

## **Anisotropy Studies Around the Galactic Center at EeV Energies with Auger Data**

The Pierre Auger Collaboration

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The Pierre Auger Observatory data have been analyzed to search for excesses of events near the direction of the galactic center in several energy ranges around EeV energies. In this region the statistics accumulated by the Observatory are already larger than that of any previous experiment. Using both the data sets from the surface detector and our hybrid data sets (events detected simultaneously by the surface detector and the fluorescence detector) we do not find any significant excess. At our present level of understanding of the performance and properties of our detector, our results do not support the excesses reported by AGASA and SUGAR experiments. We set an upper bound on the flux of cosmic rays arriving within a few degrees from the galactic center in the energy range from 0.8-3.2 EeV. We also have searched for correlations of cosmic ray arrival directions with the galactic plane and with the super-galactic plane at energies in the range 1-5 EeV and above 5 EeV and have found no significant excess.

### **1. Introduction**

The galactic centre (GC) region provides an attractive target for anisotropy studies with the Pierre Auger Observatory. On the one hand, there have been in the past observations by the AGASA experiment indicating a  $4.5\sigma$  excess of cosmic rays (CRs) with energies in the range 1-2.5 EeV in a  $20^\circ$  radius region centered at  $(\delta, \alpha) \simeq (-17^\circ, 280^\circ)$  [1]. A later search near this region with a reanalysis of SUGAR data [2], though with smaller statistics, failed to corroborate these findings, but reported a  $2.9\sigma$  excess flux of CRs with energies  $0.8 < E < 3.2$  EeV in a region of  $5.5^\circ$  radius centered at  $(\delta, \alpha) = (-22^\circ, 274^\circ)$ .

On the other hand, since the GC harbors a very massive black hole, it provides a natural candidate for CR accelerator to very high energies. Following the recent high significance observation by HESS [3] of a TeV  $\gamma$  ray source near the location of Sagittarius  $A^*$ , predictions for neutron fluxes at Auger energies have been published [4]. Since neutrons emitted by such a source would go undeflected by galactic magnetic fields, they should appear as a point-like source, just spread by the angular resolution of the experiment (the neutron decay length becomes comparable to the distance to the GC at EeV energies).

### **2. Data Selection**

In this work we use Auger data from 1<sup>st</sup> January 2004 until 6<sup>th</sup> June 2005. We use the events from the surface detector (SD) [5] that passed the 3-fold or the 4-fold data acquisition triggers and satisfying our high level physics trigger (T4) and our quality trigger (T5) [6]. The T5 selection is independent of energy and ensures a better quality for the event reconstruction. This data set has an angular resolution better than  $2.2^\circ$  for all of the 3-fold events (regardless of the zenith angle considered) and better than  $1.7^\circ$  for all events with multiplicities  $> 3$  SD stations [7]. In all our analyses we use a zenith angle cut at  $60^\circ$  like AGASA while SUGAR used all zenith angles.

One concern about the use of Auger data at 1 EeV given the 1.5 km spacing of our SD stations could be the trigger efficiency. Various studies (using Monte Carlo simulation, our Hybrid data set, or the extrapolation of the spectral shape) have shown that our 3-fold trigger efficiency is better than 30% for proton induced showers

**Table 1.** Events statistics

Data Set	>0.1 EeV	[0.8-3.2] EeV	[1.0 - 5.0]EeV	>5.0 EeV	>10.0 EeV
SD	122636	41792	29773	1359	387

and better than 50% for Iron induced shower above 0.8 EeV. The 4-fold trigger reaches the same efficiency at about 2 EeV [8]. The efficiency ratio between Iron and proton is always below 1.6 above 0.8 EeV and this difference can be taken into account when setting upper limits on point sources.

Regarding the hybrid events (i.e. those with both Fluorescence Detectors (FD) and SD signal) [9], despite the lower duty cycle of the fluorescence telescopes and consequently smaller statistics, they offer an excellent angular resolution of  $0.4^\circ$  [7] over the whole energy range and a much lower trigger threshold of 0.1 EeV.

In Table 1 we show the statistics for the SD data-set in the various energy ranges we have used for our studies. This is the first search in the southern hemisphere since the SUGAR analysis and we have over 10 times more statistics.

