Contents

2 Findings and Results

Here we describe the scientific findings and results supported by NSF grant 0601088 during the period corresponding to Year 2 of the grant: (06/01/2007 through 05/31/2008). This includes a summary of the observation made, main conclusion, and a list of published results. Information about detector performance for each instrument is found in the Activities section of this report.

2.1 Findings and Results Summary

Both STACEE and Auger have been characterized by the collection of new data and the presentation of new results. For STACEE, we have presented new results from observations and detections of galactic gamma-ray pulsars, active galactic nuclei (AGN), and gamma-ray bursters (GRB), and searches for gamma-ray signatures from dark matter.

For Auger, even as final construction is being completed, Auger has observed cosmic rays at the highest energies, and has already extended the the exposure to several times that achieved by all previous experiments combined. Auger has reported first results for cosmic ray energy spectra, new upper limits on the fraction of gamma-rays which places a strong constraint against top-down source models, and upper limits on tau neutrinos. Additionally, the Auger experiment has presented a major result in the detection of anisotropy for the highest energy cosmic rays where we have shown that the arrival directions are correlated with the positions of relatively near by Active Galactic Nuclei (AGN). This new result conclusively demonstrates the extragalactic nature of the sources of the highest energy cosmic rays and opens the door on the prospects for conducting "charged particle astronomy", with the ultimate goal of identifying individual astrophysical sources in the sky.

2.2 STACEE Finding and Results

STACEE has operated a regular observing program since early 2001. During the year 2007, we completed a series of observation on extragalactic sources, pulsars, and gamma-ray burst candidates. These observations are summarized in the Activities section of this report. Although STACEE was shut down and decommissioned during this past year, several new results from STACEE were reported. Some of the results from this year's observations, along with the completed analysis of previous years' observations, are described below.

2.2.1 Gamma-ray Pulsars: PSR1951+32

STACEE reported new results from 12.5 hours of observation of the galactic gamma-ray pulsar PSR1951+32 [1]. This source is has properties similar to other EGRET-detected pulsars such as the Crab. The measure of maximum energy for significant pulsed emission is an important constraint to distinguish between "polar cap" and "outer gap" emission models, where a detection of emission at energies up to around 100 GeV would strongly favor the outer gap models.

STACEE detected no evidence of pulsed emission at energies to to about 100 GeV. Figure 1 shows a phaseogram of STACEE observations of PSR1951+32 folded using the radio ephemeris of the pulsar. Here the flat profile shows no evidence for pulsed gamma-ray emission at higher energies. This means that the emission must cut off sharply in the energy range between EGRET observations (about 1 GeV) and STACEE observations (about 100 GeV).

2.2.2 Active Galaxies:

Results from several active galaxy observations by STACEE were reported in several publications as follows:

Markarian 421: The first STACEE detection of this sources was reported in 2001 [2]. Mrk 421 is a nearby blazar that occasionally flares to several times the brightness of the Crab in TeV energies. STACEE observed in 2004 Mrk 421 as part of a multi-wavelength campaign, shown in Figure 2. In this instance, we reported an energy spectrum for the source. The STACEE data points, which extend to considerably lower energies than other experiments, suggest a significant flattening in the Mrk 421 at about 100 TeV consistent with an Inverse Compton (peaked) emission model for the source. These results were published by June, 2007 [3].

EGRET Blazars 3C66A and OJ287: STACEE has also reported on results from observations of two related AGN named 3C66A and OJ287. These sources were detected by EGRET and identified as "Blazars" with spectral energy distributions at lower energies that suggests that an Inverse Compton spectrum from either source might peak in the STACEE energy range.

Figure 3 show the broad-band spectrum of 3C66A from radio through gamma-ray including the STACEE upper limits published in 2005 [4]. Figure 4 shows the new plot published this past year with revised limits based on a more effective method of hadron selection in the STACEE

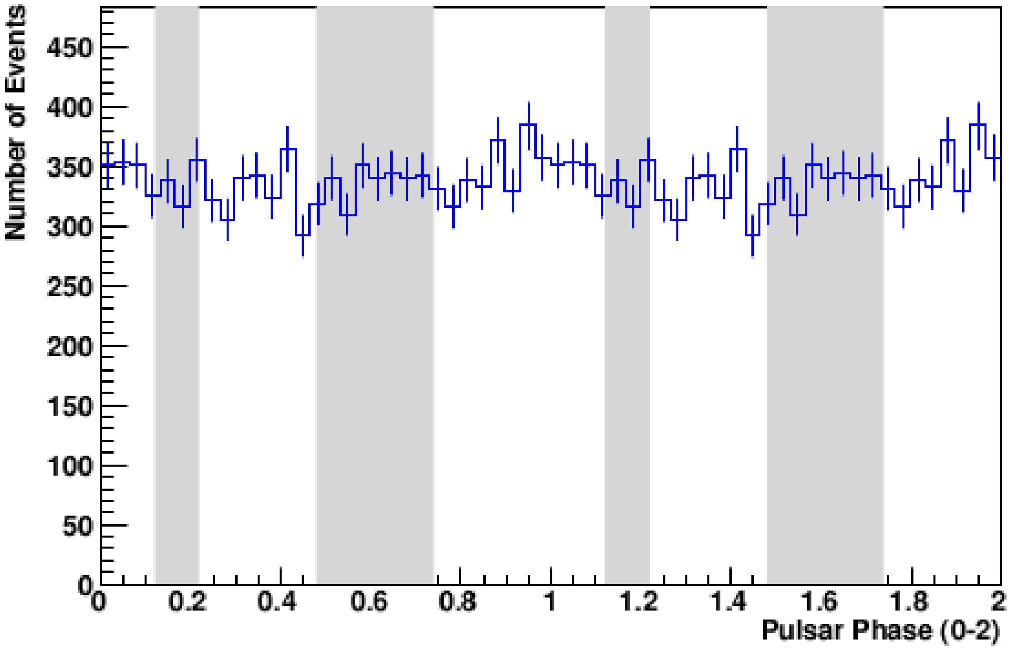


Figure 1: Phaseogram of candidate STACEE gamma-ray events for PSR B1951+32 folded using the pulsar's radio ephemeris. The shaded regions show the position of the main pulse and the interpulse as seen by EGRET.

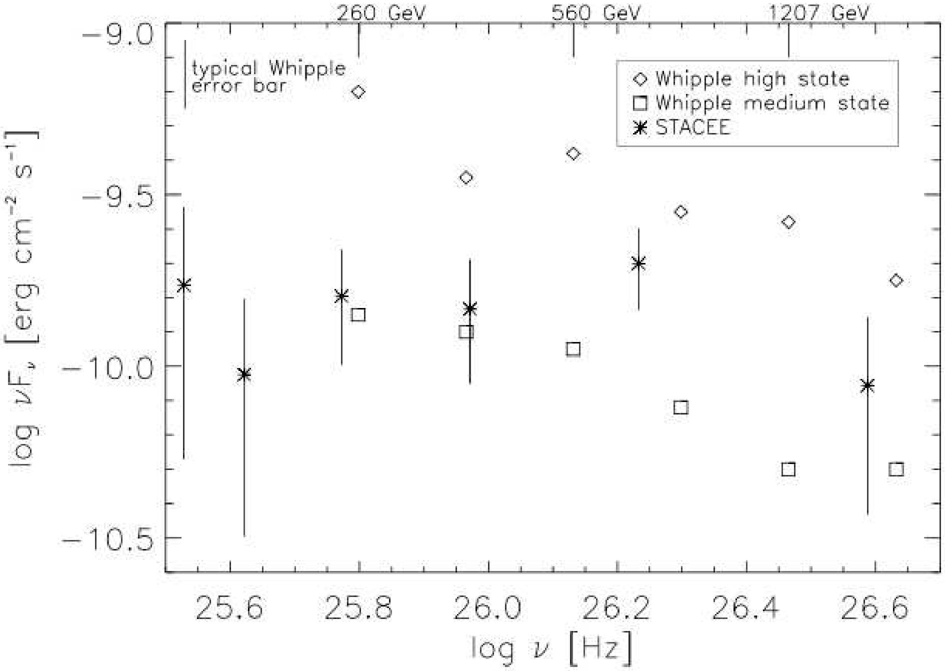


Figure 2: The spectral energy distributions of Mrk 421 from Whipple (open symbols) and STACEE (stars) [3].

analysis [5]. Similar results were obtained and presented for source OJ287 were presented in the same paper.

