

IceCube Science

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Abstract. We discuss the status of the kilometer-scale neutrino detector IceCube and its low energy upgrade Deep Core and review its scientific potential for particle physics. We subsequently appraise IceCube's potential for revealing the enigmatic sources of cosmic rays. After all, this aspiration set the scale of the instrument. While only a smoking gun is missing for the case that the Galactic component of the cosmic ray spectrum originates in supernova remnants, the origin of the extragalactic component remains as inscrutable as ever. We speculate on the role of the nearby active galaxies Centaurus A and M87.

1. The First Kilometer-Scale High Energy Neutrino Detector: IceCube

A series of first-generation experiments [1] have demonstrated that high energy neutrinos with ~ 10 GeV energy and above can be detected by observing the 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. The first second-generation detector, IceCube, is under construction at the geographic South Pole [2]. IceCube will consist of 80 kilometer-length strings, each instrumented with 60 10-inch photomultipliers spaced by 17 m. 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. The strings are arranged at the apexes of equilateral triangles 125 m on a side. The instrumented detector volume is a cubic kilometer of dark, highly transparent and totally sterile Antarctic ice. The radioactive background is dominated by the instrumentation deployed into the natural ice. A surface air shower detector, IceTop, consisting of 160 Auger-style 2.7 m diameter ice-filled Cherenkov detectors deployed pairwise at the top of each in-ice string, augments the deep-ice component by providing a tool for calibration, background rejection and cosmic ray studies.

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 the 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 that reveal the direction of the parent neutrino [3].

IceCube detects neutrinos with energies in excess of 0.1 TeV. An upgrade of the detector, dubbed Deep Core, consists of an infill of 6 strings with 60 DOMs with high quantum efficiency. They are mostly deployed in the highly transparent ice making up the bottom half of the

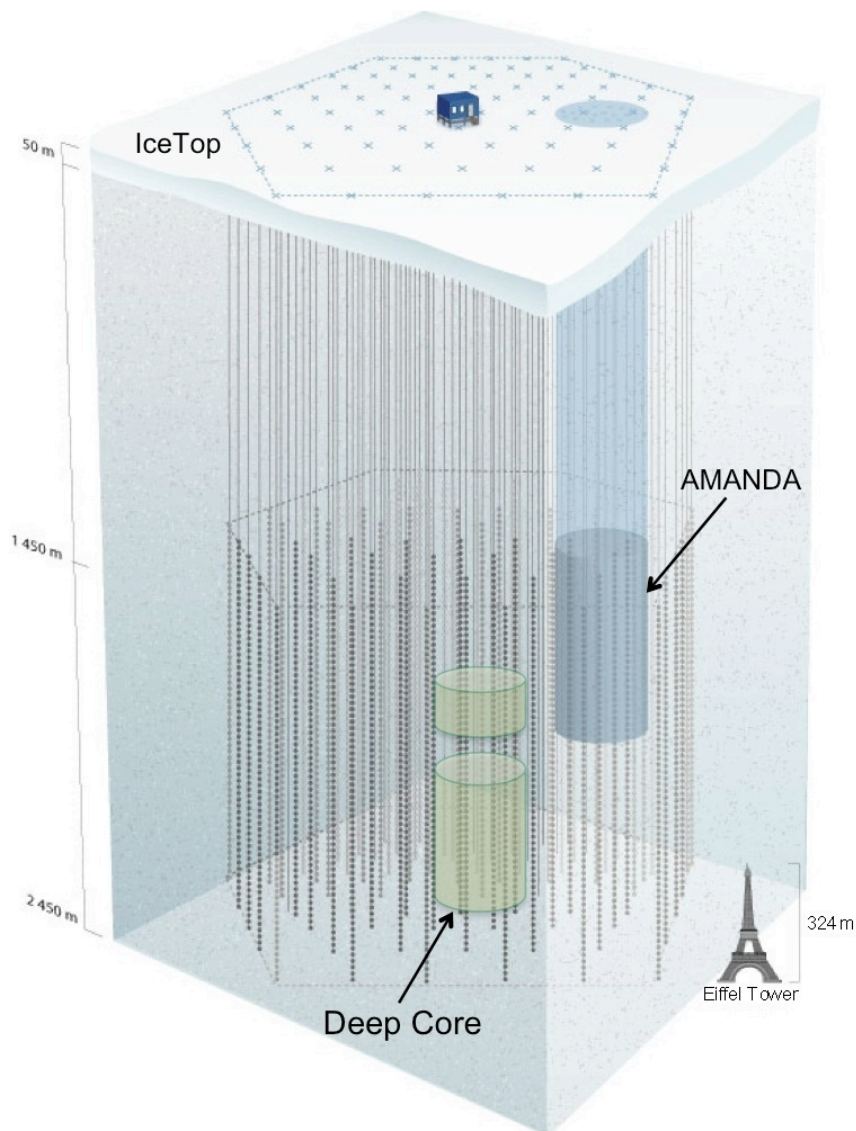


Figure 1. The IceCube detector, consisting of IceCube and IceTop and the low-energy sub-detector DeepCore. Also shown is the first-generation AMANDA detector.

IceCube detector. Deep Core will decrease the threshold to ~ 10 GeV over a significant fraction of IceCube's fiducial volume and will be complete by February 2010; see Fig. 1.

The main scientific goals of IceCube fall into broad categories:

- (i) Detect astrophysical neutrinos produced in cosmic sources with an energy density comparable to the energy density in cosmic rays[4]. Supernova remnants satisfy this requirement if they are indeed the sources of the galactic cosmic rays as first proposed by Zwicky; his proposal is a matter of debate after more than seventy years. The sources of the extragalactic cosmic rays naturally satisfy the prerequisite when particles accelerated

near black holes, possibly the central engines of active galaxies or gamma ray bursts, collide with photons in the associated radiation fields. While the secondary protons may remain trapped in the acceleration region, approximately equal numbers of neutrons, neutral and charged pions escape. The energy escaping the source is therefore distributed between cosmic rays, gamma rays and neutrinos produced by the decay of neutrons and neutral and charged pions, respectively. We will elaborate on the potential of IceCube to reveal the sources of the cosmic rays; this goal is of primary importance as it sets the scale of the detector.

- (ii) As for conventional astronomy, neutrino astronomers observe the neutrino sky through the atmosphere. This is a curse and a blessing; the background of neutrinos produced by cosmic rays in interactions with atmospheric nuclei provides a beam essential for calibrating the instrument. It also presents us with an opportunity to do particle physics [5]. Especially unique is the energy range of the background atmospheric neutrino beam covering the interval $1 - 10^5$ TeV, energies not within reach of accelerators. Cosmic beams of even higher energy may exist, but the atmospheric beam is guaranteed. IceCube is expected to collect a data set of order one million neutrinos over ten years with a scientific potential that is only limited by our imagination.
- (iii) The passage of a large flux of MeV-energy neutrinos produced by a galactic supernova over a period of seconds will be detected as an excess of the background counting rate in all individual optical modules [6]. Although only a counting experiment, IceCube will measure the time profile of a neutrino burst near the center of the Galaxy with a statistics of about one million events, equivalent to the sensitivity of a 2 megaton detector.
- (iv) IceCube will search for neutrinos from the annihilation of dark matter particles gravitationally trapped at the center of the Sun and the Earth [7]. In searching for generic weakly interacting massive dark matter particles (WIMPs) with spin-independent interactions with ordinary matter, IceCube is only competitive with direct detection experiments [8] if the WIMP mass is sufficiently large. For spin-dependent interactions IceCube already has improved the best limits on spin-dependent WIMP cross sections by two orders of magnitude [9].