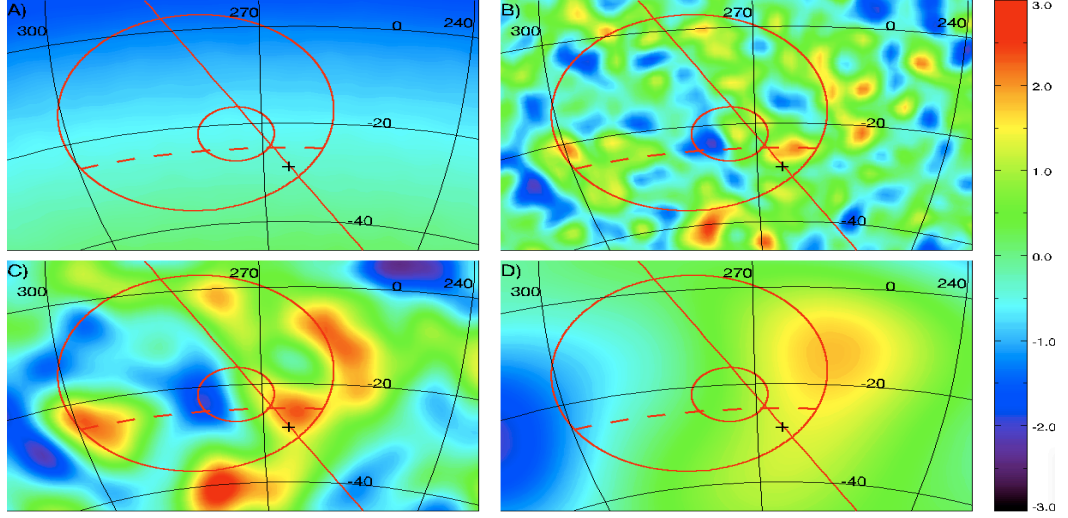
### 3. AGASA and SUGAR Excesses

To estimate the coverage map, needed to construct excess and excess probability maps, we tested two different techniques. The so-called “shuffling” technique where one uses the data to construct randomized isotropic data sets and, alternatively for the SD sample, a semi-analytical method described in [10]. Both techniques are equivalent for studying sources because the Poisson noise in our search window dominates over the uncertainty of our coverage map. This report is based on the shuffling technique. For the hybrid sample, we have defined 24 epochs each corresponding to a given telescope configuration. For the SD sample we have randomized, within 5 bands of zenith angle, the UTC hours and Julian days of the events and drawn the azimuth from a uniform distribution. We present in Fig. 1A the coverage map obtained from our SD sample in a region around the GC. Since we are well within the field of view of Auger there are no strong variation within this region.

In Fig.1B,C,D we present the chance probability distributions (mapped to positive Gaussian significance for excesses and negative for deficits) in the same region for various filtering and energy cuts corresponding to our various searches. In these map the filtering is chosen as to maximize the appearance of eventual structures at a certain scale.  $1.5^\circ$  corresponds to our  $2.2^\circ$  angular resolution and therefore to point sources,  $3.7^\circ$  is similar to a  $5^\circ$  top-hat window and also corresponds to the SUGAR excess size,  $13.3^\circ$  is similar to a  $20^\circ$  top-hat and to the size of the excess reported by AGASA. In these maps the chance probability distributions are consistent with those expected as a result of statistical fluctuations from an isotropic sky.

Regarding the region where the AGASA excess was reported, the results from the Auger Observatory are 1155 events observed, and 1160.7 expected (ratio  $1.00 \pm 0.03$ ) for the energy range [1.0-2.5] EeV. This is almost 3 times the event number of AGASA in this region due to the fact that the GC lies well within the field of view of Auger while it lies outside the one of AGASA. These results do not support the excess observed by AGASA, and in particular not at a level of 22% like the one they reported which would translate into a  $7.5\sigma$  excess. In a worst case scenario where the source would be protons and the background much heavier (e.g. Iron), the difference in detection efficiency of the Auger trigger at 1 EeV would reduce the sensitivity to a source excess. However, using the Fe/proton efficiency ratio at 1 EeV ( $70\%/50\% = 1.44$ , an upper bound in the range [1-2.5] EeV) we would still expect to see a  $5.2\sigma$  event excess in our data set.

There may be systematic differences between the energy calibrations of the two experiments, so we have scanned the region maintaining the high/low energy ratio and moving the interval center by  $\pm 40\%$ . We have also enlarged the interval to [0.8–3.2] EeV. We found no significant excess in any of those cases. Regarding the



**Figure 1.** Lambert projections of the galactic centre region, GC (cross), galactic plane (solid line), regions of excess of AGASA and SUGAR (circles), AGASA f.o.v. limit (dashed line). A) coverage map (same color scale as the significance maps, but in a range [0-1.0]). B) significance map in the range [0.8-3.2] EeV smoothed using the individual pointing resolution of the events and a  $1.5^\circ$  filter (Auger like excess), C) same smoothed at  $3.7^\circ$  (SUGAR like excess), D) in the range [1.0-2.5] EeV smoothed at  $13.3^\circ$  (AGASA like excess).