HBL object 1ES 1218+304: Another promising AGN source for STACEE was 1ES 1218+304 and during the past year, we reported on this source [7]. This source is considered an "HBL" corresponding to an X-ray bright BL Lac objects. The MAGIC experiment reported a detection of this source and presented the first gamma-ray spectrum in 2006 [6]. STACEE upper limits are (barely) consistent with the claimed MAGIC flux at just over 100 GeV as show in Figure 5

2.2.3 Gamma-ray Bursts

One of the most intriguing class of sources are Gamma-ray Bursts. During the past few year, STACEE has operated with an increasingly sophisticated rapid response protocol to observe GRB reported by the GCN. With a large effective area, STACEE has a unique sensitivity and redshift reach in the range from 100 to 250 GeV.

Figure 6 shows the tabulated results from STACEE observations of GRB during through April 2007. STACEE made 20 GRB follow-up observations at times ranging from about three minutes 15 hours after the GCN trigger. No evidence for an excess from any GRB was detected, so that we set upper limits against gamma-ray emission at energies from 150 to 650 GeV. Figure 7 shows

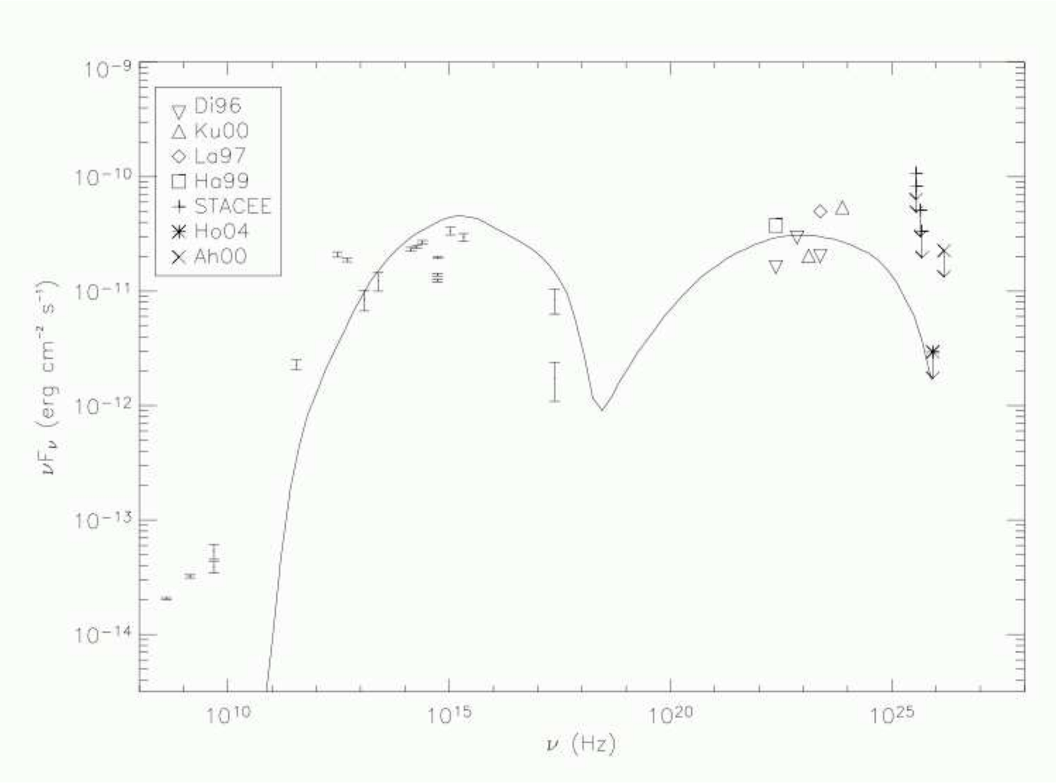


Figure 3: Broad band spectra of AGN 3C66A including the STACEE upper limit from 2005 [4].

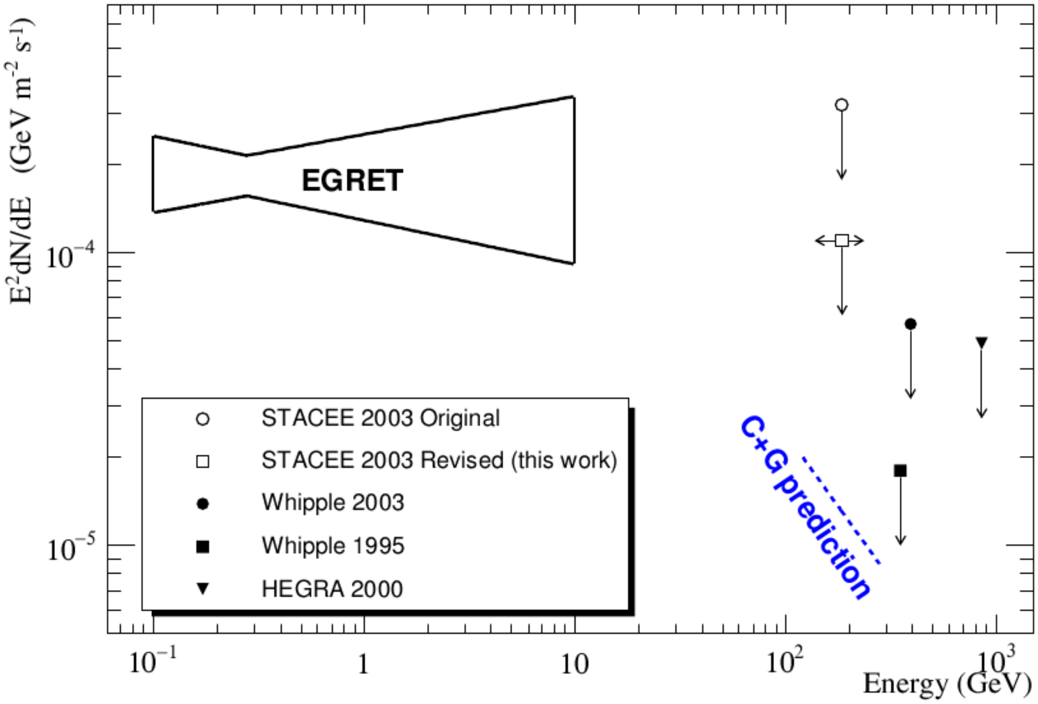


Figure 4: Latest STACEE upper limit results from EGRET blazar source 3C66A [5].

the light curve from NASA's Swift satellite experiment for GRB 050607 vs. the STACEE upper limits [8]. STACEE was able to initiate observations within 193 seconds of the Swift GCN trigger.

2.2.4 Limits on Gamma-ray Emission from Dark Matter

One intriguing possible source of gamma-rays is the dark matter that may be concentrated at the centers of galaxies. In 2006, the CACTUS experiment gave preliminary reports of a possible detection of gamma-rays at 50 GeV associated with the position of the Draco dwarf galaxy. Draco was identified as a promising candidate for emission from dark matter due to it's relatively high mass-to-light ratio. STACEE observed this source in 2006 and 2007 and reported our results this past year [9]. Figure 8 shows the STACEE upper limits against gamma-ray emission assuming a power-law spectral form similar to the Crab. We set upper limits on other spectral forms including those that result from particular assumptions about the mass and interaction cross-section for dark matter candidate particles.