Construction of IceCube and other high-energy neutrino telescopes is mostly motivated by their potential to open a new window on the Universe using neutrinos as cosmic messengers; more about this in the rest of the talk. The IceCube experiment nevertheless appeared on the U.S. Roadmap to Particle Physics [10]. As the lightest of fermions and the most weakly interacting of particles, neutrinos occupy a fragile corner of the Standard Model and one can realistically hope that they will reveal the first and most dramatic signatures of new physics.

Besides its potential to detect dark matter, IceCube's opportunities for particle physics include [11]

- (i) The search for signatures of the unification of particle interactions, possibly including gravity at the TeV scale. In this case neutrinos approaching TeV energies would interact gravitationally with large cross sections, similar to those of quarks and leptons; this increase yields dramatic signatures in a neutrino telescope including, possibly, the production of black holes [12].
- (ii) The search for modifications of neutrino oscillations that result from non-standard neutrino interactions [13].
- (iii) Searching for flavor changes or energy-dependent delays of neutrinos detected from cosmic distances as a signature for quantum decoherence.
- (iv) The search for a breakdown of the equivalence principle as a result of non-universal interactions with the gravitational field of neutrinos with different flavor.

- (v) Similarly, the search for a breakdown of Lorentz invariance resulting from different limiting velocities of neutrinos of different flavors. With energies of 10^3 TeV and masses of order 10^{-2} eV or less, even the atmospheric neutrinos observed by IceCube reach Lorentz factors of 10^{17} or larger.
- (vi) The search for particle emission from cosmic strings or any other topological defects or heavy cosmological remnants created in the early Universe. It has been suggested that they may be the sources of the highest energy cosmic rays.
- (vii) The search for magnetic monopoles, Q-balls and the like.

The Deep Core upgrade of IceCube will significantly extend IceCube's scientific potential as an atmospheric neutrino detector. It will accumulate atmospheric neutrino data covering the first oscillation dip near 20 GeV with unprecedented statistics. Its instrumented volume is of order 10 Mton. Buried deep inside IceCube, Deep Core will use the surrounding strings as a veto in order to observe the tracks of contained events; see Fig. 1. It has been shown that the event statistics is sufficient to determine the mass hierarchy to at least 90% confidence level assuming the current best-fit values of the oscillation parameters, and for values of θ_{13} close to the present bound [14]. A positive result will also require a sufficient understanding of the systematics of the measurement. This is under investigation and although a result is at this point not guaranteed, the good news is that the relevant data are forthcoming in the next few years.

The physics behind the measurement is the same as for long baseline experiments [15]; the key is to measure the Earth matter effects associated with the angle θ_{13} which governs the transitions between ν_e and $\nu_{\mu,\tau}$. The effective θ_{13} mixing angle in matter in a two-flavor framework is given by:

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (\cos 2\theta_{13} \pm \frac{\sqrt{2}G_F N_e}{\Delta_{13}})^2}, \quad (1)$$

where the plus (minus) sign refers to (anti) neutrinos. N_e is the electron number density of the Earth, $\sqrt{2}G_F N_e$ (eV) = $7.6 \times 10^{-14} Y_e \rho$ (g/cm³) and Y_e, ρ the electron fraction and the density of the Earth's interior. The critical quantity is $\Delta_{13} = \Delta_{13}^2/2E$; its sign determines the mass hierarchy. The resonance condition is satisfied for neutrino energies of order 15 GeV for the baselines of thousands of kilometers studied in atmospheric neutrino experiments. Deep Core extends the threshold of IceCube to this energy. Both the disappearance of muon neutrinos and the appearance of tau and electron neutrinos can be observed.

In the presence of Earth matter effects the neutrino (antineutrino) oscillation probability is enhanced if the hierarchy is normal (inverted). Long baseline detectors, unlike IceCube, measure the charge of the secondary muon thus selecting the sign associated with each event in above equation. The hierarchy is determined by simply looking in which channel, neutrino or antineutrino, the signal is enhanced by matter effects. Provided that the mixing parameter $\sin^2 2\theta_{13}$ is not too small and the statistics sufficient, the magnitude of the Δ_{13} term can be measured even without charge discrimination. This is in principle possible with Deep Core [14] but cannot be guaranteed until the systematics of the detector has been studied in the unexplored low energy range.

We next return to IceCube's prospects to detect cosmic neutrinos and, possibly, reveal the sources of the cosmic rays prior to the one hundredth anniversary of their discovery by Victor Hess in 1912. Although impressive progress has been made, driven by the commissioning of a new generation of air Cherenkov telescopes and the Auger air shower array, the origin of cosmic rays is as enigmatic as ever. Observations show that candidate cosmic accelerators such as supernova remnants, active galaxies and gamma ray bursts emit roughly equal energies in cosmic rays and gamma rays. We will argue that a similar amount of energy should be radiated in neutrinos and that, in this case, IceCube will reveal the sources.

2. The energetics of cosmic ray sources

Cosmic accelerators produce particles with energies in excess of 10^8 TeV; we still do not know where or how [16]. The flux of cosmic rays observed at Earth is shown in Fig. 2. The energy spectrum follows a broken power law. The two power laws are separated by a feature dubbed the “knee” at an energy¹ 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. 2. Above the ankle, the gyroradius of a proton in the Galactic magnetic field exceeds the size of the Galaxy and it is routinely assumed that 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 [17] 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 Greisen-Zatsepin-Kuzmin cutoff². The origin of the flux in the intermediate region covering PeV to EeV energies remains a complete mystery. Although the routine assumption is that it results from some high energy extension of the reach of the Galactic accelerators, no convincing mechanism for this has been identified.

It is assumed that cosmic rays originate in cosmic accelerators³. Acceleration to TeV energy and above requires massive bulk flows of relativistic charged particles. These are likely to originate from the exceptional gravitational forces in the vicinity of black holes or neutron stars. Gravity powers large currents of charged particles that are the origin of high magnetic fields. These create the opportunity for particle acceleration by shocks. It is a fact that black holes accelerate electrons to high energy; astronomers observe them indirectly by their synchrotron radiation. Some must accelerate protons because we detect them as cosmic rays.

The Swiss astronomer Fritz Zwicky suggested as early as 1933 that supernova remnants could be sources of the Galactic cosmic rays. It is assumed that the accelerators are powered by the conversion of 10^{50} erg of energy into particle acceleration by diffusive shocks associated with young (~ 1000 year old) supernova remnants expanding into the interstellar medium [18]. Like a snowplough, the shock sweeps up the ~ 1 proton/cm³ density of hydrogen in the Galactic plane. The accumulation of dense filaments of particles in the outer reaches of the shock, clearly visible as sources of intense X-ray emission, are the sites of high magnetic fields. It is theorized that particles crossing these structures multiple times can be accelerated to high energies following an approximate power-law spectrum $dN/dE \sim E^{-2}$. The mechanism is familiar from solar flares where filaments of high magnetic fields accelerate nuclear particles to tens of GeV. The higher energies reached in cosmic ray accelerators are the consequence of particle flows of much larger intensity powered by the gravitational energy of collapsed objects such as neutron stars and black holes.

From a myriad of ideas, speculations on the sites for the acceleration of extragalactic cosmic rays have converged on the supermassive black holes at the centers of active galactic nuclei (AGN) or the primary engines of gamma ray bursts (GRB). It should surprise nobody, however, if the final answer turned out to be neither of these.