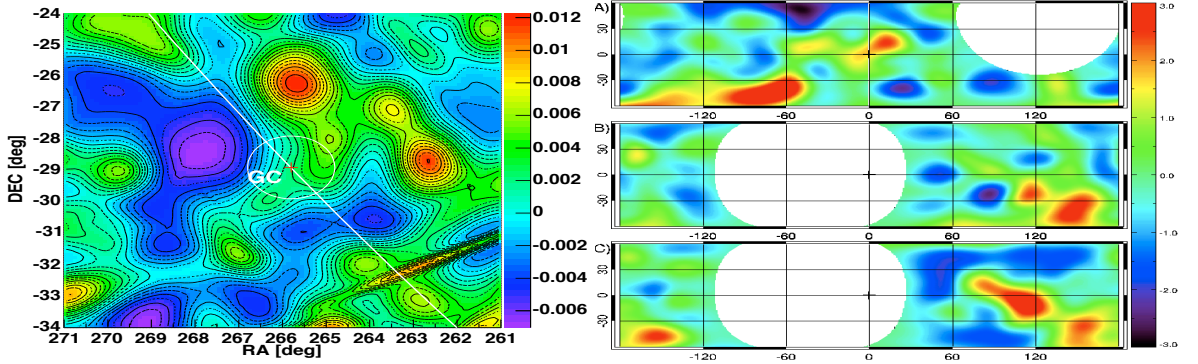
excess claimed by SUGAR, we find in their angular/energy window 144 events observed, and 150.9 expected (ratio  $0.95 \pm 0.08$ ), and hence with over an order of magnitude more statistics we are not able to confirm this claim.

#### 4. Galactic Center

We then searched for signals of a point-like source in the direction of the GC. Using a  $1.5^\circ$  Gaussian filter corresponding to the angular resolution of the SD [7]. In the energy range [0.8–3.2] EeV, we obtain 24.3 events observed and, 23.9 expected (ratio  $1.0 \pm 0.1$ ). A 95% CL upper bound on the number of events coming from a point source in that window is  $n_s(95\%) = 6.3$ . This bound can be translated into a flux upper limit if we know how many events ( $n_s$ ) are expected for a given flux ( $\Phi_s$ ) integrated in this energy range. Since the detector efficiency is energy (and primary composition) dependent at EeV energies, the ratio  $\Phi_s/n_s$  will depend on the spectral shape and nature of the source. In the simplest case in which the source has a spectrum similar to the one of the overall CR spectrum ( $dN/dE \propto E^{-3}$ ), we can relate the two with  $\Phi_s = n_s \Phi_{CR} 4\pi\sigma^2/n_{exp}$  where  $\sigma$  is the size of the Gaussian filter used. Using  $\Phi_{CR}(E) = 1.5 \xi (E/EeV)^{-3} \times 10^{-12}$  ( $EeV^{-1} m^{-2} s^{-1} sr^{-1}$ ) where  $\xi \in [1, 2.5]$  denotes our uncertainty on the CR flux ( $\xi$  is around unity for Auger and 2.5 for AGASA), introducing  $\varepsilon$  the Iron/proton detection efficiency ratio ( $1 < \varepsilon < 1.6$  for  $E \in [0.8, 3.2]$  EeV) and, integrating in that energy range we obtain :

$$\Phi_s < 2.5 \xi \varepsilon \times 10^{-15} m^{-2} s^{-1} \quad @ 95\% \text{ CL.}$$

Since the detector efficiency grows with energy, a harder source flux would lead to a stronger flux bound. In a worst case scenario, where both  $\xi$  and  $\varepsilon$  take their maximum value, the bound is  $\Phi_s = 10.0 \times 10^{-15} m^{-2} s^{-1}$ , and still excludes the neutron source scenario suggested in [1, 11] to account for the AGASA excess, or in [4] in connection with the HESS measurements.



**Figure 2.** Left, the GC region seen by the hybrid detector, the excess map is built using the individual pointing resolution of the events. Right, significance map from the SD data in galactic coordinates for events with  $1 \text{ EeV} < E < 5 \text{ EeV}$  (top), in super-galactic coordinates for events with  $E > 5 \text{ EeV}$  (middle), idem for events with  $E > 10 \text{ EeV}$  (bottom).

Using the better angular resolution of the hybrid reconstruction, we can set a point-like flux limit inside a  $1^\circ$  radius cone around the direction of the galactic center. Due to the limited statistics, all hybrid events with energies above 0.1 EeV (10589) are used in this analysis, we find in this window 4 events observed and, 3.4 expected, showing no significant excess. At 95% CL an upper limit for a neutron source at the GC above 0.1 EeV is:

$$\Phi_s < 1.2 \xi \times 10^{-13} \text{m}^{-2} \text{s}^{-1} \quad @ \text{ 95\% CL.}$$

## 5. Galactic/Super-Galactic Plane Studies

It is expected that the origin of cosmic rays changes from galactic to extra galactic in the 1-10 EeV range. We have looked for an excess of events inside a  $\pm 10^\circ$  band along the Galactic Plane in the energy range from 1 EeV to 5 EeV and along the Super Galactic Planes above 5 and 10 EeV. We observed 5077, 229, and 68 events respectively for expectations of 5083.3, 235.6, and 67.4 (ratios  $1.00 \pm 0.01$ ,  $0.97 \pm 0.07$ , and  $1.0 \pm 0.1$ ) showing no significant deviations. On Fig. 3 we show our corresponding probability maps smoothed on a  $10^\circ$  scale. Again all chance probabilities are consistent with isotropy.

## References

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