2.2.5 Optical Flashes

As an aside, several members of the STACEE collaboration have been contemplating the potential of using light-collecting systems like STACEE which are designed for Cherenkov detection to be used for detecting possible optical digital communication signals that might be arriving to the earth from distance civilizations. The search for such signal at optical wavelengths has been promoted

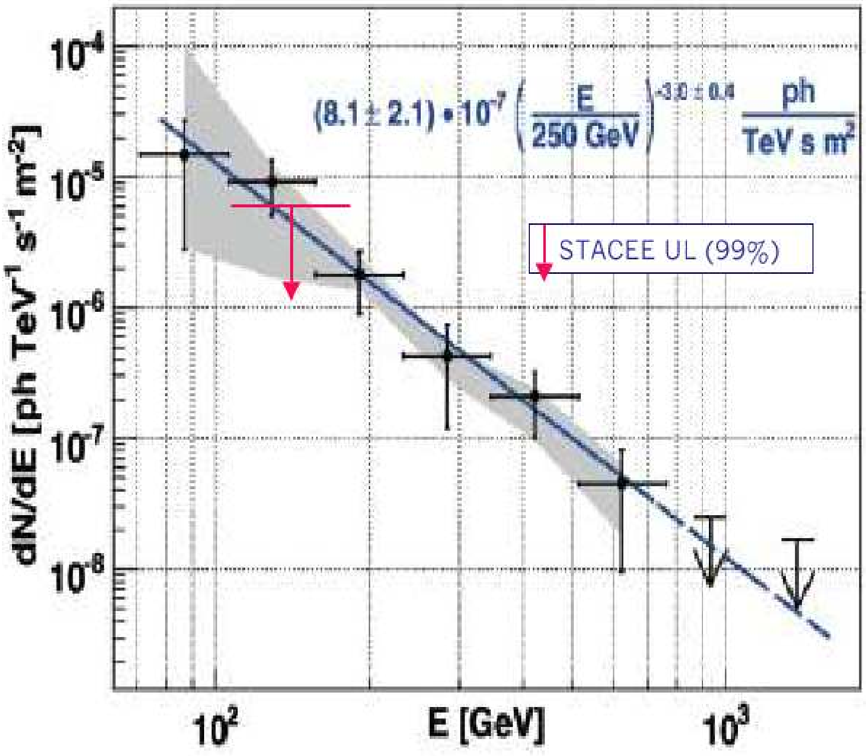
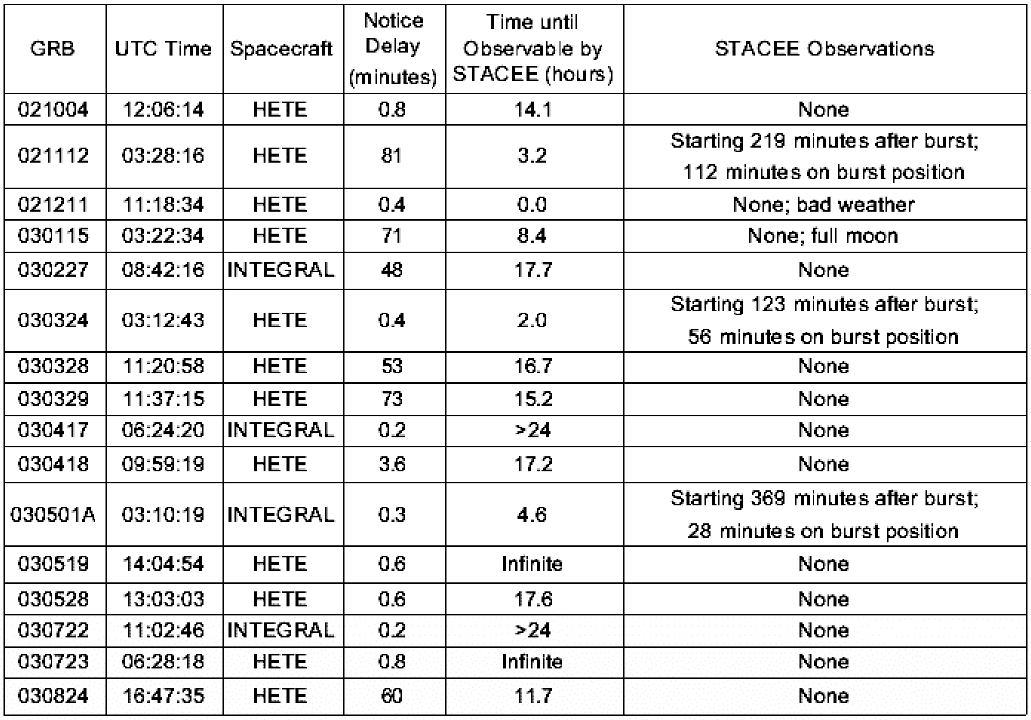


Figure 5: STACEE upper limits vs. MAGIC gamma-ray spectrum for the HBL source 1ES 1218+304 [7].



GRB	UTC Time	Spacecraft	Notice Delay (minutes)	Time until Observable by STACEE (hours)	STACEE Observations
021004	12:06:14	HETE	0.8	14.1	None
021112	03:28:16	HETE	81	3.2	Starting 219 minutes after burst; 112 minutes on burst position
021211	11:18:34	HETE	0.4	0.0	None; bad weather
030115	03:22:34	HETE	71	8.4	None; full moon
030227	08:42:16	INTEGRAL	48	17.7	None
030324	03:12:43	HETE	0.4	2.0	Starting 123 minutes after burst; 56 minutes on burst position
030328	11:20:58	HETE	53	16.7	None
030329	11:37:15	HETE	73	15.2	None
030417	06:24:20	INTEGRAL	0.2	>24	None
030418	09:59:19	HETE	3.6	17.2	None
030501A	03:10:19	INTEGRAL	0.3	4.6	Starting 369 minutes after burst; 28 minutes on burst position
030519	14:04:54	HETE	0.6	Infinite	None
030528	13:03:03	HETE	0.6	17.6	None
030722	11:02:46	INTEGRAL	0.2	>24	None
030723	06:28:18	HETE	0.8	Infinite	None
030824	16:47:35	HETE	60	11.7	None

Figure 6: Tabulated results from STACEE observation of GRB [8].

by several researchers, include the group lead by Paul Horowitz at Harvard. During the past year, several STACEE collaborators have considered the application of the large mirror areas associated with Cherenkov experiments to this problem [10]. During 2007 just before shutting down the experiment, STACEE observed 182 nearby stars. We set upper limits against the emission of any nanosecond optical flashes at a level of about 10 photons per square meter.

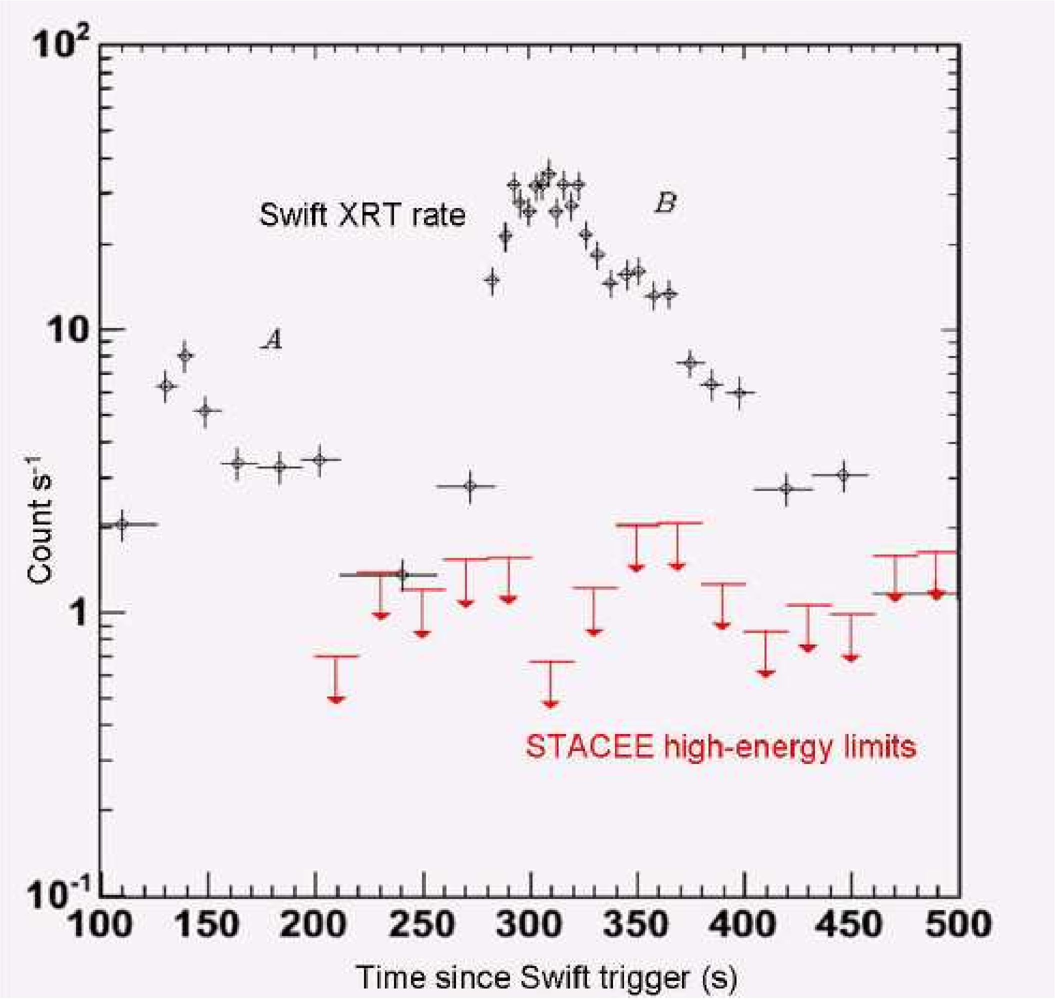


Figure 7: STACEE upper limits for GRB 050607 vs. the Swift XRT light curve. STACEE observations of this source began 193 seconds after the Swift trigger [8].