AGN are of special interest because some emit most of their luminosity at TeV energy and above. Their inferred isotropic luminosities can be as high as $10^{45} - 10^{49}$ erg s⁻¹. They produce a typical spectrum $dN/dE_\gamma \propto E^{-2}$ in the MeV-GeV range. The energetics requires mass accretion

¹ We will use energy units TeV, PeV and EeV, increasing by factors of one thousand from GeV-energy.

² The possibility has not been eliminated that the “cutoff” is simply the maximum energy reached by the accelerator(s).

³ Speculations on the origin of the highest energy cosmic rays fall into two categories, top-down and bottom-up. In top-down models it is assumed that the cosmic rays are the decay products of cosmological remnants or topological defects associated with, for instance, Grand Unified theories with unification energy $M_{\text{GUT}} \sim 10^{24}$ eV. These models predict, besides cosmic rays, large fluxes of gamma rays and neutrinos that have not been observed.

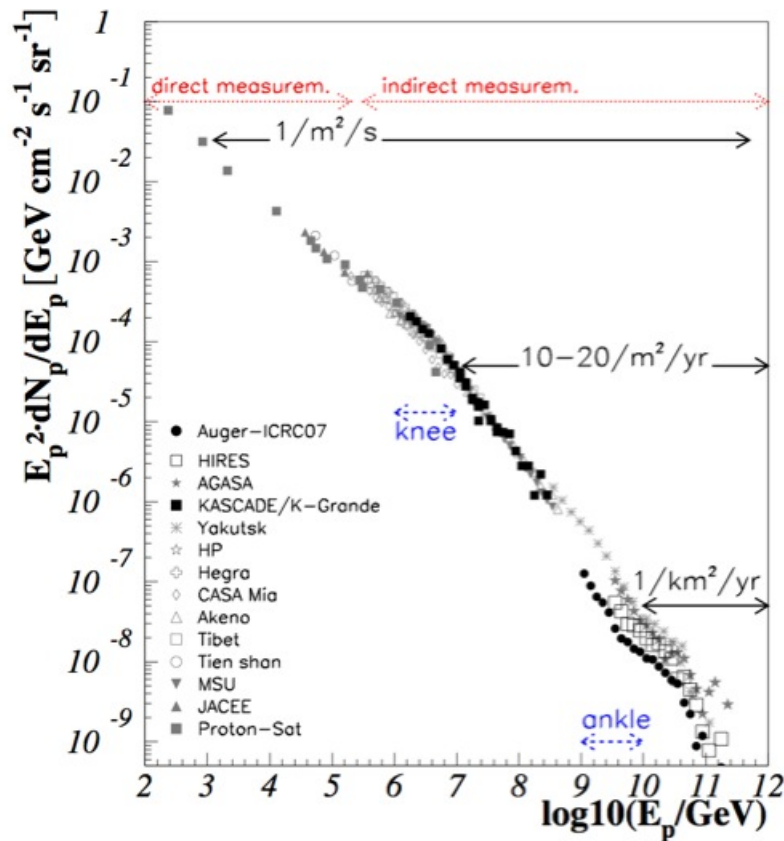


Figure 2. At the energies of interest here, the cosmic ray spectrum follows a sequence of 3 power laws. The first two are separated by the knee, the second and third by the ankle. The cosmic rays beyond the ankle are a new population of particles produced in extragalactic sources.

on a black hole that is up to one billion times more massive than our Sun. Some of the matter falling onto the black hole is deflected and accelerated in highly beamed jets aligned along its rotation axis. Both the inflow onto the central engine and the jet provide opportunities for the buildup of large magnetic fields and shock acceleration. For all these reasons AGN were pinpointed by Ginzberg and Syrovatskii [19] as far back as 1964 as candidate cosmic ray accelerators. A subset, called blazars, emit high-energy radiation in collimated jets pointing at the Earth and are the sources of photons with energies of tens of TeV. Their emission is highly variable over several time scales. TeV-energy bursts as short as minutes have been observed. Exceptionally, the nearest active galaxies, Centaurus A (Cen A) and M87 have been detected in TeV gamma rays even though their jets are not pointing at us.

Some argue instead that gamma ray bursts (GRB), outshining the entire Universe for the duration of the burst, are the best motivated sources of high energy cosmic rays [20]. The collapse of a massive star to a black hole has emerged as the origin of “long” GRB with durations of tens of seconds. In the collapse a fireball is produced of electromagnetic plasma that expands with a highly relativistic velocity powered by radiation pressure. The fireball eventually runs into the stellar material that is still accreting onto the black hole. If it successfully punctures through this stellar envelope the fireball emerges to produce a GRB display. While the energy transferred to highly relativistic electrons is observed in the form of synchrotron radiation, it is a matter of speculation how much energy is transferred to protons. The assumption that GRB

are the sources of the highest energy cosmic rays determines the energy of the baryons in the fireball. Accommodating the observed energy spectrum of extragalactic cosmic rays leads to the requirement of roughly equal efficiency for conversion of fireball energy into the kinetic energy of protons and electrons.

It is routinely emphasized that the flux of cosmic rays, especially at the highest energies, is very low. For example, at the onset of the extragalactic component near 10 EeV the flux is only at the level of one particle per kilometer squared per year for a typical array with a steradian acceptance in angle. This can be translated into an energy flux

$$E \left\{ E \frac{dN}{dE} \right\} = \frac{10^{19} \text{ eV}}{(10^{10} \text{ cm}^2)(3 \times 10^7 \text{ s}) \text{ sr}} = 3 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (2)$$

The particles may be few, but each carries an enormous energy that can be expressed in macroscopic units, tens of Joules for the highest energies. We can derive the average energy density ρ_E of cosmic rays in the Universe using the relation that the total flux = velocity \times density, or

$$4\pi \int dE \left\{ E \frac{dN}{dE} \right\} = c\rho_E. \quad (3)$$

We obtain

$$\rho_E = \frac{4\pi}{c} \int_{E_{\min}}^{E_{\max}} \frac{3 \times 10^{-8}}{E} dE \frac{\text{GeV}}{\text{cm}^3} \simeq 10^{-19} \frac{\text{TeV}}{\text{cm}^3}, \quad (4)$$

taking the extreme energies of the accelerator(s) to be $E_{\max}/E_{\min} \simeq 10^3$. This is the value for cosmic rays corresponding to the energy density of, for instance, microwave photons of 410 photons of 2.7 K per cubic centimeter.⁴

The energy content derived “professionally” by integrating the observed extragalactic spectrum in Fig. 2, including the GZK feature, is $\sim 3 \times 10^{-19} \text{ erg cm}^{-3}$ [21]. This is within a factor of our back-of-the-envelope estimate (1 TeV = 1.6 erg).

It has been realized for a long time that the corresponding quantity for the Galactic component of the spectrum may be a revealing number. If one repeats the integration that we just introduced for the Galactic flux in Fig. 2, from TeV-energy up to the knee near 3 PeV, one obtains an energy density of the cosmic rays in our Galaxy of

$$\rho_E \sim 10^{-12} \text{ erg cm}^{-3}.$$

This happens to be very close to the energy density of light in our Galaxy and to the energy density $B^2/8\pi$ in its microgauss magnetic field. This density, as well as the one for extragalactic cosmic rays in the Universe, represent informative benchmarks for speculating on the sources.

