TeV gamma rays into a neutrino flux, although interpreting TeV gamma-ray observations is in this case challenging. The high-energy emission of AGN is indeed extremely variable, and it is difficult to compare multi-wavelength data taken at different times. A best guess of the gamma-ray flux yields a neutrino flux from a single source such as Cen A that is small, typically less than one event per year, even if all gammas in the TeV range are assumed to be of pionic origin. The diffuse flux from all FRI yields a more comfortable event rate of between 19 and 0.5 neutrinos per year, assuming a spectral index between 2 and 3. A detailed discussion of these estimates has been presented elsewhere[29)].

4. Neutrinos from GZK Interactions

Whatever the sources of the extragalactic cosmic rays may be, a cosmogenic flux of neutrinos originates from the interactions of cosmic rays with the cosmic microwave background (CMB). Produced within a GZK radius from a source located at a cosmological distance, GZK neutrinos point back to it with good precision. The calculation of the GZK neutrino flux is relatively straightforward, and its magnitude is very much determined by their total energy density in the universe; this brings back the crossover from the Galactic to the extragalactic component as a critical parameter. Recent calculations[31)] are shown in Fig.6. It is also important to realize that, among the $\mathrm{p}\,\gamma$ final state products produced via the decay of pions, the neutrinos are accompanied by electrons, positrons and γ-rays that quickly cascade on the CMB and intergalactic magnetic fields to lower energies. An electromagnetic cascade develops with a maximum in the GeV-TeV energy region. Here the total energy in the electromagnetic cascade is constrained by recent Fermi-LAT measurements of the diffuse extragalactic γ-ray background[30)].

The increased performance of IceCube at EeV energy has opened the possibility for IceCube to detect GZK neutrinos. We anticipate 2.3 events in 3 years of running the completed IceCube detector, assuming the best fit in Fig.6, and 4.8 events for the highest flux consistent with the Fermi constraint.

Throughout the discussion, we have assumed that the highest-energy cosmic rays are protons. Experiments disagree on the composition of particles around 10^{20} eV. Little is known about the chemical composition from just below to beyond the GZK cutoff, where the most significant contribution to cosmogenic neutrinos is expected. In any case, uncertainties in extrapolation of the proton-air interaction cross-section, elasticity and multiplicity of secondaries from accelerator measurements to the high energies characteristic for air showers are large enough to undermine any definite conclusion on the chemical composition[32)]. Therefore, the conflicting claims by these experiments most likely illustrate that the particle physics is not sufficiently known to derive a definite

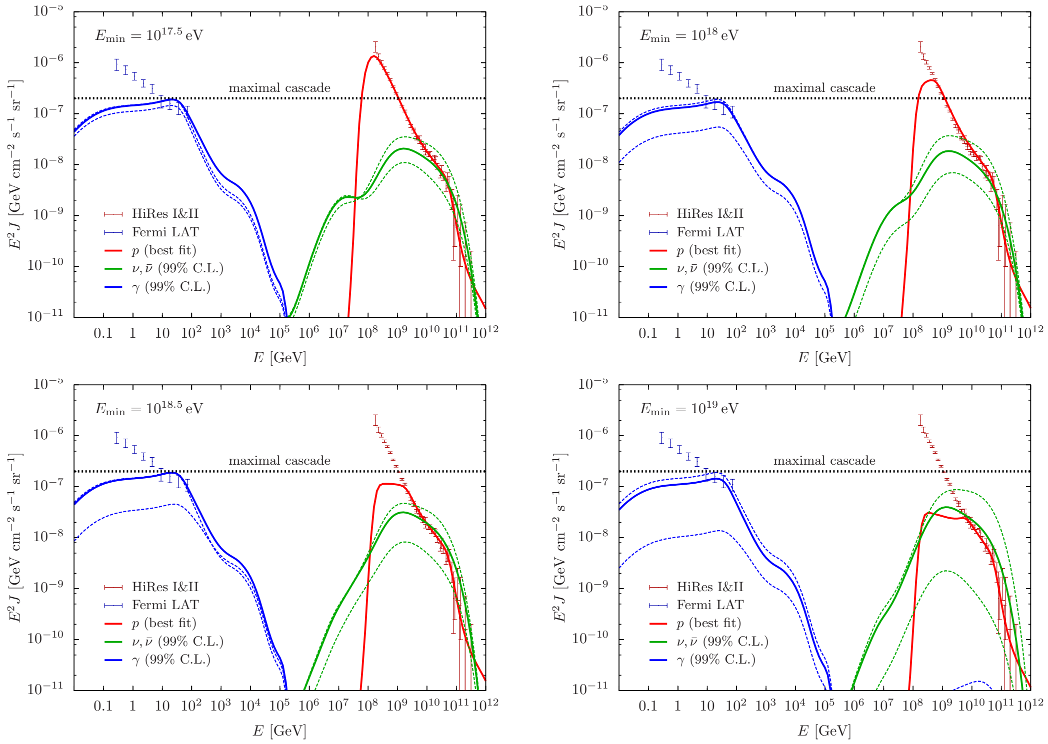

Figure 6: Comparison of proton, neutrino and gamma ray fluxes produced in interactions on the CMB by cosmic-ray protons fitted to HiRes data. We repeat the calculation for 4 values of the crossover energy marking the transition to the extragalactic cosmic ray flux. We show the best fit values (solid lines) as well as neutrino and gamma-ray fluxes within the 99% C.L. with minimal and maximal energy density (dashed lines). The γ-ray fluxes are marginally consistent at the 99% C.L. with the highest-energy measurements by Fermi-LAT. The contribution around 100 GeV is somewhat uncertain, due to uncertainties in the cosmic infrared background.

result. Dedicated experiments at the LHC may remedy this situation.

5. Conclusion: Stay Tuned

In summary, IceCube was designed for a statistically significant detection of cosmic neutrinos accompanying cosmic rays in 5 years. In this talk, I attempted to make the case that we are indeed closing in on supernova remnants, GRB (if they are the sources of cosmic rays) and GZK neutrinos. One should not forget, however, that the most exciting IceCube science may come from the detection of dark matter, the observation of a Galactic supernova explosion, or from the particle physics of the neutrinos themselves.

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