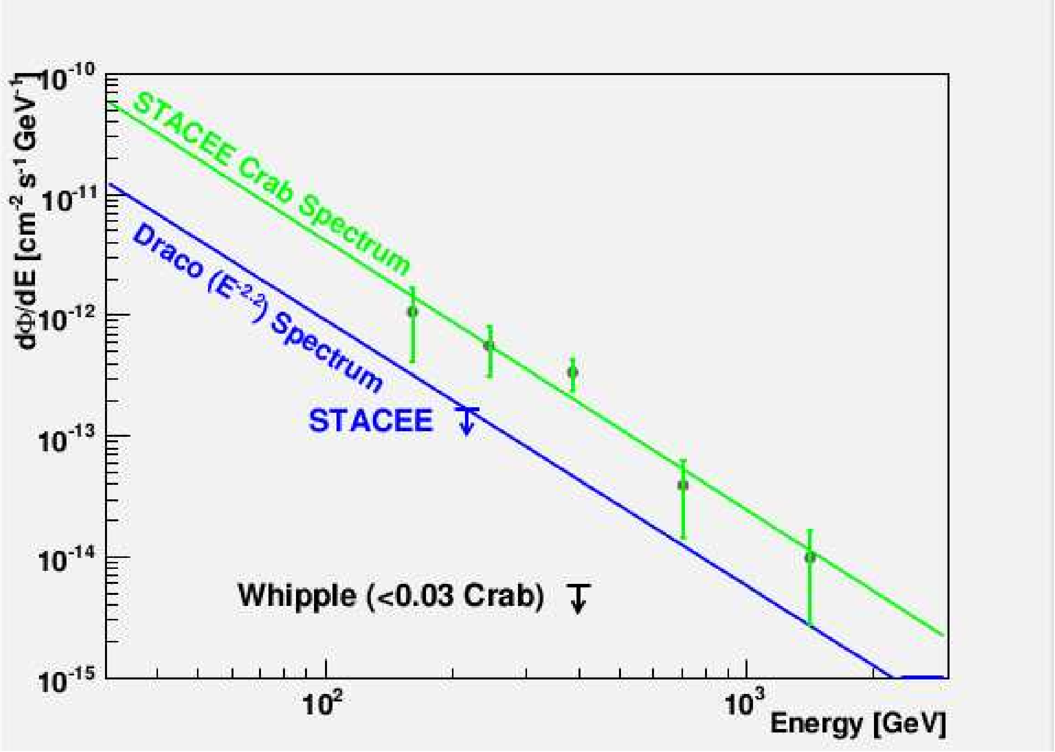


Figure 8: STACEE upper limits from the Draco dwarf galaxy, which as been proposed as a possible source of of gamma-rays due to dark-matter annihilation, assuming a Crab-like spectral form. STACEE upper limits are inconsistent with initial reports of an excess signal from Draco that was reported by the CACTUS experiment but which were subsequently withdrawn. Also shown is the STACEE Crab spectrum [9].

2.3 Pierre Auger Observatory Findings and Results

The Pierre Auger Observatory is the world's largest area cosmic ray detector, and it has already collected considerably more data at the top of the energy scale than have all previous experiments combined. The past year has been characterized by two key milestones: (1) the completion of construction and deployment of the experiment in Argentina, and (2) the first major release of scientific results from the experiment. Results from Auger have been coming out all year, starting with presentation at the 30th International Cosmic Ray Conference in Merida, Mexico, followed by a series of publications in peer-reviewed journals.

Auger has presented result in many areas of cosmic rays physics. Auger has published our latest cosmic energy spectrum, confirming the existence of a significant spectral feature that is consistent with the expected GZK cutoff. Meanwhile, the fluorescence detector has been key for the release of the first Auger compositional results, including significant constraints on the photon fraction of cosmic rays, upper limits on the flux of high energy tau neutrinos, and the first elongation rate measurements that suggest (quite surprisingly) that the composition might be getting heavier at the very highest energies. And perhaps the most exciting result is that Auger has reported the first compelling detection of anisotropy in the arrival directions of the highest energy cosmic rays which appear to be correlated with the positions of nearby Active Galactic Nuclei (AGN). This result categorically demonstrates that the sources of these cosmic rays must be *extragalactic*. Furthermore this result shows that we can use arrival directions to identify source locations, offering significant promise that, with more data, we may be able to someday unambiguously identify individual astrophysical objects as sources of particular cosmic rays.

In the sections that follow we provide some details for each of these new results.

2.3.1 Auger Cosmic Ray Energy Spectrum

The first spectral results from the Pierre Auger Observatory were reported at the 29th International Cosmic Ray Conference in Pune, India, 2005 [14]. Since then, the amount of data has improved several-fold in quantity and the analysis method have been refined. During the 30th ICRC conference in Merida, Auger presented our first energy spectrum with an exposure significantly more than either HiRes Fly's Eye or AGASA [15]. Very recently, the Auger collaboration has submitted a Letter to the Physical Review which includes the latest definitive cosmic ray spectrum [16].

Figure 9 shows the Auger cosmic ray spectrum along with several candidate flux models. As can be seen, there is a clear feature in the spectra consistent with a cutoff at just over $10^{19.5}$ eV expect from the "GZK cutoff". The statistical significance of the cut-off in the spectra is nearly six sigma.

2.3.2 Auger Cosmic Ray Composition

Shower Depth measurements Another important measurement of the cosmic rays is composition, that is identification of the primary particle. Most ultra-high energy cosmic rays are presumed to be hadronic – protons and/or some combination of heavy nuclei. However, there may be significant contributions due to photons, neutrinos, or even more exotic particles. The identification of

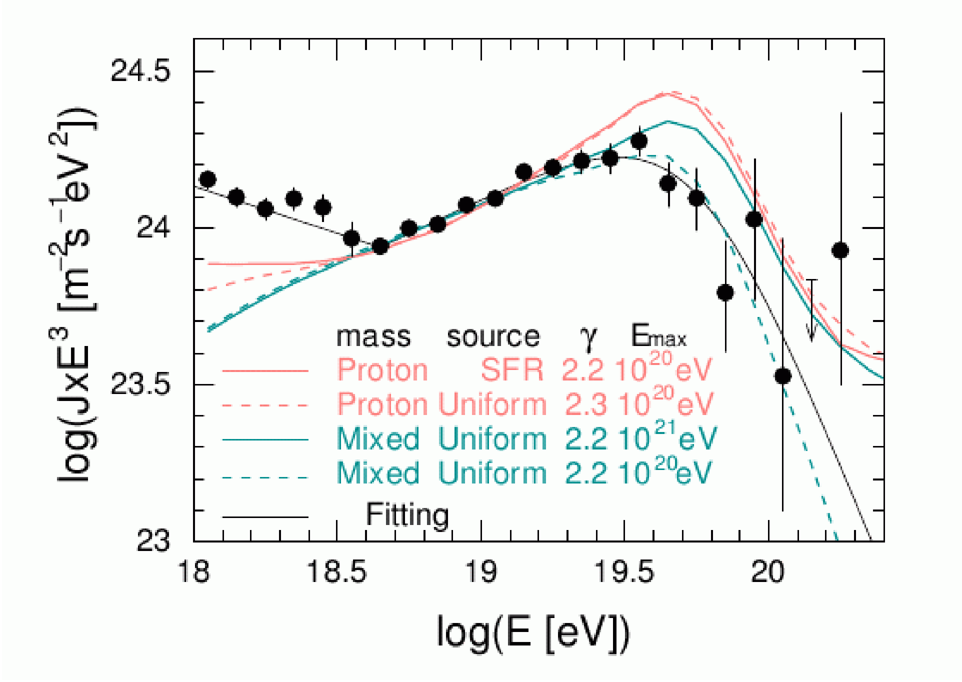


Figure 9: The Auger cosmic ray energy spectrum [15]. The statistical significance of the feature in the spectrum above $10^{19.5}$ is nearly six sigma. The shape of the spectrum is consistent with the form expected from the “GZK cutoff”.

cosmic ray composition would be a powerful signature of their origin. However, identification of individual cosmic rays is challenging because they are detected only indirectly as a result of the air shower. Indeed, in order to make progress in this area, we must rely to some degree on detailed Monte Carlo simulations of air showers which rely on models for particle interactions corresponding to energies that are currently beyond the reach of present-day accelerator-based experiments. Since the systematic uncertainties on such models may be large and difficult to assess, we must proceed with caution, especially with regards to details related to high-energy deep-inelastic hadronic interactions.