3. Multi-wavelength Astronomy: Cosmic rays, gamma rays and neutrinos

Although the origin of cosmic rays remains a matter of speculation, particle astrophysicists have developed ambitious instrumentation that probes their sources with increased sensitivity detecting cosmic rays, gamma rays and neutrinos. In the 3-prong attack on the cosmic ray problem, TeV-astronomy is by far the most mature [22]. A new generation of ground based air Cherenkov detectors has revealed plausible candidate cosmic ray sources, some, surprisingly, had not been previously identified in other wavelengths. However, the basic hurdle to conclusively identify the observed TeV gamma rays as the decay products of pions produced by a cosmic ray accelerator has not been overcome. Synchrotron radiation by energetic electrons, routinely

⁴ We note that the energy density of photons changes by less than 5 orders of magnitude over the electromagnetic spectrum, from radio waves to GeV-photons, while the flux drops by almost 20 orders of magnitude.

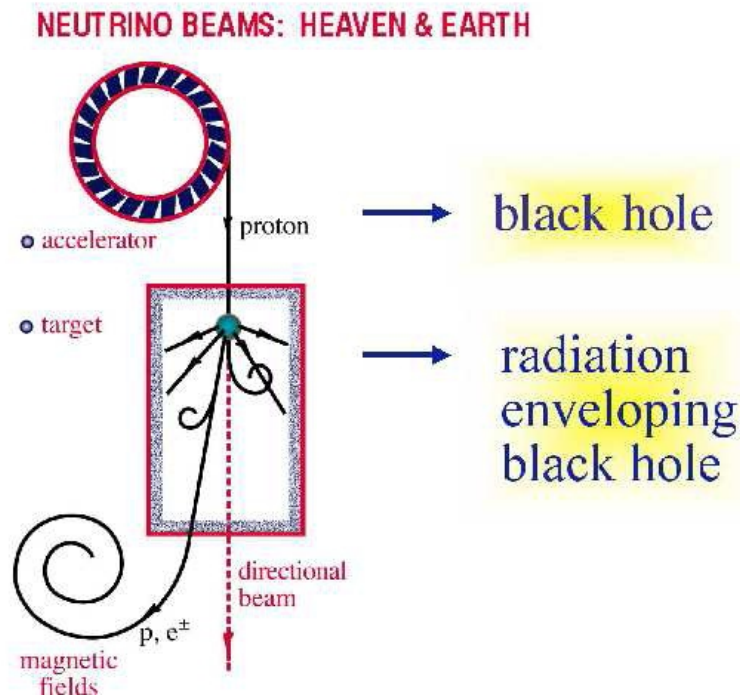


Figure 3. Sketch of a cosmic ray accelerator producing photons and neutrinos. Cosmic rays accelerated in the vicinity of a black hole produce pions in interactions with the radiation and gases surrounding it. Neutral and charged pions decay into photons and neutrinos, respectively.

observed in non-thermal sources such as supernova remnants, AGN and GRB, cannot be excluded as their origin. Neutrinos from the decay of charged pions accompanying pionic gamma rays can provide incontrovertible evidence for cosmic ray acceleration. The predicted fluxes are small and difficult to detect [23]. Let's quantify the problem.

How many gamma rays and neutrinos are produced in association with the cosmic ray beam? For orientation, consider the neutrino beam produced at an accelerator laboratory in Fig. 3. The accelerated protons interact with a target, referred to as a beam dump, producing pions that decay into gamma rays and neutrinos.⁵ 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 the radiation surrounding it, for instance, UV photons in active galaxies or the MeV-photons in GRB fireballs. In these interactions they generate neutral and charged pions by the processes

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

While the 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 reality the relation between the secondary fluxes is more complex. The cosmic rays may interact with gas besides radiation producing equal numbers of pions of all three charges in

⁵ For earthbound accelerators the dump is designed to reabsorb all secondary electromagnetic and hadronic showers. Only neutrinos exit the dump. If Nature constructed such a "hidden source" in the heavens, conventional astronomy would not reveal it.

hadronic collisions $p + p \rightarrow n[\pi^0 + \pi^+ + \pi^-] + X$. Pionic gamma rays may cascade in the source steepening their spectrum and, as already pointed out, there may be an additional contribution to the gamma ray flux originating from purely electromagnetic processes.

The secondary flux of neutrinos and gamma rays in astrophysical sources can be related to the initial accelerated proton spectrum by specifying the final-state multiplicities of the pions and their average fractional energies x_i relative to the proton. For instance, in hadronic collisions of cosmic rays interacting with gas in or near the source, equal numbers of each pion charge $\pi^0 + \pi^+ + \pi^-$ are produced. The neutral pions decay into two gamma-rays $\pi^0 \rightarrow \gamma + \gamma$ and the charged pions into leptons and neutrinos $\pi^\pm \rightarrow e^\pm + \nu_\mu + \nu_e$. The effect of neutrino oscillations is to equalize the number of neutrinos of each flavor arriving at Earth, resulting into one neutrino of each flavor per charged pion. In summary, we obtain two-thirds of a charged pion per interacting proton and one neutrino (of each flavor) per charged pion; and one-third of a neutral pion per interacting proton and two photons per neutral pion. Therefore,

$$\frac{dN_\nu}{dE}(E) = 1 \times \frac{2}{3} \times \frac{1}{x_\nu} \times \frac{dN_p}{dE}\left(\frac{E}{x_\nu}\right) \quad (5)$$

$$\frac{dN_\gamma}{dE}(E) = 2 \times \frac{1}{3} \times \frac{1}{x_\gamma} \times \frac{dN_p}{dE}\left(\frac{E}{x_\gamma}\right) \quad (6)$$

The fractional energies x_i are determined by the average pion inelasticity measured to be approximately 0.2 at accelerators. In the approximation that the pion decay products carry equal energies, we obtain that $x_\nu \simeq 0.25 \times x_\pi \simeq 0.05$ and $x_\gamma \simeq 0.5 \times x_\pi \simeq 0.1$.

Notice that one can eliminate the initial cosmic ray flux to obtain a relation between secondary gammas and neutrinos. It just follows from the fact that there are 2(1) charged pions for every neutral pion in pp(p γ) interactions and, after taking into account oscillations, 2(8) photons for every ν_μ . The flux referred to sums over neutrinos and anti-neutrinos which the experiments cannot separate. For instance, for the case of a E^{-2} spectrum elimination of the cosmic ray flux from above equations yields:

$$\frac{dN_\nu}{dE}(E) = \frac{1}{4} \times \frac{x_\gamma}{x_\nu} \frac{dN_\gamma}{dE}(E) \simeq \frac{1}{2} \frac{dN_\gamma}{dE}(E). \quad (7)$$

We expect one muon neutrino (and antineutrino) for every two TeV gamma ray of pion origin. In the photoproduction case the neutrino flux is reduced by a factor 4.

4. The Sources of Galactic Cosmic Rays

In 1934, Baade and Zwicky[24] pointed out that supernovae could be the sources of the Galactic cosmic rays provided that a substantial fraction of the energy released in the explosion is converted into the acceleration of relativistic particles. Their proposal has been commonly accepted despite the fact that to date no source has been conclusively identified, neither of cosmic rays, nor of accompanying gamma rays and neutrinos produced when they interact with Galactic hydrogen. Galactic cosmic rays reach energies of at least several PeV, the ‘‘knee’’ in the spectrum; therefore their interactions should generate gamma rays and neutrinos from the decay of secondary pions reaching hundreds of TeV. Such sources are referred to as PeVatrons. Straightforward energetics arguments are sufficient to conclude that present air Cherenkov telescopes have the sensitivity to detect TeV photons from PeVatrons.