One of the more powerful indicators of hadronic composition can be derived from fluorescence observations of the longitudinal development of air showers. The atmospheric depth corresponding to the location in the shower development with the largest fluorescence brightness (and hence the largest number of ionizing particles) is called X_{max} and for any given type of primary cosmic ray, we expect the value of X_{max} to evolve with energy, but in a way that is dependent on composition, with lighter-mass primaries penetrating the atmosphere to a greater depths than heavier-mass primaries at the same energy.

Figure 10 shows the measured evolution of X_{max} as a function of energy presented by Auger [17]. Also shown are red and blue lines corresponding to the expected evolution of pure proton and pure iron primaries respectively according to several different interaction models. Although the statistics are still quite small, we see a somewhat surprising result that there is some

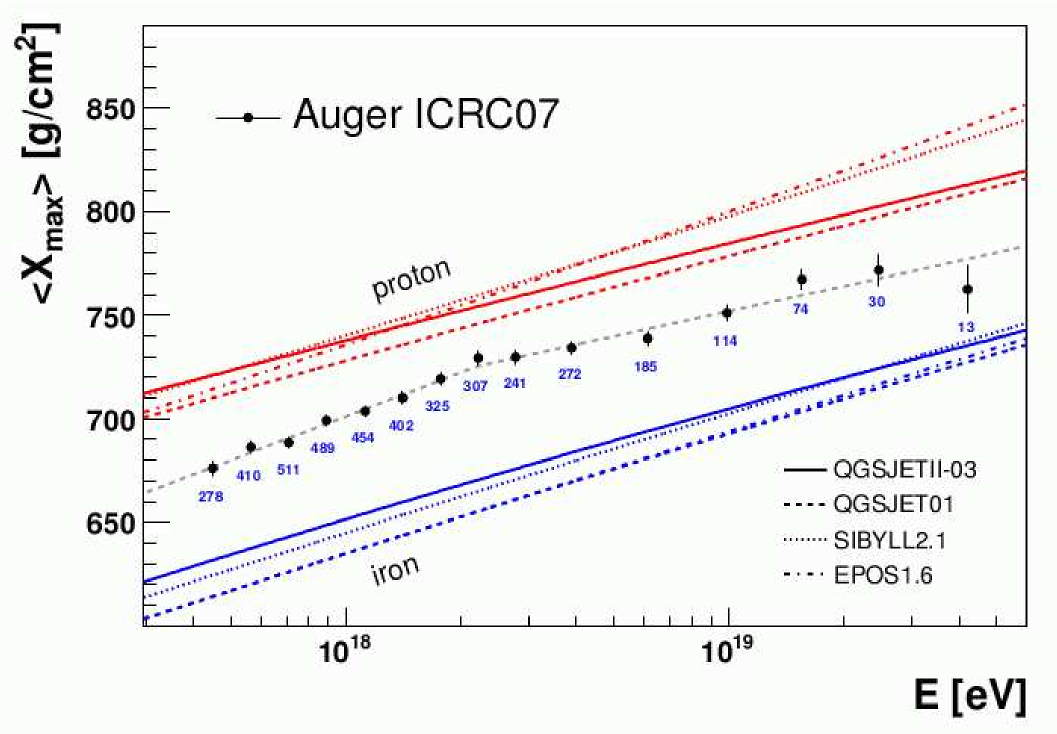


Figure 10: Preliminary average shower maximum depth X_{max} vs. energy for cosmic rays detected by the Auger fluorescence detector [17]. The evolution of X_{max} is a indicator of composition. As can be seen in the plot, there is some indication that the composition of cosmic rays may be evolving from light (proton-dominated) to mixed or heavy (iron-dominated) at the very highest energies.

indication that the composition of cosmic rays may be evolving from light (proton-dominated) to mixed or heavy (iron-dominated) at the very highest energies.

Upper limits on Photon Fraction Since gamma-rays are expected to be more penetrating in the atmosphere and should create cascades that develop differently relative to showers generated by charged hadronic primaries, we can use reconstructed shower information to place strong constraints against the presence of gamma-rays within any subset of Auger detected events. We have used both the fluorescence detector and the surface detector to report new results on photon fraction during the past year [19, 20]. Figure 11 shows the best Auger results so far for the upper limit of the photon fraction n vs. energy. Photon fractional flux upper limits correspond to 2.010^{19} eV, 2×10^{19} eV, and 4×10^{19} eV, respectively. Also shown in the figure are prediction due to various source models. Photon flux limits are particularly constraining against "top-down" models where cosmic rays are due to super-massive relic particle which decay into a large collection of energetic particles at lower energies. Such models unavoidable result in a significant release of high energy gamma-rays due to the decay of unstable particles at higher masses. The results from Auger published this past summer now place considerable constraints against most top-down models.

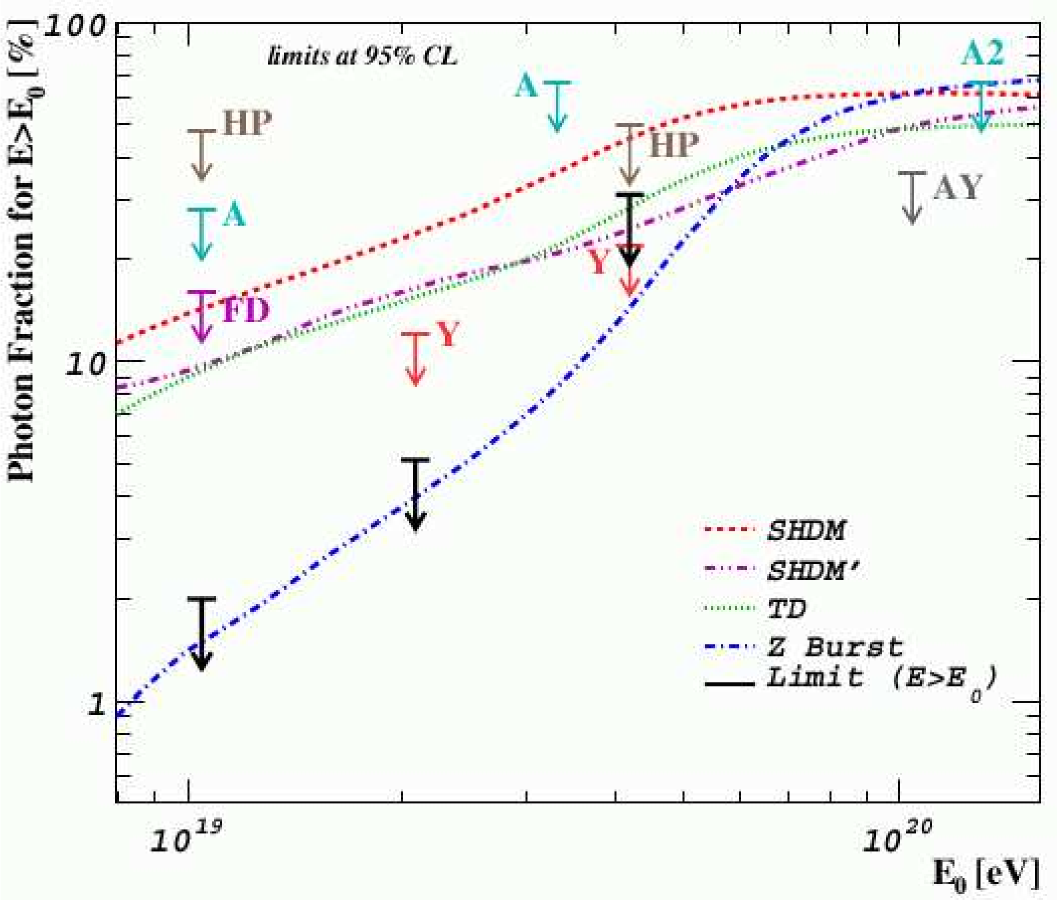


Figure 11: The Auger upper limit on the photon fraction in ultra-high energy cosmic rays [20]. These result place strong constraints against “top-down” cosmic ray models involving the decay of super-heavy relic particles.

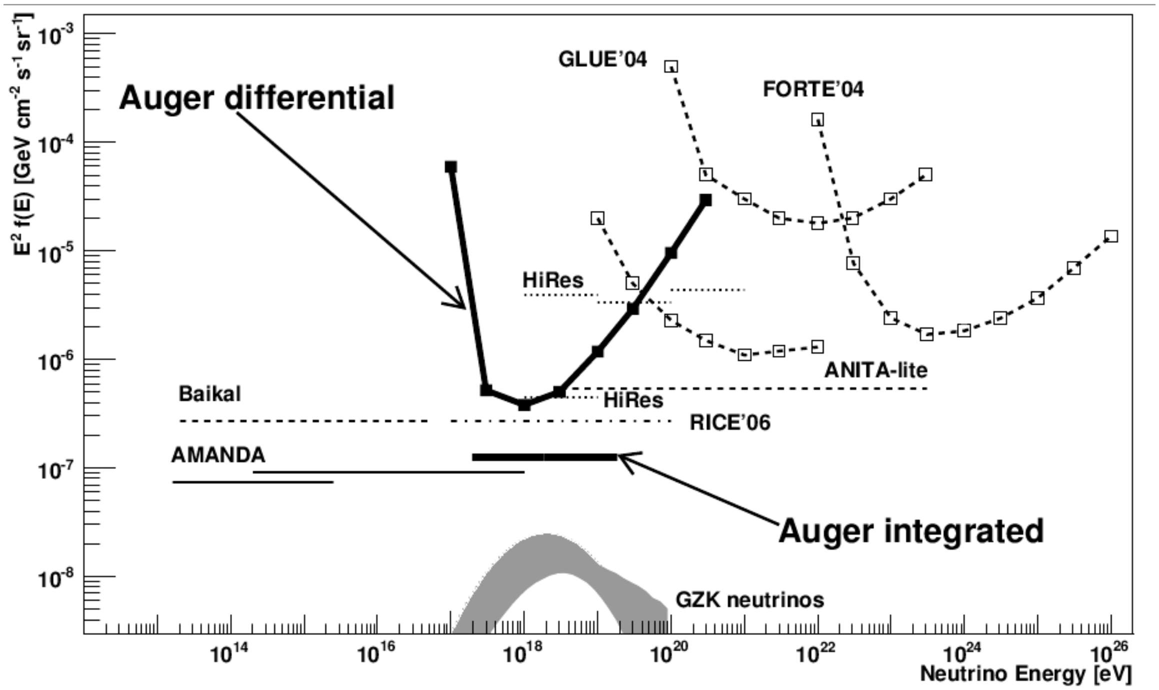


Figure 12: The Auger upper limits on tau neutrinos [18].

Limits on Neutrinos The Auger experiment is also sensitive to neutrinos which can be identified as near-horizontal showers with relatively low reconstructed ages indicating that the shower initiated deep within the atmosphere. Auger is especially capable of detecting tau neutrinos due to the prospects of showers due to "earth-skimming" or mountain-interactions. Figure 12 show the our upper limits against the flux of tau neutrinos in comparison to model predictions and expectations from other experiments [18]. As can be seen, Auger already sets the most sensitive limits in our energy range and has reasonable prospects for detecting the neutrinos that are expected to result due to GZK interactions.

2.3.3 Detection of Anisotropy at the Highest Energies

Probably the most exciting result to come out of Auger this past year involves the search for evidence of anisotropy at the highest energies. These searches are based on the expectation that magnetic deflections will be smallest at the highest energies and therefore the arrival directions of the very highest energy events may be quite closely associated with the positions of the sources in the sky.

Anisotropy Search Protocol: The PI and his student are members of the Auger anisotropy and arrival direction analysis group for the Pierre Auger Observatory. This group is particularly active on the question of whether or not the arrival directions of cosmic rays at the highest energies can give an indication of the source of cosmic rays. Since there is no "standard model" for the nature of cosmic ray sources, we explore anisotropies that might take many forms, depending on the nature of the sources of cosmic rays, ranging from subtle non-statistical anisotropy on large angular scales, to “obvious smoking gun” signals such a large concentration of arrival directions coming from one point in the sky.

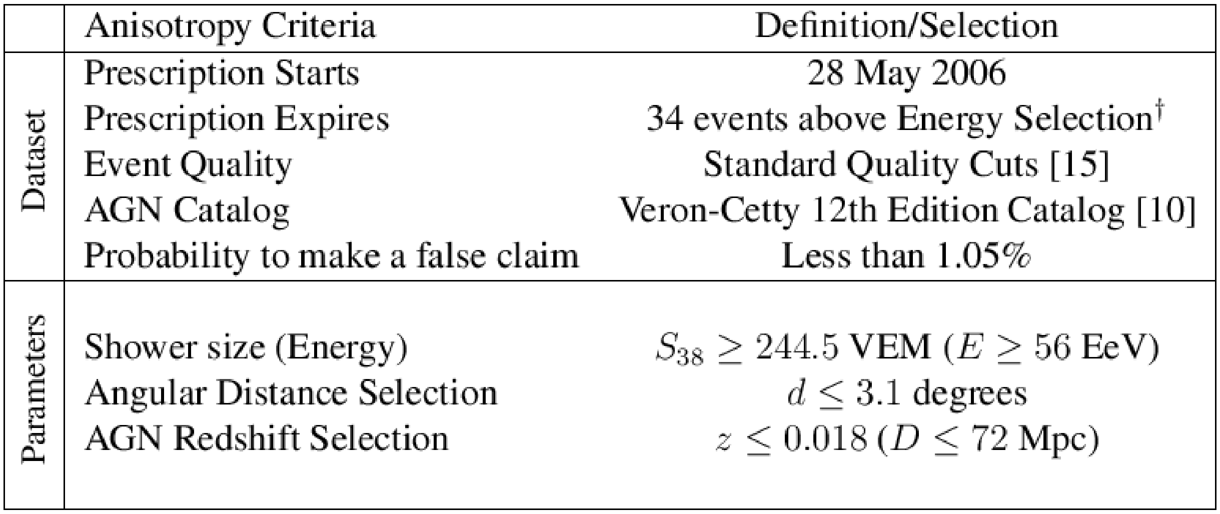
Unfortunately, the history of past searches for correlations between cosmic ray arrival direction and particular candidate astrophysical sources is peppered with statistically dubious effects that remain unconfirmed in subsequent searches. The Auger Collaboration has been especially sensitive to the prospect of mis-identifying signal as a result of improper probability calculations which often significantly underestimate the effect of hidden “trials factors” that result when several investigators on a team try a variety of different cuts on the data to bring out a signal from the noise.

To inoculate our group from such mis-identification, the Auger Collaboration has, from inception, adopted a *prescription protocol* which delineates a formal and statistically specific procedure for searching and reporting on possible anisotropic signals. The key concept is the definition of a “prescription” in the wake of any internally reported candidate signal so that the signal can be independently verified using subsequent (post-prescription) observations. Since the prescription (including all cuts and probability thresholds) is established *a priori* relative to the confirmation dataset, the probability calculation can be done accurately.

The PI has been especially active in the context of investigating potential candidate sources and verifying the proper statistical application of the Prescription Protocol. In essence, the PI serves with a small, independent group designed to internally regulate the consideration, analysis and reporting and policy-related issues related to any putative signals. This task has required considerable activity during the past two years. However, this effort has lead to a considerable benefit for Auger since this Prescription Protocol is what has allowed us to identify and self-verify a new and very exciting results.

AGN Correlation: In November 2007, the Auger group announced that we had detected evidence for anisotropy based upon a measured correlation between the very highest energy cosmic rays and the positions of relatively nearby AGN. These results were reported in a letter to Science [11] which were then quickly followed up by a longer paper to *Astroparticle Physics* [12].