A first step into pinpointing the sources of the Galactic cosmic rays may have been taken when an all-sky survey in the 10 TeV energy region revealed a subset of sources not readily associated with known supernova remnants or with non-thermal sources observed at other wavelengths [25]. They are associated with nearby star forming regions in Cygnus and in the vicinity of galactic

latitude $l = 40$ degrees. Subsequently air Cherenkov telescopes were pointed at 3 of the sources revealing them as potential PeVatrons with a very hard gamma ray energy spectrum that extends to tens of TeV without evidence for a cutoff [26, 27]. This is in sharp contrast with the best studied supernova remnants RX J1713-3946 and Vela Junior.

Pions are produced when the cosmic rays in the expanding remnant interact with the hydrogen in the Galactic plane. In the star forming regions where supernova are more likely to occur, the cosmic rays can interact with dense molecular clouds. Expecting an association of supernova and molecular clouds, the Milagro sources are suspected to be molecular clouds illuminated by the cosmic ray beam from remnants within ~ 100 pc. One expects that multi-PeV cosmic rays are accelerated only during a short period when the remnant transitions from the 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 times as they diffuse through the interstellar medium to interact with nearby molecular clouds; for a detailed discussion see reference [28].

Despite directed observations to reveal plausible candidate TeV sources, the basic hurdle to conclusively associate the observed TeV gamma rays with the decay of pions produced by a cosmic accelerator has not been overcome. Synchrotron radiation by energetic electrons followed by inverse Compton scattering, routinely observed in non-thermal sources, cannot be excluded as their origin. Neutrinos from the decay of charged pions accompanying pionic gamma rays can provide incontrovertible evidence for cosmic ray acceleration in the source. It has been argued for some time that the brightest sources produce TeV neutrino rates comparable to the background of atmospheric neutrinos[31]. It is likely that a neutrino signal should emerge after several years from the data of a kilometer-scale detector as the predicted fluxes are at the level of the background from atmospheric neutrinos. Especially for the case of molecular clouds, the neutrino flux should be predictable at a quantitative level as any confusion of pionic gamma rays with gamma rays of electromagnetic origin should be minimal[28]. Let's try to quantify these claims.

The energy density of the cosmic rays in our Galaxy is $\rho_E \sim 10^{-12}$ erg cm $^{-3}$. Galactic cosmic rays are not forever; they diffuse within the microgauss fields and remain trapped for an average containment time of 3×10^6 years. The power needed to maintain a steady energy density requires accelerators delivering 10^{41} erg/s. This happens to be 10% of the power produced by supernovae releasing 10^{51} erg every 30 years (10^{51} erg correspond to 1% of the binding energy of a neutron star after 99% is initially lost to neutrinos.) This coincidence is the basis for the idea that shocks produced by supernovae exploding into the interstellar medium are the accelerators of the Galactic cosmic rays.

A generic supernova remnant releasing an energy of $W \sim 10^{50}$ erg into the acceleration of cosmic rays will inevitably generate TeV gamma rays by interacting with the hydrogen in the Galactic disk. The emissivity in pionic gamma rays Q_γ is simply proportional to the density of cosmic rays n_{cr} and to the target density n of hydrogen atoms. Here $n_{cr} \simeq 4 \times 10^{-14}$ cm $^{-3}$ by integrating the spectrum for energies in excess of 1 TeV. For a E^{-2} spectrum,

$$Q_\gamma \simeq c \left\langle \frac{E_\pi}{E_p} \right\rangle \lambda_{pp}^{-1} n_{cr} (>1 \text{ TeV}), \quad (8)$$

$$\simeq 2cx_\gamma \sigma_{pp} [n n_{cr}]. \quad (9)$$

or

$$Q_\gamma(> 1 \text{ TeV}) \simeq 10^{-29} \frac{\text{photons}}{\text{cm}^3 \text{ s}} \left(\frac{n}{1 \text{ cm}^{-3}} \right). \quad (10)$$

The proportionality factor is determined by particle physics; x_γ is the average energy of secondary photons relative to the cosmic ray protons and $\lambda_{pp} = (n\sigma_{pp})^{-1}$ is the proton interaction

length ($\sigma_{pp} \simeq 40$ mb) in a density n of hydrogen atoms. The corresponding luminosity is

$$L_{\gamma}(>1 \text{ TeV}) \simeq Q_{\gamma} \frac{W}{\rho_E} \simeq 10^{33} \text{ photons s}^{-1}, \quad (11)$$

where W/ρ_E is the volume occupied by the supernova remnant. We here made the approximation that the volume of the young remnant is approximately given by W/ρ_E or, that the density of particles in the remnant is not very different from the ambient energy density $\rho_E \sim 10^{-12} \text{ erg cm}^{-3}$ of Galactic cosmic rays.

We thus predict a rate of TeV photons from a supernova at a nominal distance d of order 1 kpc of

$$E \frac{dN_{\text{events}}}{dE} (>1 \text{ TeV}) = \frac{L_{\gamma}}{4\pi d^2} \simeq 10^{-12} - 10^{-11} \left(\frac{\text{photons}}{\text{cm}^2 \text{ s}} \right) \left(\frac{W}{10^{50} \text{ erg}} \right) \left(\frac{n}{1 \text{ cm}^{-3}} \right) \left(\frac{d}{1 \text{ kpc}} \right)^{-2}. \quad (12)$$

Such sources must emerge in an all-sky TeV gamma ray survey performed with an instrument with the sensitivity of the Milagro experiment [25].

Above estimate ignores the fact that supernovae are not uniformly distributed but are associated with regions of star formation such as the Cygnus region and the center of the Galaxy. Dense molecular clouds, common in star forming regions, should be efficient at converting cosmic rays into pions that decay into gamma rays and neutrinos. To date, the Milagro collaboration has identified 6 such PeVatron candidates. Not surprisingly, they cluster in star forming regions in the nearby spiral arms, four in the Cygnus region (MGRO J2019+37, MGRO J2031+41, MGRO J2043+36 and MGRO J2032+37) and two more (MGRO J1908+06 and MGRO J1852+01) near galactic longitude of $l = 40$ degrees. One has to realize that, after subtracting the sources considered here, an excess of TeV gamma rays persists in the Milagro's skymap from the general direction of the Cygnus region [29]. This "diffuse" flux almost certainly originates in unresolved sources that contribute additional neutrinos.

The spectrum of 3 of the sources supports their identification as a PeVatron. H.E.S.S. observations of MGRO J1908+06 reveal a spectrum consistent with a E^{-2} dependence from 500 GeV to 40 TeV without evidence for a cutoff [26]. In a follow-up analysis the MILAGRO collaboration [30] showed that its own data are consistent with an extension of the H.E.S.S. spectrum to at least 90 TeV. This is suggestive of pionic gamma rays from a PeVatron whose cosmic ray beam extends to the knee in the cosmic ray spectrum at PeV energies. MGRO J2031+41, has been observed [27] by the MAGIC telescope with a spectrum that is also consistent with E^{-2} . The lower flux measured by MAGIC, which we will conservatively adopt in our calculations, is likely attributed to the problem of differentiating the source from the background in a high density environment like the Cygnus region. Finally, the failure of Veritas to observe MGRO J2019+37 at lower energies implies that the slope of the spectrum must be larger than -2.2.

In the end, despite the suggestive evidence, conclusively tracing the observed gamma rays to pions produced by cosmic-ray accelerators has so far been elusive. It is one of the main missions of neutrino telescopes to produce the smoking gun for cosmic-ray production by detecting neutrinos associated with the charged pions.