The AGN correlation result follows the Auger protocol described above. In early 2006, a search for correlation between Auger events and AGN positions was conducted. This first search corresponds to an *exploratory scan* where the minimum probability was found while searching over three parameters: (1) energy bound, (2) angular displacement and (3) AGN redshift distance. Based on the exploratory scan, a prescription was established and endorsed by the Auger collaboration, and then applied to future data. Figure 13 shows a table of the prescription parameters established for conducting an *a priori* search with fixed cuts on future data (after 28 May 2006). We defined a *running prescription* (also known as a “sequential test”) which allowed us to calculate probabilities after each new event arrived. By mid-summer 2007, the prescription was fulfilled and the results were soon reported, corresponding to a probability against the null hypothesis of isotropy of less than 1.0 percent. We emphasize here that this is *proper* probability, calculated *a priori* and not after the fact.



	Anisotropy Criteria	Definition/Selection
Dataset	Prescription Starts	28 May 2006
	Prescription Expires	34 events above Energy Selection†
	Event Quality	Standard Quality Cuts [15]
	AGN Catalog	Veron-Cetty 12th Edition Catalog [10]
	Probability to make a false claim	Less than 1.05%
Parameters	Shower size (Energy)	$S_{38} \geq 244.5$ VEM ($E \geq 56$ EeV)
	Angular Distance Selection	$d \leq 3.1$ degrees
	AGN Redshift Selection	$z \leq 0.018$ ($D \leq 72$ Mpc)

Figure 13: Prescription parameters established for future a priori search probabilities based on exploratory scan.

Figure 14 summarizes the essential Auger correlation result. For 27 events with reconstructed energies above 56 EeV, 20 of these correlate with 3.2 degrees of AGN within 71 Mpc distance, while the expected number is less than 6 events.

Although not part of the prescription, it is worth considering the events in our sample that do not correlate with AGN. The misses are highlighted in Figure 15. Most of these are near the galactic plane where it is known that the AGN catalog that we used is incomplete.

AGN: sources or tracers? It is worth emphasizing here, as we do in our paper, that the fundamental conclusion of this result is that the cosmic rays are not isotropic. In particular *we do not claim that AGN are the likely sources of cosmic rays.* It is possible that AGN are the sources, but it is also possible that the AGN are *tracers* for the sources. Since AGN are approximately scattered in the vicinity of matter (galaxies, etc.) our result strongly implies that these cosmic rays are arriving from extragalactic distances scales. With such a small level of statistics, we cannot say more at this time.

Our Central Scientific Claim: We Detect Anisotropy: The fundamental result of anisotropy appears to be quite robust and can be seen, even by eye, as shown in Figure 16 where we have only plotted the high energy positions alone. The Auger collaboration is currently preparing a publication to present evidence that establishes the anisotropic nature of the cosmic rays without reference to any specific class of astrophysical sources. This result should be out soon. Meanwhile, Auger collaborators are developing new analysis approaches and are considering new catalogs of potential sources to check against the cosmic ray positions. This work is also being done in the

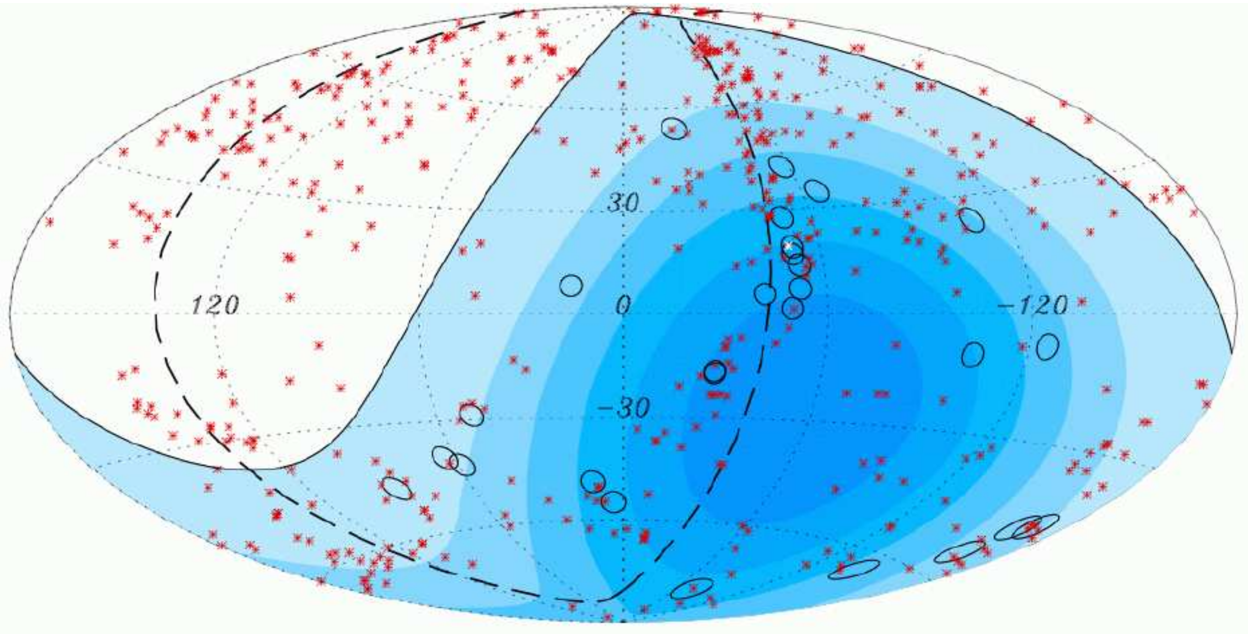


Figure 14: Aitoff projection of the celestial sphere in galactic coordinates with circles of $3.2°$ centered at the arrival directions of 27 cosmic rays detected by the Pierre Auger Observatory with reconstructed energies $E > 57$ EeV [11]. The positions of the 442 AGN (292 within the field of view of the Observatory) with redshift $z \leq 0.017$ ($D < 71$ Mpc) from the 12^{th} edition of the catalog of quasars and active nuclei [13] are indicated by asterisks. The solid line draws the border of the field of view for the southern site of the Observatory (with zenith angles smaller than $60°$). The dashed line is, for reference, the super-galactic plane. Darker color indicates larger relative exposure. Each coloreds band has equal integrated exposure. Centaurus A, one of the closest AGN, is marked in white.

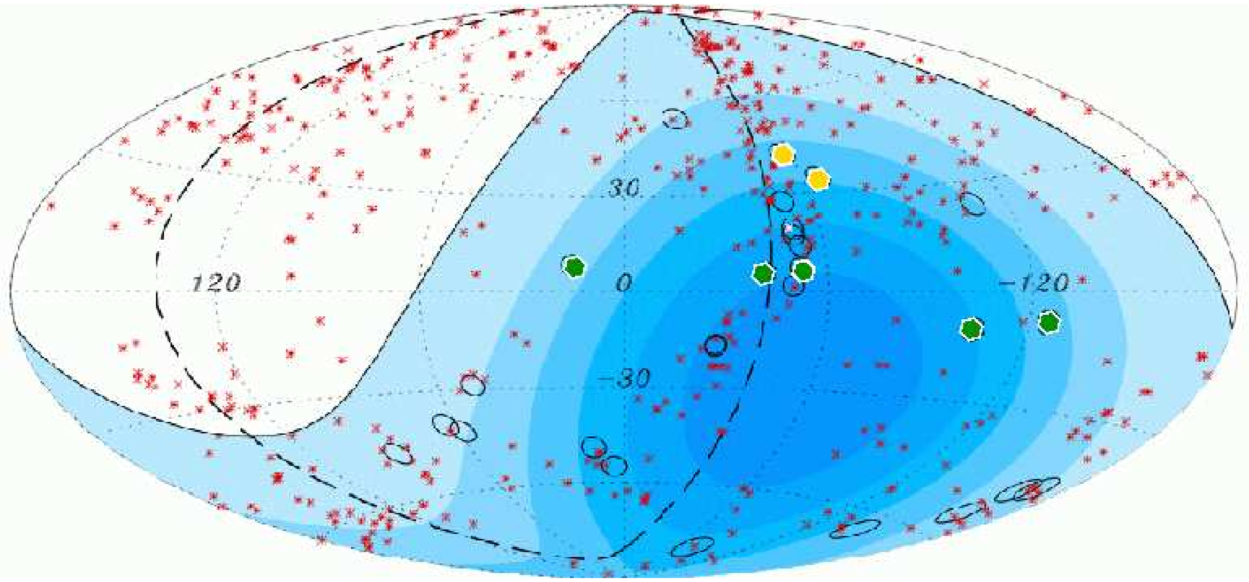


Figure 15: Same as Figure 14 but now events that do *not* correlate are highlighted. Of the seven events that do not correlate, five of these are located within 12 degrees of the galactic plane where the AGN catalog is known to be incomplete.

larger community since Auger has published all cosmic ray source positions and energies for events above 56 EeV which are included in our longer paper [12].

AGN Correlation Result vs. Composition: New Physics? We note that from one common point of view, the correlation result from Auger suggests that the primary cosmic ray particles should be *protons* and not heavier hadronic nuclei. This interpretation is based on the expectation that protons at these energies may be deflected by galactic magnetic field by as much as a few degrees, while heavier nuclei, such as iron, would be deflected by several tens of degrees at least. Thus the anisotropy itself suggests a light cosmic ray composition. But as was described in section 2.3.2, reconstruction parameters suggest that the composition at the highest end is getting *heavier*, not lighter. This apparent contradiction between these two fundamental measured remains unresolved at this time. One possibility is that given the relatively small statistics, the two results may evolve in time to resolve the apparent discrepancy. Another possibility is that the actual cosmic ray deflection is quite a bit larger than would be inferred from the correlation study. Another very intriguing possibility is that the compositional data are misinterpreted because some sort of “new physics” is coming into play at these highest energies. For example, it is possible that the proton cross-section may increase dramatically at these center-of-mass-frame energies, which are just out of reach of collider experiments.

Anisotropy and the case for Auger North: Finally, we note that as it appears to be the case that the sources of cosmic rays are to be found co-located with large-scale structure in the relatively near neighborhood of our galaxy. This implies that the distribution and possibility the spectrum of

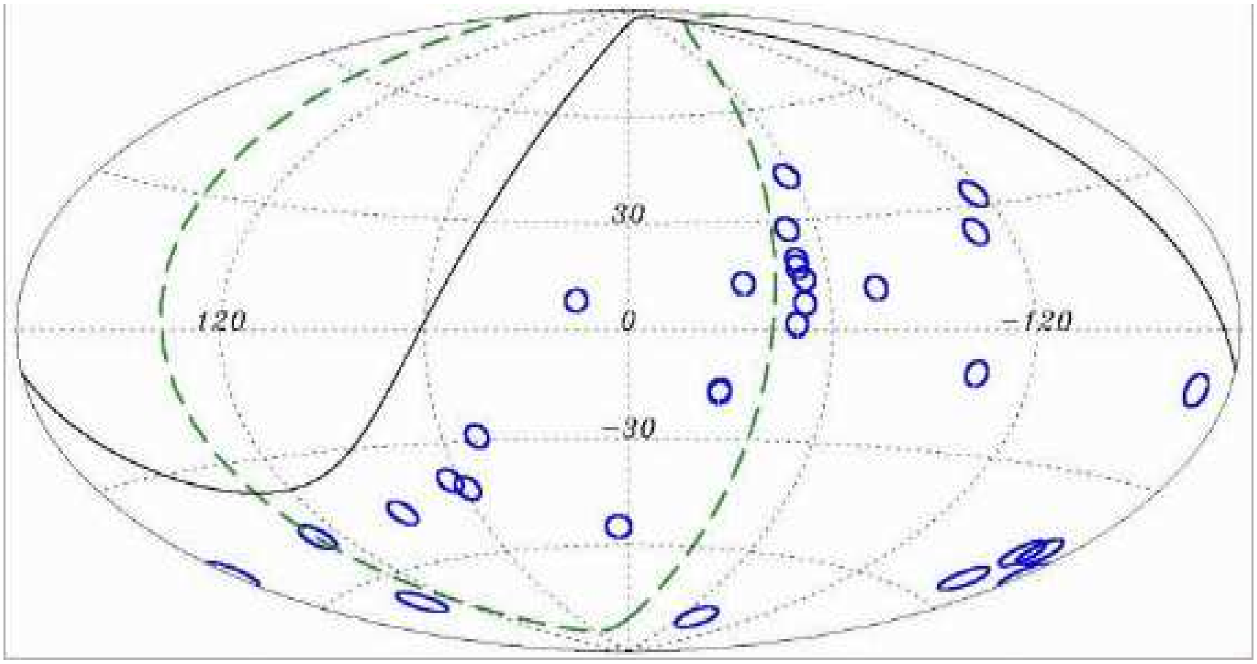


Figure 16: Same as Figure 14 but only high energy events above 56 EeV are shown. Even by eye, the distribution can be seen to be anisotropic. Auger collaborators have developed several analyses to demonstrate that this distribution is statistically inconsistent with an isotropic distribution.

the sources in the northern hemisphere might be quite different from that measured in the southern hemisphere.

Figure 17 demonstrates this, where we have shown the same correlation but now in a celestial (equatorial) coordinate system. As can be seen, all of the exposure for Auger in Argentina corresponds only to the southern hemisphere sky. Auger North will be able to map the arrival of cosmic rays from the remainder of the northern sky where some of largest collections of nearby extragalactic structure can be seen.

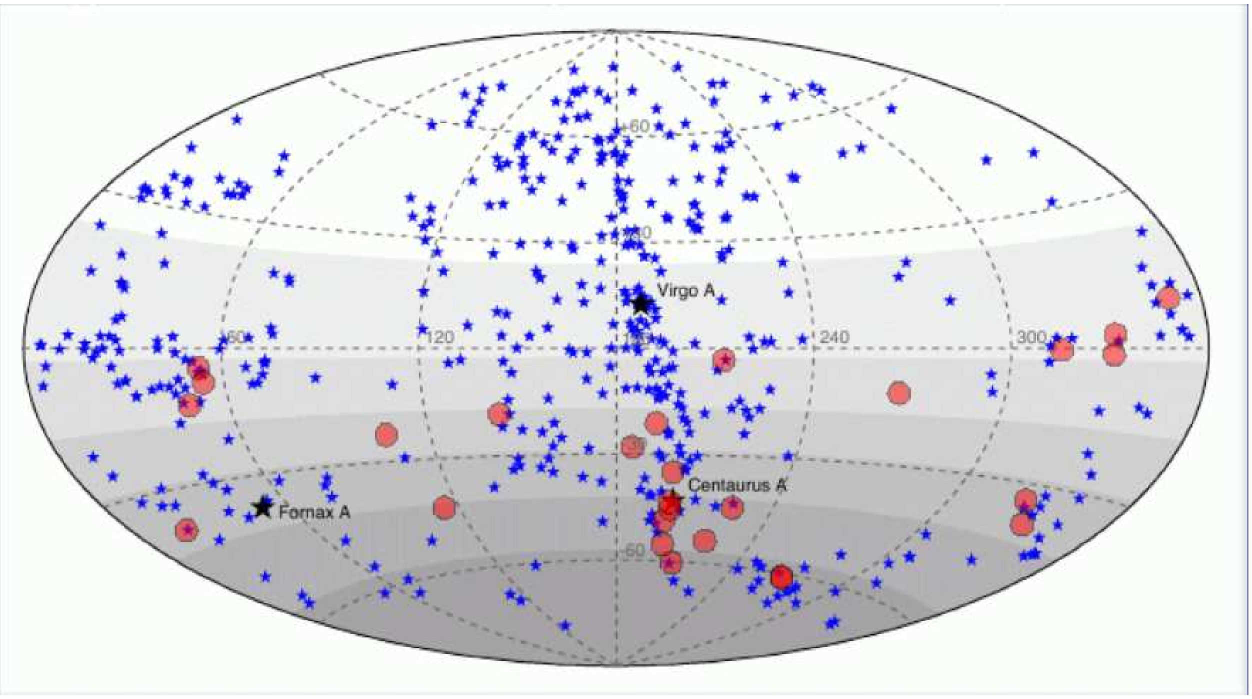


Figure 17: Same as Figure 14 but now projected in celestial (equatorial) coordinates, highlight the concentration of exposure in the southern hemisphere. Also shown are three relatively bright nearby AGN that might be especially promising candidates as sources of cosmic rays.

2.4 References for Findings and Results

References

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