As previously emphasized, particle physics is sufficient to compute the neutrino fluxes associated with pionic gamma rays. The neutrino flux associated with MGRO J1908+06 is shown in Fig. 4 along with the TeV gamma ray observations from which it is derived. Note the approximate factor of 2 between the gamma ray and neutrino flux previously argued for. The sensitivity of IceCube to the Milagro sources has been evaluated assuming that the 6 sources represent the imprint of the Galactic cosmic-ray accelerators on the TeV sky [31]. While the number of events with energies of tens of TeV is relatively low, it is clear that this is the energy

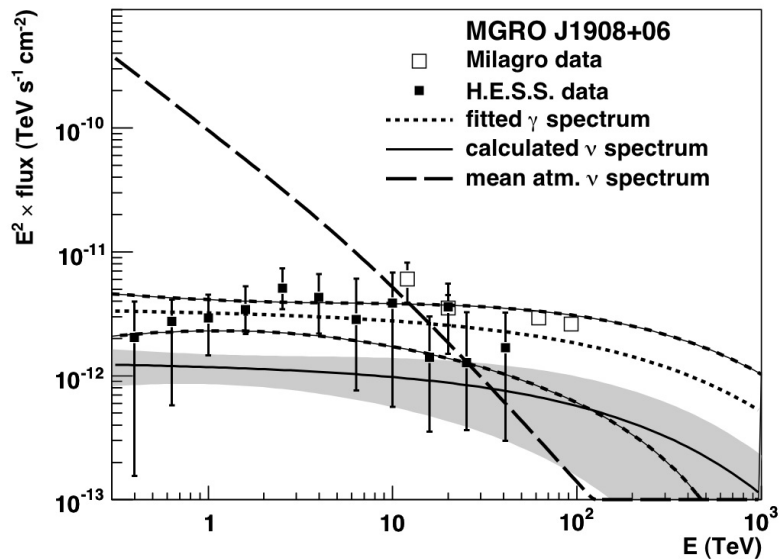


Figure 4. The gamma ray and neutrino fluxes from MGRO J1908+06. The shading surrounding the neutrino flux represents the range in spectra consistent with the statistical and systematic uncertainties on the input gamma ray flux. Also shown is the flux of atmospheric neutrinos at the same zenith angle as the source (dashed line), taking into account the source size and angular resolution.

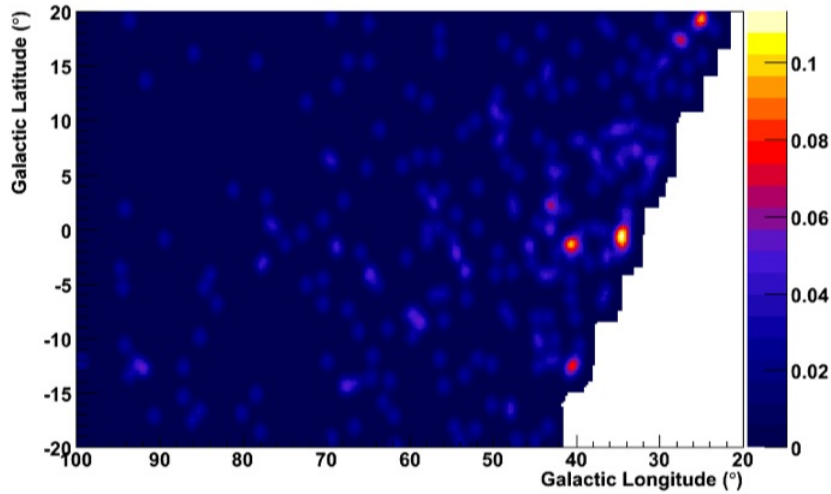
region where the atmospheric neutrino background, also shown in Fig. 4, is suppressed and an excess from these sources can be statistically established. While observing individual sources may in some cases be challenging, establishing a correlation between the Milagro and IceCube sky maps should be conclusive after several years; see Fig. 5. A “stacked” source search that will look for correlations between all six Milagro sources and the IceCube sky map shown in Fig. 5 has a Poisson probability of $3\text{--}5\sigma$ after 5 years; for a sample calculation see Fig. 6. The range reflects the imprecise knowledge of the gamma ray fluxes. The use of optimised methods using unbinned searches beyond the simple binned method considered here will further increase IceCube’s sensitivity.

In conclusion, it is important to emphasize again that the photon flux from the Milagro sources is consistent with the flux expected from a typical cosmic-ray-generating supernova remnant interacting with the interstellar medium. In other words, the TeV flux is consistent with the energetics that is required to power the cosmic ray flux in the Galaxy. Alternative sources such as microquasars have been theorized to contribute to the Galactic cosmic rays. If this were indeed the case, cosmic ray energetics would require that they leave their imprint on the Milagro skymap, but none have been observed so far.

5. The Sources of the Extragalactic Cosmic Rays

We first return to the observable that seemed so revealing in the case of the Galactic component, the energy density which is $\sim 3 \times 10^{-19} \text{ erg cm}^{-3}$ for extragalactic cosmic rays. The power required for a population of sources to generate this energy density over the Hubble time of 10^{10} years is $\sim 3 \times 10^{37} \text{ erg s}^{-1}$ per $(\text{Mpc})^3$ or, as often quoted in the literature, $\sim 5 \times 10^{44} \text{ TeV}$ per $(\text{Mpc})^3$ per year.

As previously discussed, a GRB fireball converts a fraction of a solar mass into the acceleration



IceCube 5 years ($E > 40$ TeV)

Figure 5. Simulated sky map of IceCube in Galactic coordinates after 5 years of operation of the completed detector. Two of the 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.

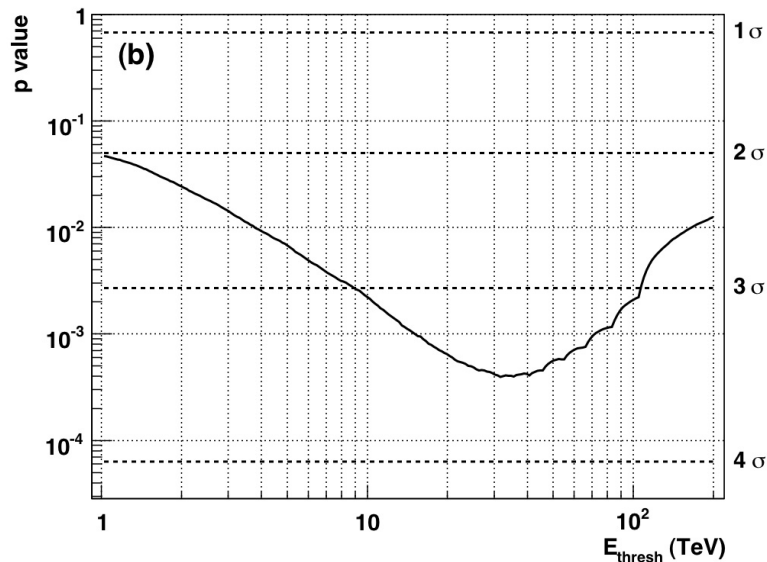


Figure 6. Poisson probability of the excess from the 6 Milagro hotspots after 5 years as a function of the energy of the neutrino-induced muons and a gamma-ray cut-off of the source at 300 TeV. Clearly most sensitivity is associated with muons with energies in excess of 40 TeV.

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 energies into the acceleration of electrons and cosmic rays. It so happens that $\sim 2 \times 10^{52}$ erg per cosmological gamma ray burst will yield the observed energy density in cosmic rays after 10^{10} years given that their rate is of order 300 per Gpc³ per year. Hundreds of bursts per year over Hubble time produce the observed cosmic ray density, just like 3 supernova per century accommodate the steady flux in the Galaxy. Problem solved? Not really, it turns out that the same result can be achieved with active galaxies.

The energy density of 3×10^{-19} erg cm⁻³ works out to not only [21]

- $\sim 2 \times 10^{52}$ erg per cosmological gamma ray burst, but also to
- $\sim 3 \times 10^{42}$ erg s⁻¹ per cluster of galaxies,
- $\sim 2 \times 10^{44}$ erg s⁻¹ per active galaxy.

The coincidence between above numbers and the observed output in electromagnetic energy of these sources explains why they have emerged as the leading candidates for the cosmic ray accelerators. Whether GRB or AGN, the observational evidence that the 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, neutral and charged pions whose energy ends up in cosmic rays, gamma rays and neutrinos, respectively.

Can IceCube reveal the extragalactic cosmic ray sources? Naively, the neutrino flux should be the same as the observed flux of cosmic rays of Eq. 1. Not so naively, it is about 5 times smaller⁶; we will refer to the energetics estimate for the neutrino flux accompanying the extragalactic cosmic ray accelerators as the band shown in Fig. 7, or

$$E_\nu^2 dN/dE_\nu = 1 - 5 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (13)$$

As illustrated in the figure, after 7 years of operation AMANDA's sensitivity is approaching the interesting range, but it takes IceCube to explore it.

If AGN are indeed the sources, the proximity of Cen A and M87 single them out as potential accelerators. We will review the information on their spectral energy distribution and argue that the observations are consistent, within large ambiguities, with the neutrino flux estimated above. In fact, Cen A and M87, the next nearest FRI whose jet is not aligned to our line of sight, have previously been singled out as potential cosmic ray accelerators on the basis of gamma-ray data [34].

Interpreting TeV gamma ray observations is challenging because the high energy emission of AGN is highly variable and it is difficult to compare multi-wavelength data taken at different times. Extragalactic TeV sources observed so far are all BLLacs, a subclass of Fanaroff-Riley I (FRI) active galaxies whose jets are oriented along our line of sight. The data have yielded no hints of cosmic ray acceleration so far; the observed spectra can be readily accommodated by synchrotron radiation by electrons, followed by inverse Compton scattering of the photons to TeV energy. Exceptionally, the nearby FRI M87 was observed in the late 1990's by the HEGRA stereoscopic system of five imaging atmospheric Cherenkov telescopes despite the fact that its jet is angled to more than 30° from our line of sight [35].

Where Cen A is concerned, there exists archival data of TeV emission collected in the early 1970's with the Narrabri optical intensity interferometer of the University of Sydney [36]. At the time the Sydney interferometer unsuccessfully searched the sky for gamma ray sources detecting the highest fluctuation in the direction of Cen A. As a followup they exclusively observed the

⁶ For experts, it is the Waxman-Bahcall "bound" adjusted downward because only 20% of the proton energy is transferred to pions [32].

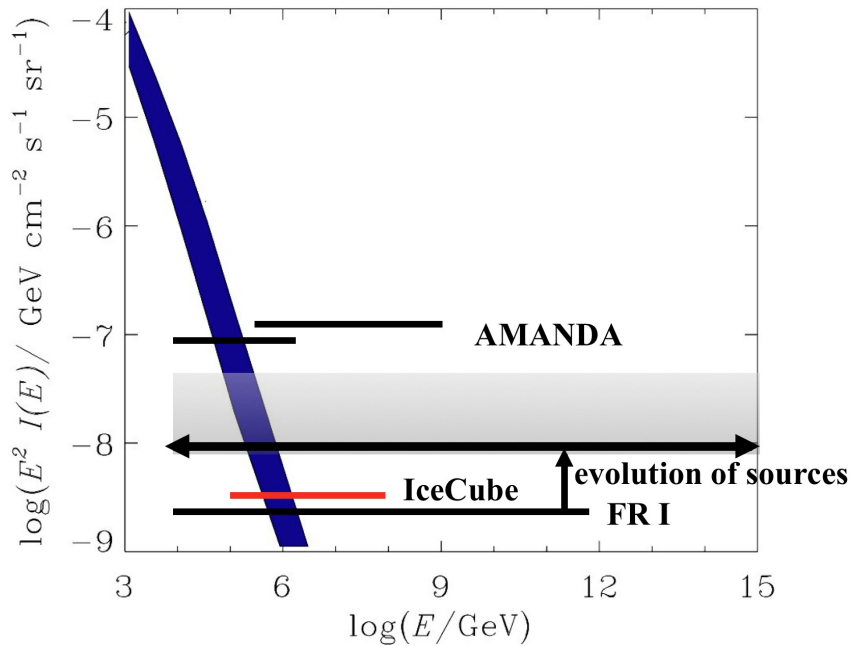


Figure 7. Our energetics estimate of the flux of neutrinos associated with the sources of the highest energy cosmic rays (the shaded range) is compared to the limits established by the AMANDA experiment and the sensitivity of IceCube [33]. Also shown is the flux derived from the assumption that AGN are the sources which we model using spectral energy information on the nearby active galaxies Cen A and M87; see Fig. 8. Integration of AGN to larger redshifts can reconcile the two estimates which differ by a factor 3. Also shown is the background flux of atmospheric neutrinos.

source for a 3 year period. A variable flux was observed in two periods of heightened activity lasting roughly one year, pointing at a region of coherent emission of size of order 0.3 pc. This is consistent with the idea that the high energy emission is from an isotropic region near the base of the jet or the central black hole of mass 2×10^8 solar masses, about two orders of magnitude more massive than the one at the center of our Galaxy [34]. The fact that the interferometer beam did not include the radio lobes at the end of the jets further supports the idea of a central engine at the base of the jets. An average flux of

$$dN_{\gamma}/d(\ln E)(E_{\gamma} > 0.3 \text{ TeV}) = 4.4 \pm 1.0 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \quad (14)$$

was reported for the period of 3 years over which the source was variable.

The integrated flux of Cen A is close to the one observed by HEGRA [37] from M87

$$dN_{\gamma}(E_{\gamma})/d(\ln E)(E_{\gamma} > 0.73 \text{ TeV}) = 0.96 \pm 0.23 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}, \quad (15)$$

after scaling the flux of M87 at 16 Mpc to the distance to Cen A and adjusting for the different thresholds of the experiments. The observations are therefore consistent with identical source luminosities of roughly $7 \times 10^{40} \text{ erg s}^{-1}$, assuming an E^{-2} gamma-ray spectrum. This suggests that they may be generic FRI, a fact we will exploit to construct the diffuse neutrino flux from all FRI. Recently, MAGIC reported short day-long bursts of M87 [38] pointing at acceleration of particles even closer to the black hole. This, as well as the absence of associated X-ray activity expected in the case of electromagnetic processes, further supports the possibility of cosmic ray acceleration.

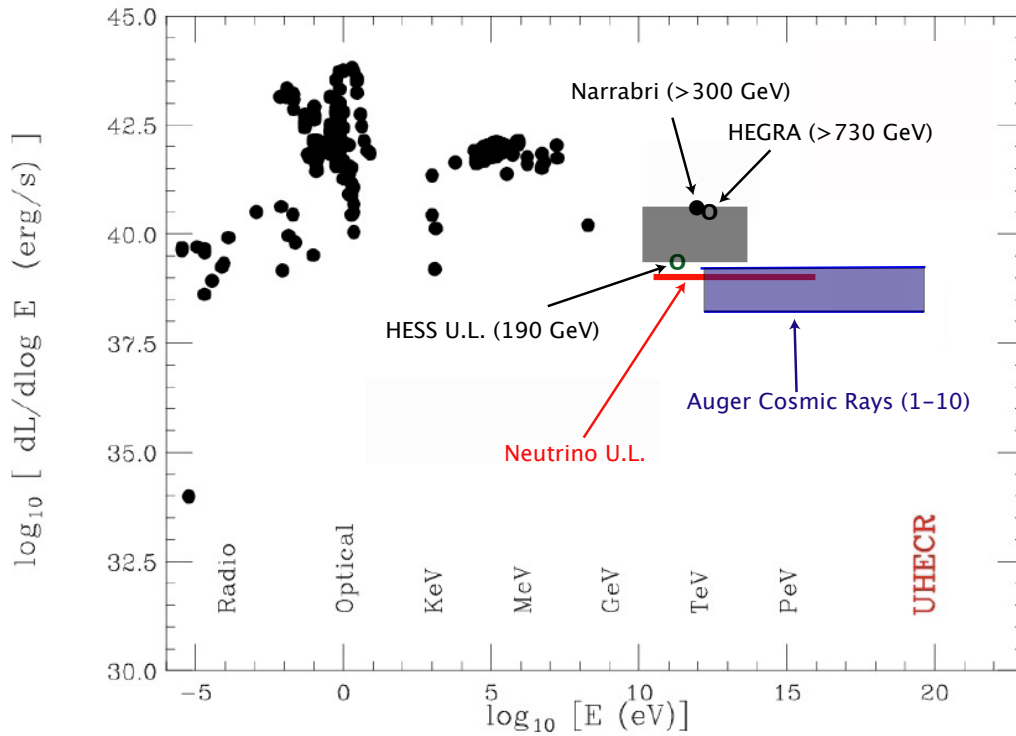


Figure 8. Spectral energy distribution of Cen A (black dots). Having in mind that the source is variable, we show our estimates for the flux of TeV gamma rays (gray shading) and cosmic rays assuming that between 1 and 10 events observed by Auger originated at Cen A (blue shading). We note that the cosmic ray and TeV gamma ray fluxes estimated in this paper are at the level of the electromagnetic component shown from radio waves to GeV photons. Our estimate for the neutrino flux (labeled upper limit) is shown as the red line.

For completeness, the H.E.S.S. experiment obtained a limit on Cen A [39] of 10^{-12} in the same units, a flux smaller than the one just argued for. Given the burst nature of the data the disagreement may be acceptable. We have compiled the TeV gamma ray data in Fig.8 along with other observations on the multi-wavelength emission spectrum of Cen A recently compiled by Lipari [40].

The same conversion of TeV gamma rays to neutrinos, exploited for Galactic sources, yields a neutrino flux of

$$\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left(\frac{E}{\text{TeV}} \right)^{-2} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}, \quad (16)$$

conservatively normalized not to exceed the contemporary limit of the H.E.S.S. experiment.

Finally, having previously argued for a relation between the energetics of TeV gamma rays, cosmic rays and neutrinos, we ask the question what Auger data may reveal about the flux of the source. The answer depends on the number of events in their sky map, N_{events} , that actually correlate with Cen A, a number that depends on the angular broadening of the source by the deflection of the particles by magnetic fields [41]. N_{events} is therefore a matter of speculation. We estimate the flux assuming a power-law spectrum of the form $dN/dE = N_0(E/E_0)^\alpha$, where the normalization N_0 is fixed by the number of events observed N_{events} . For $\alpha = -2.0$, we have $N_{\text{events}} = \text{field of view} \times \text{time} \times \text{efficiency} \times N_0/E_{\text{thresh}}$. This gives us $dN_{\text{cr}}/dE = N_{\text{events}} \times 10^{-13}(E/\text{TeV})^{-2} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$. The number of events with

energy in excess of 6×10^7 TeV may be as many as 10, thus obtaining the range of cosmic ray fluxes shown in Fig. 8. It is close to, but below the flux of TeV gamma rays and suggest an even smaller neutrino flux than the one derived from TeV gamma ray information. The variability of the source and the possibility of a more complicated shape of the spectrum clearly prevent us from reaching quantitative results on the basis of the present data.

The neutrino flux from a single source such as Cen A is clearly small: repeating the calculation for power-law spectra between 2.0 and 3.0, we obtain, in a generic neutrino detector of effective muon area 1 km^2 , between 0.8 and 0.02 events/year only. Having estimated the neutrino flux from a point cosmic ray source, we calculate next the total diffuse flux from all such sources within our horizon. Given an FRI density of $n \simeq 8 \times 10^4 \text{ Gpc}^{-3}$ within a horizon of $R \sim 3 \text{ Gpc}$ [42], the total diffuse flux from all $4\pi \text{ sr}$ of the sky is simply the sum of the luminosities of the sources weighted by their distance:

$$\frac{dN_\nu}{dE_{\text{diff}}} = \sum \frac{L_\nu}{4\pi d^2} = L_\nu n R = 4\pi d^2 n R \frac{dN_\nu}{dE}, \quad (17)$$

where dN_ν/dE is given by Eq. 1. We performed the sum by assuming that the galaxies are uniformly distributed. This evaluates to:

$$\frac{dN_\nu}{dE_{\text{diff}}} = 2 \times 10^{-9} \left(\frac{E}{\text{GeV}} \right)^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (18)$$

approximately a factor 3 below the flux estimated on the basis of source energetics. Varying the spectral indices as before, we obtain an event rate per km^2 year from the northern sky of between 19 and 0.5 neutrinos per year. Considering sources out to 3 Gpc, or a redshift of order 0.5 only, is probably conservative. Extending the sources beyond $z \sim 1$ increases the flux by a factor 3 or so as was discussed in connection with the results in Fig. 7. We can thus bridge the gap between this and the previous estimate of the cosmic neutrino flux based solely on the energetics of the cosmic rays.

The predicted flux of Eq. 16 should be within reach of IceCube and a future Mediterranean kilometer-scale neutrino telescope. The flux is close to IceCube's 90% confidence level sensitivity in a single year. It follows that detection at the 5σ level should be possible within ~ 5 years.⁷

It is not challenging to produce models that generate a neutrino flux at the level proposed here. For instance [34], the central engine in FRI such as Cen A and M87 may feed a beam dump consisting of the gas surrounding the supermassive black hole⁸.

In summary, while the road to the identification of the sources of the Galactic cosmic ray has been mapped, the origin of the extragalactic component remains as mysterious as ever.

Acknowledgments

I would like to thank my collaborators C. Gonzalez-Garcia, D. Grant, Alexander Kappes and Aongus Ó Murchadha as well as John Beacom, Julia Becker, Peter Biermann, Steen Hannestad and Stefan Westerhoff for valuable discussions. This research was supported in part by the National Science Foundation under Grant No. OPP-0236449, in part by the U.S. Department of Energy under Grant No. DE-FG02-95ER40896, and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

⁷ We here used the atmospheric background flux from charm particles predicted by [43] rather than the larger flux conservatively implemented in the sensitivity calculation presented in the IceCube publication. The enhancement in the charm flux relative to the one used here is a direct consequence of the assumption that charm fragmentation functions scale and therefore clearly unphysical.

⁸ Given the paucity of data, models can be invoked where, alternatively, the gamma rays are produced in photohadronic ($p\gamma$) rather than hadronic (pp) interactions [44] and in the jet rather than the black hole.

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